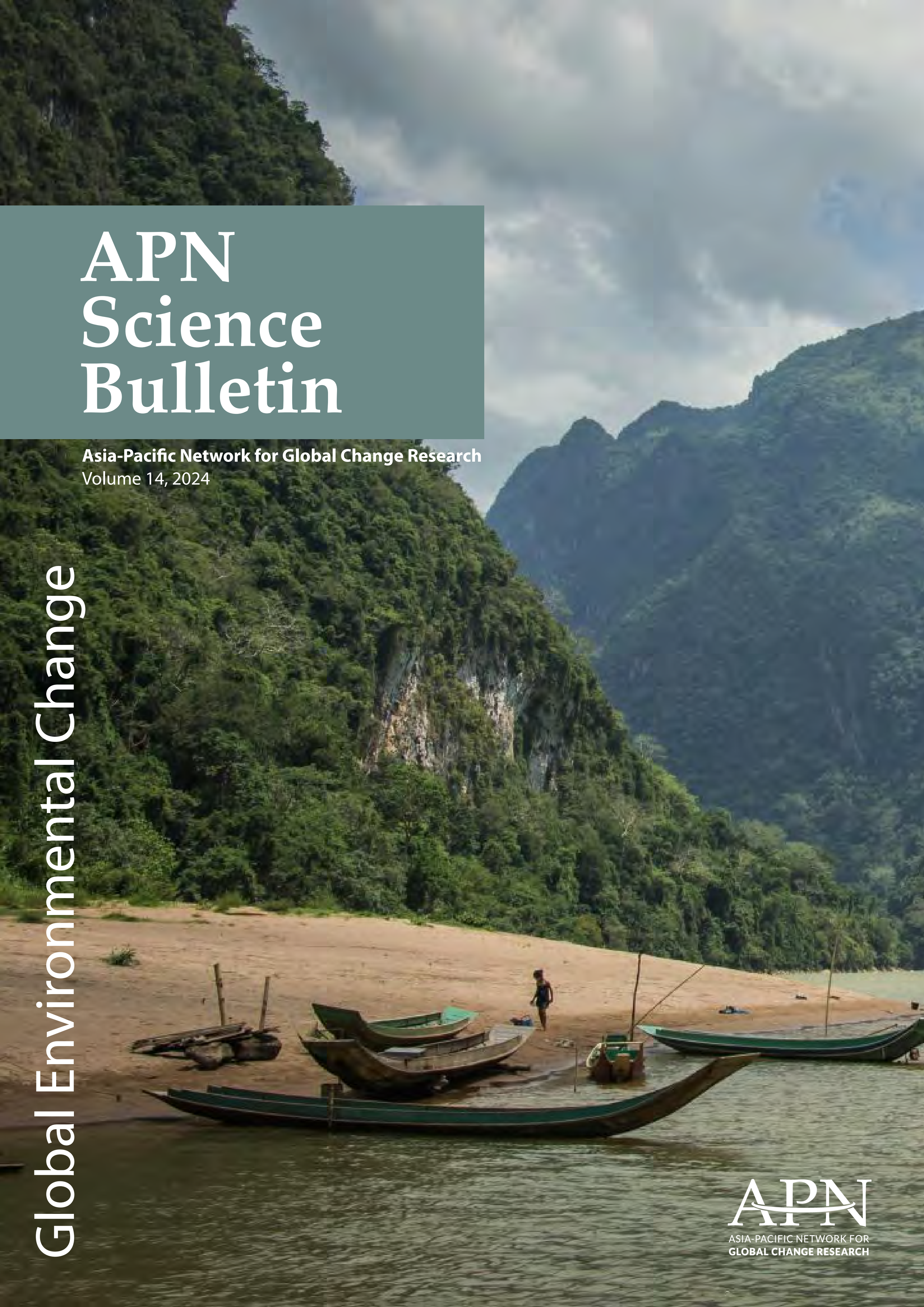

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■ The APN Science Bulletin is a peer-reviewed digital publication that features research and capacity building projects funded by APN. The Science Bulletin is intended for readers from both science and policy-making communities, as well as young scientists in the Asia-Pacific region who are keen on promoting global environmental change, sustainable development and the science of sustainability.

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Preface

On behalf of the editorial board, it is my great pleasure to present the 14th issue of the APN Science Bulletin, our flagship annual publication showcasing the outcomes of APN-supported research and capacity development activities across the Asia-Pacific region.

This issue captures the breadth and depth of scientific inquiry and regional collaboration on key themes that align with APN's strategic agenda, including climate change adaptation and mitigation, sustainable resource management, biodiversity conservation, risk reduction, and ecosystem-based approaches to development. The contributions featured here represent the diverse and timely work of researchers, practitioners, and institutions striving to address global environmental challenges through regionally relevant and locally embedded solutions.

This volume presents a wide array of insights, including ecosystem restoration and river health management in India; scenario-based analysis of mangrove ecosystem services; and grassroots efforts in flood risk management and aquifer recharge across South and Southeast Asia. The issue also features innovative work on climate-smart paddy cultivation, sustainable shrimp aquaculture in the Mekong Delta, and the use of crop simulation modelling for agricultural adaptation in the face of increasing climate risks. Urban sustainability is addressed through integrated assessments of nature-based water treatment systems in Sri Lanka, the Philippines, and Vietnam, while blue carbon ecosystems and marine biodiversity are examined through regional studies in the Coral Triangle and East Asia. These articles collectively contribute to a growing knowledge base for evidence-based policymaking and the strengthening of adaptive capacities across the region.

Each contribution has undergone a rigorous peer-review process to ensure the scientific quality and policy relevance of the work published. I extend my deepest appreciation to all authors and reviewers for their dedication and commitment to advancing regional science and knowledge-sharing.

As we continue to experience the increasing complexity of environmental challenges, this publication aims to foster dialogue and inform science-based decision-making among stakeholders. We hope that the articles in this volume will inspire new collaborations, innovative research, and meaningful action toward building a more sustainable, resilient future for the Asia-Pacific region.

Sincerely,

Linda Anne Stevenson

Managing Editor, APN Science Bulletin
Programme Director, APN Secretariat

Contents

Case study

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Equipping local self governments and development practitioners in managing common pool resources – A case of *Pampa* River in Kerala State, India

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ABSTRACT

Governments face challenges and constraints in managing Common Pool Resources (CPRs) worldwide. Almost all developing countries have begun to implement decentralised policies and decision-making systems for delivering public services and the management of environmental goods. In any government structure, distributing public goods is difficult as it will be challenging to exclude potential beneficiaries from obtaining the goods. Similarly, it's challenging to exclude potential beneficiaries from obtaining benefits from common pool resources. The phenomenal work 'Governing of Commons' argues that the CPRs can be managed locally, provided there need to be well-defined institutions at the local level. The actors can govern CPRs themselves to obtain mutual benefits from the CPRs by avoiding problems of exclusion of beneficiaries, conflicts and exploitation of resources. For establishing well-defined rules and norms, it is essential to have constant deliberations and participation of various actors for collective action in managing CPRs. However, at the decentralised level, most local governments have given less attention to prompt decision-making in CPRs, especially concerning environmental resources. This article investigates the capacity and role of local-level institutions in managing CPRs by discussing a Training of Trainers (ToT) programme associated with the health of the *Pampa* River in Kerala State, India. The ToT programme has helped 41 development practitioners to change their approach toward river health management. The deliberations have resulted in an alliance of practitioners and a people's framework for action projects. It was also studied that the role of local governments and civil society organisations in influencing the decisions made regarding river health management has to be improved.

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KEYWORDS COMMON POOL RESOURCES, RIVER HEALTH, BIOLOGICAL INDICATORS, PAMPA RIVER, LOCAL SELF GOVERNMENTS, DEVELOPMENT PRACTITIONERS

HIGHLIGHTS

- Science-based research should lead to education, public awareness and communication in managing Common Pool Resources.
- Capacity enhancement of the Local Self Governments and development practitioners is crucial in managing Common Pool Resources.
- Deliberations and public participation are crucial for the management of Common Pool Resources.

1. INTRODUCTION: COMMON POOL RESOURCES (CPRS) AND THEIR MANAGEMENT

Common Property/Pool Resources (CPRs) can be generally defined as nonexclusive resources to which the rights of use are distributed among several owners. Magrath (1989, p. 21) also observes that 'membership in the group of co-owners of CPRs is typically conferred by membership in some other groups, such as a village or a tribe, etc.'. The resources managed as common property can contribute to people's employment, income and asset accumulation in several direct and indirect ways that are seldom quantified (Jodha, 1994). Worldwide, governments have been facing challenges and constraints in managing such resources. Managing (CPRs) is a significant governance challenge involving different social actors and institutions. The three influential models[1] for the management of the CPRs are:

1. The 'Tragedy of Commons' in which Hardin (1968) argues that individuals or communities extract the resources without limit and, thus, natural resources get depleted,
2. The 'Prisoners' Dilemma' where the individuals act for their self-interest and don't produce an optimal outcome, and
3. The 'Logic of Collective Action' by Olson (1965) which argues that an individual has little or no incentives to voluntarily contribute when it is difficult to exclude the individual from getting the benefits of the resources.

Considering these models, many major policy solutions to address the issue of the management of resources are focused on the principles of centralisation and privatisation. In both methods of policy solutions, the primary assumption is that the governing agency has complete authority in managing the CPRs. However, these institutions may lack accurate information on the available resources and the number of benefiting users and other stakeholders. Another argument is that CPRs could be managed effectively by the community at the local level (Ostrom, 1990). It is also noted that through interaction and deliberation, the actors at the community level collectively develop institutions that identify the availability of resources, issues and conflicts among the actors. Thus, decentralisation provides an institutional mechanism that allows power to resolve issues at the local level through deliberations. However, at a decentralised level, most institutions or local governments will likely have given less attention to prompt decision-making concerning CPRs (Agrawal & Ostrom, 2001). As a classic example, CPRs, such as rivers, can be effectively managed at the local level, but unfortunately, this is not happening as there are hardly any deliberations between the stakeholders. By discussing the case of the River *Pampa* in the State of Kerala, India, this article aims to investigate the capacity and role of local-level institutions in providing deliberations and public participation for the effective management of River Health Management. The theoretical framework for Managing CPRs, the science and the practice for River Health Assessment (as an example used in the case study) are discussed in Section 2. Section 3 provides a detailed methodology of an independent stakeholder analysis (Section 3.2) and a ToT (Training of Trainers) model project at the mentioned location (Section 3.3). By discussing the results of the analysis and the project, Section 4 discusses the role of local institutions in the effective management of CPRs and Section 5 concludes the paper.

		Subtractability of use	
		Low	**High**
Difficulty of excluding potential beneficiaries	**Low**	Toll Goods	Private Goods
	High	Public Goods	Common Pool Resources

TABLE 1. Types of Goods. Source: Understanding Institutional Diversity (Ostrom, 2005).

2. THE THEORETICAL FRAMEWORK FOR MANAGING COMMON POOL RESOURCES

The phenomenal book "Governing of Commons" (Ostrom, 1990) defines CPRs as a resource system, either artificial or natural resources, where the benefits of resources are shared among a large population, and it is difficult to exclude other beneficiaries from obtaining the use of such resources. Generally, the availability of CPRs will get reduced as it is used by different actor(s), raising the issue of "Subtractability of Use" (Table 1, Ostrom, 2005). This situation of high subtractability and high excludability makes it difficult to manage and govern CPRs. However, access to CPRs can be well managed at individual or community levels who are dependent on the resources. However, the situation in managing CPRs becomes complex as the area of benefit increases and when multiple actors become involved.

In this complex system, where multiple appropriators (the actors who withdraw or use the resources from the resources system) are involved and when the area of benefit is large, these appropriators interact and deliberate with each other to devise rules and norms to manage the CPRs (Ostrom, 1990). These rules and norms could be formal or informal and are enforced collectively to shape individual behaviour in a complex social situation. These rules and norms are defined as institutions (North, 1991). Such institutions evolved through repetitive interactions and deliberations among various actors. Considering the importance of institutions, it is essential to understand how they have evolved and changed, how the actors deliberated these rules and norms, and how they are operationalised. This section discusses the analytical framework of Institutional Analysis and Development (IAD), Decentralisation, Deliberative Public Participation and River Health Management, which are used in this paper to analyse the case of the *Pampa* River.

2.1. An institutional analysis development framework for managing Common Pool Resources

Institutions are defined as a set of rules, norms and shared values (Kiser & Ostrom, 1982; North, 1991; Ostrom et al., 1994). These institutions are invisible and difficult to identify in the complex social structure. The institutions can be categorised as both formal and informal institutions. Formal institutions are rules, laws and regulations. They are written and found in explicit form at the constitutional or operational level, influencing the decisions taken by participants and organisations. The institutions, such as beliefs, norms and customs, form through the traditional interaction among the people in a society. These institutions are defined as informal institutions (North, 1991). The informal institutions are often unwritten and sometimes shared as implicit knowledge. In collective action situations, these institutions shape individual behaviour by achieving collective interest.

Ostrom et al. (1994) have developed an IAD framework to analyse institutional arrangements. It is a systematic study of how the institutions evolve, interact and influence political, economic and social decisions at the individual or collective level. This framework has been widely used in a collective situation to study the provision management of common resources or goods (McGinnis, 2011). Using the IAD framework, Heikkila et al. (2011) studied the interstate rivers and identified the role of cross-scale institutional linkages in the management of CPRs. The IAD framework classifies the institutional arrangements as rules-in-use and categorises them into three types:

1. **Constitutional choice rules** – At the constitutional level (highest level), through governance, the decisions and collective choice rules can be modified. These modifications can determine who is eligible to participate in developing and changing the collective-choice rules, which can influence outcomes and the operational rules.

2. **Collective choice rules** – At the collective choice level, the activities include – policymaking, management and decision-making. These activities can determine who can participate in decisions and how the rules can be changed. At this level, the people involved in the collective choice situations deliberate and discuss the rules which can influence the activities and outcomes at the operational level.
3. **Operational rules** – At the operational level, monitoring and enforcement occur. It "includes decisions about when, where and how to do something; who should monitor the actions of others; how actions should be monitored; what information should be exchanged or withheld; and what rewards and sanctions will be assigned to combinations of actions and outcomes." (Ostrom, 1990, p. 52).

2.2. Decentralisation for managing Common Pool Resources

One basic principle of decentralisation is having power, resources and administrative capabilities for the local communities to govern themselves. The role of local governments is to provide accountability and responsiveness to the citizens for their basic needs and wants. The decentralisation of the governance structure enables citizens to redistribute resources through collective actions. Bardhan and Mookherjee (2006) noted that for developing countries, decentralisation has emerged as an effective strategy for providing public goods and services. The transfer of powers to local government in such countries was political and promoted by domestic or external pressures. And the transfer of powers to govern certain matters is reserved for a centralised system. However, decentralisation provides an institutional arrangement to govern themselves, allowing the citizens to communicate their preferences to elected officials through public participation. These actions are aimed at minimal intervention by the centralised government system. In Governing of Commons, Ostrom et al. (1994) argue that CPRs can be effectively managed locally. The institutional arragement of decentralisation is essential to manage CPRs and the delegation of powers to the local level significantly impacts outcomes related to resource management (Ostrom, 1990). This process of decentralisation affects actions at collective choice and operational level institutions. In India, the transfer of powers was due to domestic pressures. The 73rd and 74th Amendment acts enabled the decentralisation process. The constitutional level rules gave the local governments the power to distribute and allocate public goods. The Gram Sabha, legislative at the local level, acts as the collective-choice rules, and the deliberation at the collective-choice level affects the actions at the operational level. The Gram Sabha provides an institutional mechanism for deliberation and public participation.

2.3. Deliberation and public participation in managing Common Pool Resources

Deliberation is an ability to have consensus in the distribution of resources, resolve conflicts, improve knowledge and establish coordination among the community members, which shapes their identity and preferences. In a complex society, collective choice decisions are made through discussions, debates and critical analysis of the problems through repetitive discussions to have a collective consensus among community members. In other words, it is a governance in which "free and equal citizens (or their representatives) justify decisions in a process in which they give one other reason that is mutually acceptable and generally accessible with the aim of reaching the conclusion that is binding in the present on all citizens but opens to challenge in future" (Padvetnaya, 2017, p. 63). It is a continuous and ongoing process that constitutes a public sphere enabling public participation to achieve sustained success.

Theories such as political philosophy (Rawls, 1999), democracy (Elster, 1998) and participatory governance (Fung, 2006) provide a related conceptual framework for public participation for effective deliberation. In public participation, power, knowledge, interest and influence of the stakeholders affect the process of deliberation. For effective decisions through participation in river basin management, Carr (2015) discusses the three overlapping mechanisms: (1) consensus building and space for deliberation should be provided, (2) "mobilising and developing human and social capital", and (3) improving the legitimacy. Democratic participation of the stakeholders through deliberation is crucial for river basin management. Wester et al. (2003) discuss how stakeholder representation is lacking in Mexico and South Africa, affecting the river basin management and argue that stakeholders in the river basin management, such as water users, etc., should be involved in deliberation and have the capacity to influence decision-making.

2.4. River health management: The science and the practice

Rivers are the main sources of freshwater that not only support human beings but also provide a home to a wide range of flora and fauna. They have many vital ecological values while providing cultural, social and economic benefits to communities. Extensive human interventions cause fast shifting of river systems from healthy, sustainable entities to unsustainable units. The Commonwealth Scientific and Industrial Research Organisation of the Australian Government [CSIRO] (1992) listed eight direct causes of changes to rivers, which are (1) manipulating stream channels, (2) damming watercourses, (3) manipulating streamflow, (4) draining wetlands, (5) transferring water to urban and industrial consumers, (6) disposing of waste, (7) extracting groundwater and 8) irrigating agricultural land. Karr (1991) defined river health as the degree to which three main physical and chemical attributes of a river (its energy source, water quality and flow regime), plus its biota and their habitats, match the natural condition at all scales. This five-component definition of river health implies a need for comprehensive, sensitive and quantitative tools (or indicators) for integrating and assessing the condition of each of the components. An effective river-health indicator must also be ecologically based, efficient and rapid, and reveal the condition of ecosystems rather than narrowly defined components of ecosystems (Harris & Silveira, 1999).

An important precursor to improving river health is establishing a framework to assess river health through community participation. It can help people better understand and communicate the current state of local watercourses and take appropriate remediation measures for effective waterway management. The concept of River Health Assessment (RHA) has emerged as an attempt to measure the health of rivers using reliable protocols and tools. For a long time, RHA protocols have focused on water quality alone, which covered analysing the physicochemical properties of the water through periodic sampling and analysis. The approach offered a record of water quality over time and identified the situations where plant and animal life were put at risk but did not provide inclusive information on the actual damage done. In other words, the nature and magnitude of impacts of disturbances on life forms and habitats were seldom considered in such attempts. In fact, the health of a river depends on its ability to sustain its structure and function, maintain key processes such as sediment transport, nutrient cycling and energy exchange, recover after disturbances, support local biota, and perform as an undisturbed ecosystem. Currently, RHA protocols emphasise factors that contribute to the ecological fitness of the river, such as catchment health, floodplain health, channel health, flow health, quality health and biotic health indicators.

Biological indicators for river health monitoring: In general, a number of physical, chemical and biological assessments are carried out, individually or in combination, to understand the health conditions of a river system. For example, the assessment of land use change coupled with soil erosion status indicates the health of the catchment area. Similarly, physicochemical and biological analysis of river water with respect to pH, electrical conductivity, salinity, dissolved Oxygen (DO), suspended solids (SS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), total phosphorus (TP), total nitrogen (TN), ammonia, *E. coli*, total coliform, etc. indicates water quality health. Since changes in hydrology are rapid and often difficult to estimate in running waters, such measurements cannot reflect the integration of various environmental factors, including life forms and the long-term sustainability of river ecosystems. The use of biological indicators has been proven to be supplementary to conventional monitoring techniques. Aquatic and amphibious organisms, such as diatoms and other periphytons, benthic micro- and macroinvertebrates, fishes, amphibians, reptiles, birds, riparian vegetation, etc., can serve as biological indicators to integrate the total river system and their responses to complex environmental conditions. In short, they offer the possibility to obtain an ecological overview of the status of streams or rivers. The species composition, diversity and distribution pattern of these bio-indicators change from river to river or even from different stretches of an individual river depending on various environmental and climatic factors. Therefore, the geographical location of a river or given river segment is of relative importance and location/basin-specific studies must be carried out to evolve an effective framework. Such comprehensive RHA frameworks, which are scientifically sound, reflect local conditions, easy to use and scalable, will identify rivers or river stretches that are in poor health, recognise their causes, help prioritise river restoration and

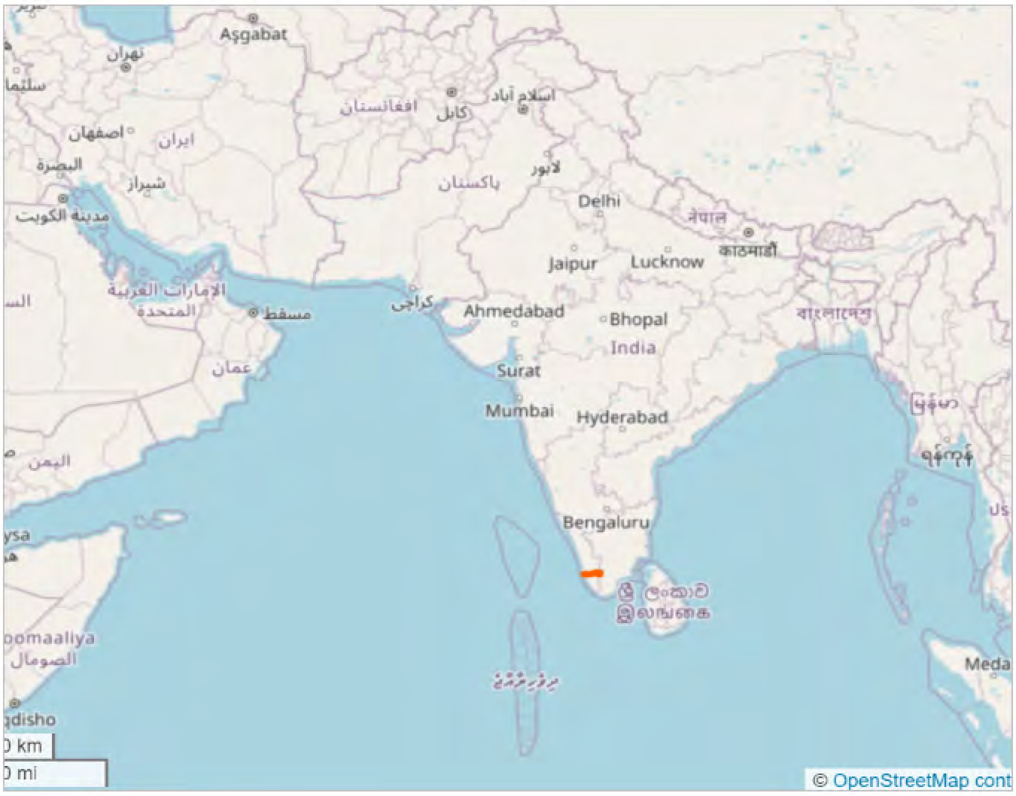

FIGURE 1. *Pampa* River, Kerala State, India – The red mark indicates the position (A detailed map is available at: https://www.openstreetmap.org/relation/15461371#map=4/19.08/83.23).

management and evaluate the effectiveness of subsequent management actions.

3. METHODOLOGY

3.1. A brief of River *Pampa* and the challenges

Pampa is the third-longest river in Kerala, India, after River *Periyar*. The river spans about 176 km in total length and is enriched by 13 tributary streams. The river, which emanates from *Pulachimala* on Peerumedu upper plateau of the Idukki district (1830 m above mean sea level) and flows through the midlands of the Pathanamthitta district, enriches the lowlands of Alappuzha district-the *Kuttanad*[2] region, and eventually drains into the *Vembanad* Lake,[3] which joins the Arabian Sea (Figures 1 and 2). The river flows through 36 Local Self Governments[4] in four districts (KSBB, 2020). The river is famous mainly for its sacredness associated with pilgrimages to the *Sabarimala* Hindu Temple and the *Maramon* Christian Church. Millions of devotees visit *Sabarimala* Hindu Temple to carry out the ultimate ritual, 'The Holy Dip,' every year by disposing of their clothes in the flowing river and tainting it significantly. Due to modern agricultural practices along the river basin and floodplain regions from the midstream to downstream areas, excess pesticides, herbicides and fertiliser effluents are being discharged into the river, eventually resulting in heavy metal accumulation, eutrophication and algal blooms. A substantial degree of sand mining has happened from the riverbanks of *Pampa* (KSBB, 2020).

3.2. Management of River *Pampa*: An institutional and stakeholder analysis

The first step involved identifying relevant institutions and stakeholders with a direct or indirect influence on the River *Pampa*. Initially, data collection relied on content analysis of websites, research articles, and reports related to the river. Subsequently, a sample questionnaire was designed and distributed to 37 Grama Panchayats, with a 15-day response period. Due to unsatisfactory results, the data collection method shifted to semi-structured key-person interviews, group discussions, field conversations and observations during the Training of Trainers programme (refer to Section 3.3). Key-person interviews included farmers, ex-panchayat representatives involved in the Pampa River management project, researchers specialising in river health parameters, represen-

FIGURE 2. *Pampa* River - Views from different locations.

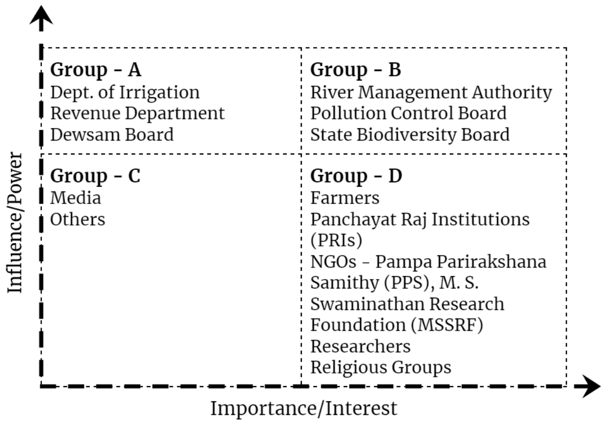

FIGURE 3. Stakeholder Analysis for Pampa River Management (Source: Authors' analysis).[7b]

tatives of non-governmental organisations actively involved in river protection and monitoring events, and local residents. Group discussions involved residents, farmers, students and researchers, focusing on their challenges in using and managing the river, as well as actions taken for river protection and management by various stakeholders. Respondents were selected using snowball sampling based on their roles in river management.

3.3. Training of Trainers (ToT) in river health assessment, monitoring and management

The project supported by the Asia-Pacific Network for Global Change Research (APN) and implemented by the M. S. Swaminathan Research Foundation (MSSRF) was titled 'The health and restoration of economically and culturally important rivers of India in the context of climate change impacts and sustainable development: A project for the capacity enhancement of practitioners and for devising restoration plans.' Through two sessions conducted in Kerala, India, the project has trained 41 development practitioners consisting of scientists, researchers, students and grassroots level actors in River Health Assessment and Monitoring (RHA&M). The River *Pampa* was taken as a case for field observations and hands-on training. The training titled 'River Health Monitoring and Restoration: The use of Biological Indicators for River Health and Restoration' was conducted in two cohorts-one from 14–16 March 2022 and another from 18–22 April 2022, covering 8-day theory classes and field visits to three hotspots of the *Pampa* River basin, followed by the formation of an active discussion platform. The participants were given lectures by eminent experts in the field, covering the river health assessment parameters focusing on the health of catchment, biota, flood plains, environmental flow and channel. The module included a theoretical framework and field-level methodologies for assessing river health from a system perspective.[5] The hands-on activities included transect studies in the hilly watershed, populated mid-plains and the lower portion of the *Pampa* River, where it merges with the Arabian Sea (Figures 4–6).[6] Key-person interviews and focus group discussions were also conducted to propose an action alliance for river health needs and a people's framework for action.

4. RESULTS AND DISCUSSION

4.1. Institutional analysis

The institutions were identified and analysed in the context of the *Pampa* River by using the analytical framework discussed before. The three rules in use in the management of the *Pampa* River are discussed below.

1. **Constitutional level** – Article 21 of the Indian Constitution states that every human has the right to live in a healthy environment and Article 51-A states that everyone is responsible for protecting and managing the environment. The rules to manage the rivers at the constitutional level identify that the power of regulation and development of the interstate rivers and river

FIGURE 4. Participants at the State and National level training sessions.

FIGURE 5. Panel discussion and hands-on training session.

FIGURE 6. Participants in the two-tier training sessions.

valleys are under the Government of India's control and Parliament can declare it by law. The rules for managing interstate rivers are mentioned in the Interstate River Water Disputes Act 1956 and issues are managed at collective choice rules through an interstate river management board. Meanwhile, at the constitutional level, the state government can regulate and develop rivers that follow within the state boundaries (Seventh Schedule, Article-246, List-I, 56, The Constitution of India). In the case of *Pampa* River, the state government has complete authority to manage the rules in use at the collective choice and operational level (Table 2).

The 73rd and 74th constitutional amendment acts give local governments the power to provide water resources to citizens as public goods. At the state government level, the government has enacted the *Kerala Panchayati Raj Act* 1994. This act provides the power to manage local water resources and water supply. The act, through its rules, makes Gram Sabha and panchayats responsible for the management of water resources and supply and sanitation. However, the act and the amendment give less attention

Articles	Key features
Article 21	"Every individual has the right to live in a healthy environment."
Article 51-A (g)	Casts a fundamental duty on every citizen of India "to protect and improve the natural environment including forests, lakes, rivers, wildlife and to have compassion for living creatures."
Article 246, List-I, 56	"Regulation and development of interstate rivers and river valleys to the extent to which Parliament declares such regulation and development under the control of the Union to be expedient in the public interest."
Article 246, List-II, 17	"Water, that is to say, water supplies, irrigation and canals, drainage and embankments, water storage and waterpower subject to the provisions of entry 56 of List I."
Part IX & IX-A (73^{rd} and 74^{th} Amendment Act)	Establishing Local Governments in States: Amendments 73^{rd} and 74^{th} gave powers to the state governments to establish *Grama Panchayats* and Municipalities.

TABLE 2. The Constitutional Rules with regard to Water and Environment (Authors' compilation).
Source: The Constitution of India.

to prompt decentralised decision-making in matters of CPRs, especially concerning environmental resources.

2. **Collective-choice rules** – The Government of India enacted the Water (Prevention and Control of Pollution) Act of 1974 (amended in 1988) to protect rivers from pollution. The act directs the central and state governments to establish central and state Pollution Control boards. The Water (Prevention and Control of Pollution) Cess Act 1977 and Environmental Protection Act 1986 were enacted by the Government of India to protect the environment from anthropogenic activities. These acts have come after much deliberation and public participation at the constitutional level through the legislative process. To manage and protect the river from sand mining, the Kerala State government has enacted the Kerala Protection of Riverbanks and Regulations of Removal of Sand Act 2001. It provides rules and regulations for "Protecting the riverbanks and riverbeds from large-scale dredging of river sand" by regulating indiscriminate sand mining. Later, in 2009, the Kerala state government enacted "The *Pampa* River Basin Authority Act 2009" to address the issues concerning water resources and pollution. The act provides arrangements for managing activities connected with water resource conservation in the *Pampa* River basin. These rules and regulations determine who can participate in decisions and influence actions and outcomes at the operational level (Table 3). However, these rules don't provide any information on the parameters of the RHM.
3. **Operational rules** – The monitoring and enforcement of the rules/acts are carried out at this level. The concerned local government and District Collectors/District Magistrates decide when and whom to act, who should monitor the actions of others and the monitoring method. The findings of the discussions with *Grama Panchayats* helped to identify the different rules in action. Multiple stakeholders, such as communities, local groups, and non-governmental organisations, are involved at this level. The combination of actions through different stakeholders led to outcomes in rejuvenating the river project. However, at this level, conflict of interest between various stakeholders and a lack of technical knowledge challenged implementation of activities related to RHM.

4.1.1. Stakeholder analysis[7]

The primary stakeholders have direct positive or adverse effects. From the findings and literature, the primary stakeholders are identified as farmers and local residents, three important departments of the Kerala Government (Major & Minor Irrigation, Kerala Water Authority), Local Self Governments (the *Panchayati Raj* Institutions), the Kerala state agencies like Centre for Water Resources Development and Management (CWRDM), religious groups, the *Pampa* River Management Authority, etc. The secondary stakeholders are those indirectly affected by the programs and actions. From the findings and

Acts/Rules	Key features
Water (Prevention and Control of Pollution) Act, 1974, amended in 1988	Prevention and control of water pollution and establishment of boards. Chapter 3.3 directs the central government to establish the Central Pollution Control Board (constituted in 1974). Chapter 3.4 directs the state governments to establish State Pollution Control Boards.
Water (Prevention and Control of Pollution) Cess Act, 1977	"The Act is to provide for the levy and collection of a cess on water consumed by persons carrying on certain industries and by local authorities, to augment the resources of the Central Board and the State Boards for the prevention and control of water pollution constituted under the Water (Prevention and Control of Pollution) Act, 1974."
Environment (Protection) Act, 1986	"The Act is to provide for the protection and improvement of the environment, the prevention of hazards to human beings, other living creatures, plants and property."
Biodiversity Act 2002	The act is for the conservation of biodiversity. A National Authority and State Boards are there to restrict certain activities that violate conservation objectives and develop strategies/plans for conserving biological diversity.
Kerala *Panchayati Raj* Act, 1994	The act provides particular provisions on Gram Panchayat's responsibility and powers to manage local water resources and supply. The Standing Committees at the village, block and district levels have the power to deal with sanitation and water supply.
Kerala Protection of Riverbanks and Regulation of Removal of Sand Act, 2001	The act provides provisions for protecting riverbanks and riverbeds from large-scale dredging of river sand, protecting their biophysical environment system and regulating indiscriminate mining of river sand. The District Collector and the concerned local governments can regulate sand mining.
The *Pampa* River Basin Authority Act, 2009	The act is the first of its kind constituted in Kerala state. It provides arrangements for managing activities connected with water resource conservation in the *Pampa* River Basin.

TABLE 3. The Collective Choice Rules with regard to the *Pampa* River, Kerala, India (Authors' compilation).

literature, the Secondary stakeholders are identified as non-governmental organisations like *Pampa Parirakshana Samithy*, the M. S. Swaminathan Research Foundation, etc., media, researchers and the Kerala Institute of Local Administration. Detailed characteristics of the stakeholders are given in Table 4 and Figure 3.

4.1.2. Institutional changes through public deliberation

The institution changes and evolves with constant interactions and deliberations between the actors at various levels. In a collective action situation where multiple actors are involved in deliberating their preferences and conflicts, it is essential to identify who is participating in the deliberations and whose power influences the decision-making. In the case of the *Pampa* River management focusing on water pollution and sand mining, the collective choice rules were enacted with considerable deliberation and the institutions have evolved to protect the river. The significant institutional changes were the Kerala Sand Mining Act (2001) and the *Pampa* River Protection Act (2009). Another collective action among people has led to the establishment of a civil society organisation called *Pampa Parirakshana Samithy*.[8] This group, along with a few stakeholders, established the collective choice rules for preventing sand mining in the river basin.

At the operational level, the sand mining by certain actors led to conflicts among the farmers, fishing community and environmental protectors, as it affected the river ecosystem. However, the above mentioned institutions did not influence the actions at the operational level. Water pollution and sand mining have been consistent over the years. The studies found that the water quality of the river upstream has been affected due to the *Sabarimala* Hindu temple pilgrimage. The pilgrimage season is from October to February every year. During the months of December and January, there could be an increase in the number of devotees. Many studies conducted during these months have found

Sl. no	Stakeholder	Power	Knowledge	Influence	Interest
1.	Farmers	Low	Low	Low	High
2.	Grama Panchayats (Local Self Governments)	Medium	Low	Medium	Medium
3.	Researchers	Low	High	Medium	High
4.	*Pampa Parirakshana Samithy* (Non-Government Organisation)	Medium	Medium	Medium	High
5.	Department of Irrigation, Govt of Kerala	High	Medium	Medium	Low
6.	*Pampa* River Management Authority (State Agency)	High	High	High	High
7.	M. S. Swaminathan Research Foundation (Research Organisation, Non-Government Organisation)	Low	High	Medium	High

TABLE 4. Stakeholders' Capacity on River Management. Source: Authors' analysis.[7]

a decrease in water quality. Krishna and Kumar (2014), Mayaja and Srinivasa (2016), and Narayan (2021) examined the water quality of the river during the pilgrimage season in 2011 and 2012 and found increased pollution. Narayan's study (2021) on seasonal pollution concludes that the pollution rates were higher in the *Pampa* River basin during pre-monsoon and winter.

At collective choice, the actors, through constant deliberation, established institutions at the operational level to protect and manage rivers. At the operational level, these non-governmental organisations and other environmental pressure groups were able to influence the people to check river pollution and sand mining through social policing. The power to influence the decisions and the knowledge of actors were analysed using stakeholder analysis. Based on the constitutional and collective choice rules, the power to influence the discussion is high among government institutions such as the Department of Irrigation, Kerala and the *Pampa* River Management Authority. The local institutions and non-governmental organisations have medium power to influence the decisions at the collective choice level (Table 4).

4.2. Results and discussion: Building capacity of development practitioners in river health management

The water quality of our rivers is getting tainted over time, along with increased demand for potable water. There is ample time to act to preserve our rivers before the pinnacle point of destruction. Monitoring rivers using bio-indicators provides the most integrative view of river health. With increasing industrialisation, population growth, land-use changes and developmental challenges, the natural ability of rivers to provide goods and services has been severely curtailed. In this context, a training project was planned by the MSSRF, India, with the support of APN. This Training of Trainers (ToT) model project was aimed at intensively training its stakeholders at different power levels in monitoring the comprehensive health and longevity of culturally and economically far-reaching rivers. The fact to consider is that we need more well-trained individuals with good reflexes to rectify the fluctuating health of the river and riverine resources.

The project results are detailed in Table 5. Two key results are (1) An action alliance for river health needs, and (2) A people's framework for action.

4.2.1. *Kerala River System Health Needs Assessment and Action Alliance (KRISHNA)*[10]

KRISHNA has emerged as a platform for organisations, youth, and local community leaders dedicated to River System Health Services and Management in Kerala. This open platform includes researchers, teachers, students, practitioners and community-level user groups. They are committed to taking action steps based on needs, utilising science-based tools and skills in river health management and reporting. The team adopts a comprehensive approach to river health, incorporating rejuvenation actions based on facts, values of Restoration Biology, and community/socio-cultural/ecological dynamics. Many rivers in Kerala are ailing, evidenced by declining ecosystem services, including polluted water, narrowing flow channels, loss of floodplains, degradation of catchment areas and riparian vegetation, and loss of freshwater biodiversity. If these trends persist and

Outputs	Outcomes	Impacts
Forty-one (41) trained practitioners in all aspects of River Health Assessment and Monitoring (RHA&M); some have initiated follow-up actions (Mahajan, 2023).	*Kerala River System Health Needs Assessment and Action Alliance* (Krishna), a river protection platform to facilitate need-based actions using science-based tools and skills in River Health Assessment and Monitoring (RHA&M).	Improved stakeholder skills, awareness and commitment, especially of those who associate with the River Health Assessment and Monitoring (RHA&M).
The collation of content and first-hand knowledge documentation pertains to river health assessment, monitoring and restoration science, techniques and tools.	A Guidebook for River Health Assessment and Monitoring (RHA&M).	Opportunity for designing more training for new stakeholders interested in river health management.
Mother plant materials of 22 riparian tree species ready, apart from documentation of species of instream river biota.	A Plant Nursery to raise and distribute riparian tree species.	Community efforts in restoring a degraded riparian patch of the *Pampa* River.
A discussion group for follow-up actions and monitoring of River health aspects.	A Platform for RHA of Kerala Rivers and a Plan of Action Framework for Rejuvenating the *Pampa* River.	Adequate pressure from citizen groups and detailed project proposals are expected from the sub-national and local governments for RHA&M.
Six short videos covering expert interviews on the importance of RHA&M.[9]	A Web Portal[10] for River Health Assessment science, innovations and techniques covering a good amount of scientific content and rejuvenating stories.	A science-based action in campaign mode is expected in river health assessment and rejuvenation action.
Manuscripts for two publications, including a Training Manual on RHA&M on the *Pampa* River restoration.	The expected Peer-reviewed publications will increase the team's self-esteem and help sensitise people widely on the holistic River health assessment.	More rational decisions are expected on the part of policymakers and enforcement officials in river health management and climate resilience building.

TABLE 5. The RHA&M Project Results.

worsen due to climate catastrophes, many rivers in Kerala may become lifeless channels or critically polluted water bodies dominated by invasive species.

KRISHNA aims to research, rejuvenate and report river health locally and empower the eco-restoration movement globally with the following objectives.

(i) Cross-disciplinary and participatory assessment and rejuvenation of River Ecosystem Services (RES);
(ii) Policy Advocacy in sustainable management of RES, notably riparian forests, river catchment and floodplain ecosystems and river basin agricultural landscapes;
(iii) Practical Actions for RES management like the Payment for Ecosystem Services for local community members and their institutions for protecting the river in their geographic boundaries; and
(iv) Capacity development activities at grassroots-level institutions on sustainable and equitable management of Rivers and River Ecosystem Services and reporting.

4.2.2. A People's Framework for Action Projects

4.2.2.1. The background & the purpose

The *Pampa* River in Kerala is sick to the extent that most of its vital ecological services are in a continuous state of decline. Despite several attempts from government and non-government actors to restore its health, the *Pampa* River is experiencing increasing pollution. The feeding flow channels and floodplains are progressively narrowing, becoming choked, or assuming an altered state. The present Action Framework has been formulated through consultations and meetings conducted at various levels with stakeholders, mainly local community men and women engaged daily in *Pampa* River utilisation. The plan sets out several strategies for practical actions that balance the *Pampa* River's multiple roles and objectives relating to specific human needs and natural river functions. This plan provides insights and on-ground action targets based on a strategic system-based approach by recognising the river's physical, ecological, socioeconomic, cultural and political aspects. The strategies proposed will help identify and respond to various links in the river system restoration portfolio for this river between external drivers, catchment and river functions, river health, ecosystem services and societal priorities. The plan also contributes to formulating specific action steps required to align and synergise various policies, strategies and projects already available in the state to restore the river. It also facilitates explicitly executing the powers and the critical functions outlined in the *Pampa* River Basin Authority Act, 2009.

4.2.2.2. The Targets 2030

A set of 11 action-oriented restoration targets are identified and suggested by covering 14 river ecosystem health components (Table 6). Specific detailed actions in a mission mode that are required to synergise other relevant plans of the state-specific bodies and the Local Self Governments must be formulated to reach these targets.

- Target 1. Practice science-based Catchment Area Land use-land cover management of River *Pampa*.
- Target 2. Maintain an optimum level for the *Pampa* River Environmental Flow regime.
- Target 3. Ensure improved Floodplain functions of *Pampa*.
- Target 4. Protect the geomorphology and hydrology of the *Pampa* River channel.
- Target 5. Maintain a scientific portfolio for *Pampa* riparian vegetation management.
- Target 6. Ensure a rich river biota is maintained across the *Pampa* riverine ecosystem.
- Target 7. Ensure water quality and reduced chemicals and particulate load to *Pampa*.
- Target 8. Revive and enhance the cultural heritage functions of *Pampa*.
- Target 9. Revive the socioeconomic development role of *Pampa*.
- Target 10. Research, Education, Public Awareness and Communication around *Pampa*.
- Target 11. The Resource mobilisation and Implementation support mechanisms.

5. CONCLUSION

Deliberations and public participation are crucial for the management of the CPRs. Through such constant interaction between the actors, institutions evolve and change. In the case of the *Pampa* River, the institutions at the collective choice level have developed majorly for the supply of drinking/irrigation water and the protection of the river. At the collective choice level, the local bodies, non-government organisations, and other civil society organisations have deliberated and taken actions at the operational level to address the issues of water pollution and illegal sand mining. However, the power of these organisations to influence the decisions made at the collective choice and operational level has remained weak. To address these issues at the collective choice level, the mechanism at the local self-governments should focus on decision-making on CPRs at the grassroots level. It is suggested to campaign among individuals, regional households, Local Self Governments, the Kerala State Government, the Government of India and Civil Society Organisations to mobilise necessary resource support for implementing the plan devised for River Health Management. A healthy CPR, like a river, can benefit the community through its ecological, social, cultural and economic values. The strategic targets built upon understanding the complexity of the relationship between river health and social benefits will help to formulate scale-specific projects for reviving the river. If we fail to see the system perspective, it can only lead to further degradation and destruction of this riverine system. This may significantly impact vulnerable communities such as smallholder farm families, the indigenous people and those multi-user groups who depend on this ecosystem. The involvement of these

River Ecosystem component	River restoration measures	Resultant changes
Catchment area	Catchment area land use-land cover management	• Water percolation and recharge capacity of the ground improved. • The quantity and quality of water and other matter that enter the river channel changed.
Flow regime	Flow modification Stormwater management Dam removal/retrofit	• Flow volume, timing, frequency and duration changed. • Flow pattern and storage of runoff water changed. • Movement of sediments, flow pattern and biodiversity functions like breeding behaviour of species improved.
Flood plain	Land reconnection Land acquisition	• Reduced flood risks. • Increase assimilation of pollutants. • Movement of sediments, other matter and biota between the channel and floodplain improved. • Acquired the encroached floodplain land to improve the floodplain functions.
River channel	River bank protection Channel re-configuration In-stream habitat improvement	• Reduced erosion and slumping off bank material into the river. • Increased hydraulic diversity, habitat heterogeneity and decreased river channel slope. • Enhanced biodiversity-friendly habitats.
Riparian habitat	Riparian species management	• Improved diversity and richness of the Keystone riparian species.
Biodiversity	Instream species management Removal of invasive species	• Improved species diversity and richness. • Improved native species diversity and water quality.
Water quality	Water quality management	• Improved water quality and reduced chemicals and particulate load.
Other (eg. Cultural)	Aesthetics and Recreation management and education	• Increased community value, access to and knowledge of the river and riverine ecosystem.

TABLE 6. The typology of measures suggested for the *Pampa* River restoration (Speed et al., 2016).

vulnerable communities in deliberations for managing the CPRs is important. The ToT programme has helped 41 development practitioners change their approach toward River Health Management, and the deliberations have resulted in an alliance of practitioners and a people's framework for action projects.

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NOTES

[1] The three influential models were adopted from the Governing of Commons (1990) by Ostrom. For more information, see (Ostrom, 1990, Ch-1, p. 18–22).

[2] *Kuttanad* region is a Globally Important Agricultural Heritage System accredited by the Food and Agricultural Organization where paddy farming is practiced below sea level. More details are available at: https://www.fao.org/giahs/giahsaroundtheworld/designated-sites/asia-and-the-pacific/kuttanad-below-sea-level-farming-system/en/.

[3] *Vembanad* Lake is part of the *Vembanad-Kol* Wetland Ecosystem, an accredited Ramsar site. More details are available at: https://rsis.ramsar.org/ris/1214.

[4] Consequent to the 73rd and 74th amendments to the Indian Constitution, a three-tier governance system is in place: (1) *District Panchayats*, (2) *Block Panchayats* and (3) *Grama Panchayats*/ Municipalities/ Corporations. The 3rd tier is the most powerful institution at the grassroots level. THE KERALA PANCHAYAT RAJ ACT (1994) defines these Local Self-Governments (LSGs) or Panchayat Raj Institutes – PRIs. Kerala State has *941 Grama Panchayats*, 152 *Block Panchayats*, 14 District Panchayats, 87 Municipalities and 6 Corporations. These Local Self-Government Institutions have been meaningfully empowered through massive transfer of resources and administrative powers. More details are available at: https://lsgkerala.gov.in/en/lsgd.

[5] The presentations are available at: https://www.youtube.com/playlist?list=PLVUhfEQnRD9yvszFzj6vODi0iyo6LyGOd.

[6] For more details, check the project website. https://mssrfcabc.res.in/?page_id=13904 and https://www.apn-gcr.org/wp-content/uploads/2022/07/Photo-Report-CBA2018-10SY-Kumar_MR_15May2022.pdf.

[7] The Stakeholders analysis was carried out based on three steps: (For more details, see Nishat et al. (2016).)

a. Identification of Stakeholders: The stakeholders were identified as primary and secondary, based on the literature review, interviews with individuals & and experts, and a snowball sampling. The number of stakeholders in the study is limited to the participants and training faculties of the ToT.
b. Classification of the stakeholders: The classification was based on the influence and interest grid (Figure 3).
   (i) Interest/Importance: The stakeholders' primary interest is protecting the environment or the river.
   (ii) Influence/Power: The stakeholders who have the power to make decisions that can influence the implementation of actions related to the river's health.
c. Analysis of stakeholder engagement: Based on the influence and interest grid, the analysis of the engagement of stakeholders for River Health Management is categorised into power, knowledge, influence and interest. These categorisations were ranked in terms of high, medium and low.

[8] *Pampa Parirakshana Samithy* (PPS) is a non-governmental organisation established in 1994 that focuses on environmental development in urban and rural areas. More details are available at: http://www.doaram.com/organization/pampa-pariraksha na-samithy.

[9] Details available at: https://riverhealth.in/river-health-training-project/.

[10] Details available at: https://riverhealth.in/.

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Case study

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Plausible alternative future of mangroves and their ecosystem services: Case studies from Asia-Pacific region

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ABSTRACT

Over the past few decades, scenario analysis emerged as a useful tool for environmental decision-making amidst multiple uncertainties. Using the influential drivers of change, scenarios portray the range of plausible alternative futures useful for quantifying the synergies and trade-offs of vital ecosystem services across multiple development trajectories. In this research, we demonstrate two case examples of the application of scenarios in quantifying current and future mangrove ecosystem services. The case studies are selected from two representative sites: Tamsui River Estuary in Taiwan and Bhitarkanika mangroves in Odisha, India. Using the combination of Land Change Modeller (LCM) and InVEST ecosystem services simulation tool, the research demonstrates the application and use of spatially explicit Scenarios for mangroves' current and future conservation. As such, the case studies identify an ameliorative way of future planning, particularly with respect to the eco-sensitive development of coastal regions and small islands.

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KEYWORDS SCENARIOS, MANGROVE, LAND CHANGE SIMULATION, ECOSYSTEM SERVICES, SUSTAINABLE DEVELOPMENT

HIGHLIGHTS

- Landscape scenarios are developed across two mangrove sites.
- Vital ecosystem services are simulated across different scenarios.
- Evidence-led policy planning guidelines are developed.

1. INTRODUCTION

Mangrove forests are situated at the interface between land and sea and provide a plethora of vital ecosystem services, like disaster risk reduction, water purification, nutrient recycling, control of soil erosion, habitats for fish and many more (Dasgupta et al., 2022). Some estimates suggest that these forests provide nearly 70 ecosystem services which are directly and indirectly related to human well-being in low-lying coastal areas (Bimrah et al., 2022). Thus, these forests play a critical role in ecosystem-based adaptation—a strategy that seeks the wise use of ecosystem services to negate climate change impacts. However, globally, mangrove forests are under threat from various social and environmental factors. This includes, but is not limited to, sea level rise, direct deforestation for agriculture and aquaculture, rapid coastal urbanisation and infrastructure development. Historically, the global mangrove cover used to be around 200,000 km^2; however, they suffered severe deforestation and degradation over the past decades, especially in developing and least-developed countries (Dasgupta et al., 2022). As a common pool resource, mangroves have undergone severe deforestation over the past decades. The current extent of mangroves is about 148,000 km^2, and according to the United Nations Food and Agricultural Organization (FAO), the rate of mangrove deforestation, despite the recent slowdown, continues to be alarming, especially in the Asian developing countries.

Asia, particularly South and Southeast Asia, comprises around 40% of the existing global mangroves. Among the countries, Indonesia has the highest extent of mangroves, followed by Malaysia (3.7%), Myanmar (Burma) (3.6%), Bangladesh (3.2%), India (2.7%) and the Philippines (1.9%) (DasGupta & Shaw, 2013). In Asia, mangroves spread over large river deltas, particularly in large deltas, namely the Ganges–Meghna–Brahmaputra (GBM) delta in India and Bangladesh, and the Irrawaddy Delta in Myanmar. These deltas are known to be the largest habitat of mangroves and show exceptional diversity of salt-tolerant species. Although historically, these deltas underwent massive mangrove deforestation, owing to recent global attention to mangroves and subsequent changes in national-level policies and priorities, these mangroves have been brought under strict legal protection. For instance, according to Giri et al. (2007), despite the high density of the human population in the vicinity, the mangroves of Sundarbans have not suffered much degradation over the past three decades. Nonetheless, while larger patches of mangroves are better conserved today, the smaller patches of mangroves continue to suffer severe degradation, particularly owing to a lack of legal protection. The main drivers are increasing populations and unprecedented development in coastal areas. The uncertainty attached to this rapid and mostly unplanned development is so immense that it is difficult to precisely determine the availability of the future extent of mangroves and their ecosystem services. This uncertainty also hinders integrating mangrove ecosystem services, which is important to develop an ecosystem-based adaptation (EbA) strategy. At the same time, EbA remains crucial, considering many Asian developing countries lack the economic and technical capacity required to foster resilience in low-lying coastal areas.

1.1. Scenario analysis for decision-making under uncertainty

Over the past decades, scenario analysis evolved as an important decision-making tool to manage environmental uncertainty. Scenario analysis involves both scenario development and analysis of plausible alternative futures, keeping the major uncertainties in mind. Since establishing the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), scenario analysis has been widely advocated to design a sustainable future of biodiversity and ecosystem services. Scenarios rely on a coherent and internally consistent set of assumptions and portray a spectrum of imaginative futures. These plausible alternative futures can identify conservation opportunities and analyse policy alternatives (DasGupta et al., 2019). Scenario exercises are recommended by the IPBES to mitigate the loss of biodiversity and ecosystem services.

In conventional scenario analysis, policy planners develop Business-As-Usual (BaU) scenarios and plausible alternative scenarios, depicting the best possible, the worst and several intermediate scenarios. Likewise, ecosystem services can be optimised using spatial and non-spatial Scenarios to address the synergies and trade-offs in land development and ecosystem management. Scenario analysis is an important tool for managing uncertainties. However, despite several intergovernmental bodies like Intergovernmental Panel on Climate Change and IPBES calling for scenario analysis for optimising land development in ecologically sensitive areas, there is still a dearth of case studies depicting scenario exercises related to biodiversity and ecosystem services (Hashimoto et al., 2019).

This science bulletin aims to document a new scenario-based quantification method for mangrove ecosystem services, specially customised for vulnerable small patches of island mangroves in the Asia-Pacific. Here, we discuss how state-of-the-art geospatial tools have been used for Scenario building and analysis for assessing the likely changes in current and future mangrove ecosystem services. In this article, we discuss two case studies, namely Tamsui River Estuary in Taiwan and Bhitarkanika Mangroves in Orissa, India, where we developed future scenarios for mangroves under alternative development pathways and analysed the availability of vital mangrove ecosystem services.

2. METHODOLOGY

In this project, we have used a scenario-based ecosystem services quantification tool. We have adopted the Story and Simulation Approach (SAS) suggested by Alcamo (2008), which consists of developing a robust storyline about the likely uncertainties. In the second part, using the key drivers identified in the SAS approach, either obtained from literature or participatory exercises, we simulated the land use for 2050. Based on these plausible alternative land use scenarios, we evaluated the likely state of vital ecosystem services (e.g., carbon storage, nutrient recycling, sediment trapping, habitat quality, etc.) using the InVEST model. InVEST is a set of biophysical models that consists of blue carbon, sediment retention and many others (https://naturalcapitalproject.stanford.edu/software/invest). It operates on different site-specific spatial and non-spatial information. The methodology is summarised in the following in Figure 1.

3. CASE STUDY 1: QUANTIFICATION OF MANGROVE ECOSYSTEM SERVICES THROUGH EXPLORATORY SCENARIOS IN TAMSUI RIVER ESTUARY IN TAIWAN[1]

3.1. Introduction to the Tamsui River Estuary, Taiwan

Taiwan's mangroves are mostly located on the estuary of the west coast. A considerable amount of mud is deposited in the estuary area on Taiwan's western coast, which is ideal for the growth of mangroves. The Tamsui Estuary's mangroves are mostly found in four areas, namely Wazi Wei, Zhu Wei, Guandu and Shezidao (Figure 2a). Mangrove areas have gradually risen in recent years because of the government's aggressive conservation initiatives (Wang et al., 2015) (Figure 2b). However, the Tamsui River basin region has a population of approximately 8 million people (more than 30% of the national population) and is highly developed in industry and trade. This brings significant uncertainty in the future extent of mangroves.

3.2. Scenario development

Land demand is generally proportional to population size. The population in the study region is expected to reach 7.26 million in 2035 and then decline to 6.61 million in 2050. However, the urban decline is not expected to occur in the target projection year of 2050. Continuous depopulation has a huge impact on future land demand since land usage translates into human activity, especially in the development of cities. Thus, we studied the transition from 1994 to 2007 and produced a (BaU) land use prediction for 2050. Also, mangrove forests are simulated with two alternative land use Scenarios for 2050. In Scenario 1 (S1), mangrove forests are projected to be transformed into grassland and in Scenario 2, mangroves are projected to be turned into water

[1] This is a summarized version. For details see Chung et al. (2022).

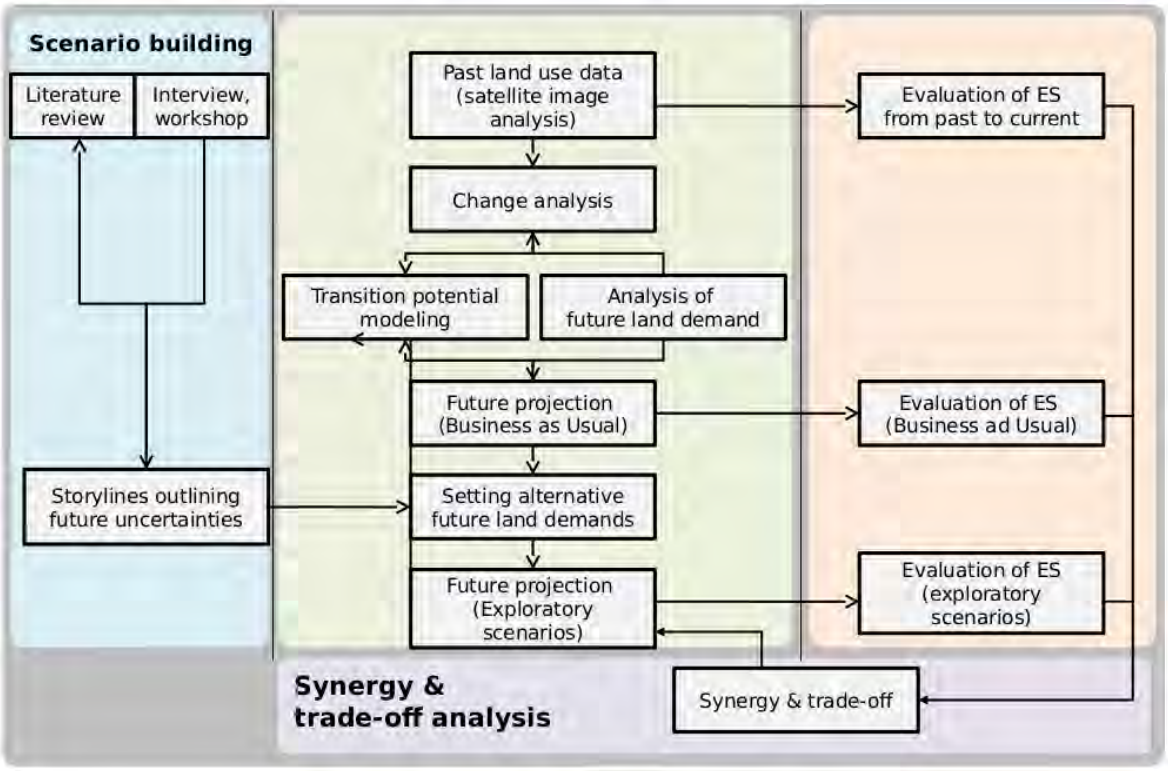

FIGURE 1. Summary of the SAS adopted in this research.

FIGURE 2a. Location of the study area.

bodies (Figure 3). The LCM, which was used to develop the spatial scenarios considers the dominant land use changes over a time-series period. We used the land-use transition from 1994–2007 to locate the dominant changes. Based on the findings, three plausible alternative future Scenarios, i.e., BaU, S1 and S2 were developed.

3.3. Scenario analysis

The three plausible alternative land use scenarios are developed which are furnished in Figure 3.

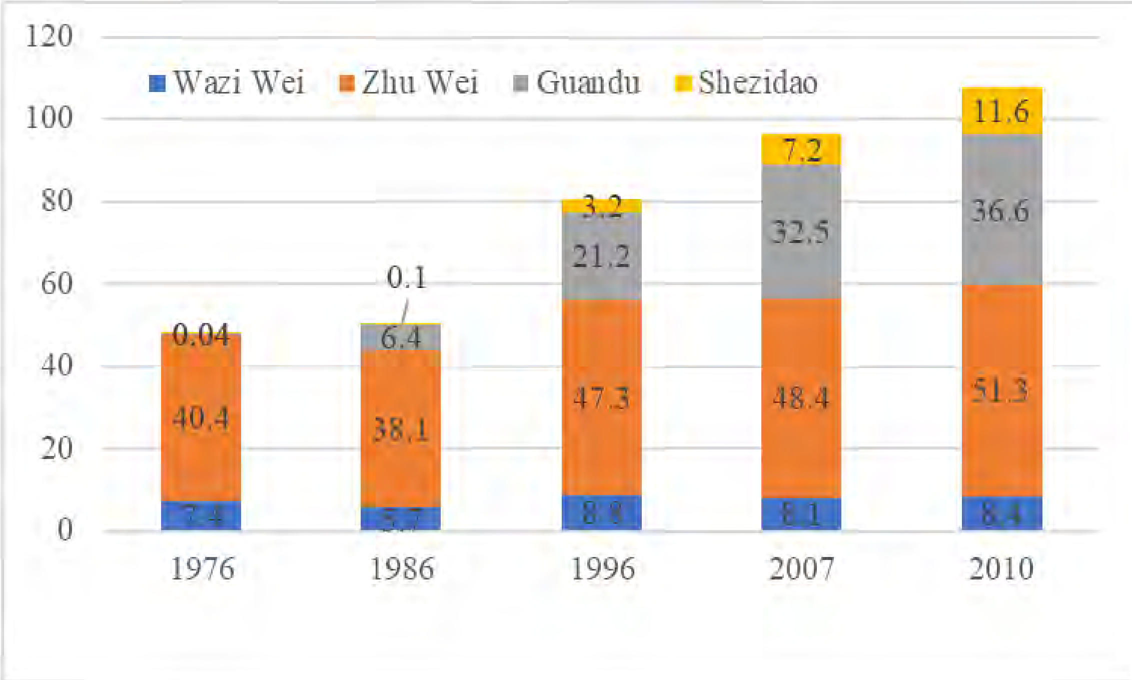

FIGURE 2b. Changes in mangrove area (hectares) over the years in the Tamsui River basin.

According to the BaU findings, when comparingland use to 2007, forest and residential land will increase, whereas grass, other urban, paddy and wasteland use will decrease. Due to the protection restrictions that forbid the development of mangroves, there will still be 92 hectares of wetland (mangrove forest) in 2050 BaU. Eighty-six hectares of wetland were turned into grassland in S1 and 86 ha into a body of water in S2. In summary, these projection findings demonstrate that the influence of policy interventions resulted in land use conversion, demonstrating the tangible implications of our scenario settings in this model.

3.4. Scenario analysis of vital ecosystem services

We utilised InVEST models (carbon storage, habitat quality, nutrient retention and sediment delivery) to evaluate the ecosystem services in the study region after assessing the data on land-use changes and land-use projections.[2] The following figure shows the changes in the study region during the previous 24 years and the upcoming 32 years. We specifically looked at carbon storage, habitat quality, nutrient recycling and sediment retention services, as these consist of important mangrove ecosystem services. The regional distribution of ecosystem services is shown. The average ES value for each raster cell in three different future scenarios (BaU, S1 and S2) and historical land usage (1997, 2006 and 2018) are shown in Figure 4.

Overall, the study area's ecosystem services, such as carbon storage and habitat quality, showed a slight increase, indicating a gradual improvement in environmental quality. Toward 2050, nitrogen retention and the ratio of sediment delivery tended to decrease. An evident change in carbon storage was also strongly correlated with the amount of forest land among the ecosystem services. The forests surrounding the Tamsui River basin have a high capacity for storing carbon and the amount of carbon in the ecosystem changes as the forest area grows. This is primarily because the urban plan places a high value on protecting catchment areas, which have converted a lot of wasteland and paddy fields into forests. It was observed that carbon storage in 2050 BaU would be higher than in 2018; BaU land use with a mangrove convention policy has the highest potential for carbon storage when compared to 2050 S1 and 2050 S2. Similarly, BaU land use is evaluated as the best for improving habitat quality than past land uses; however, the mangrove convention seems unchanged across the three scenarios, possibly owing to the smaller patch of existence and the fact that it is well covered under the current policy guidelines.

[2]For the details of model set up and boundary variables, please see Chung et al. (2022).

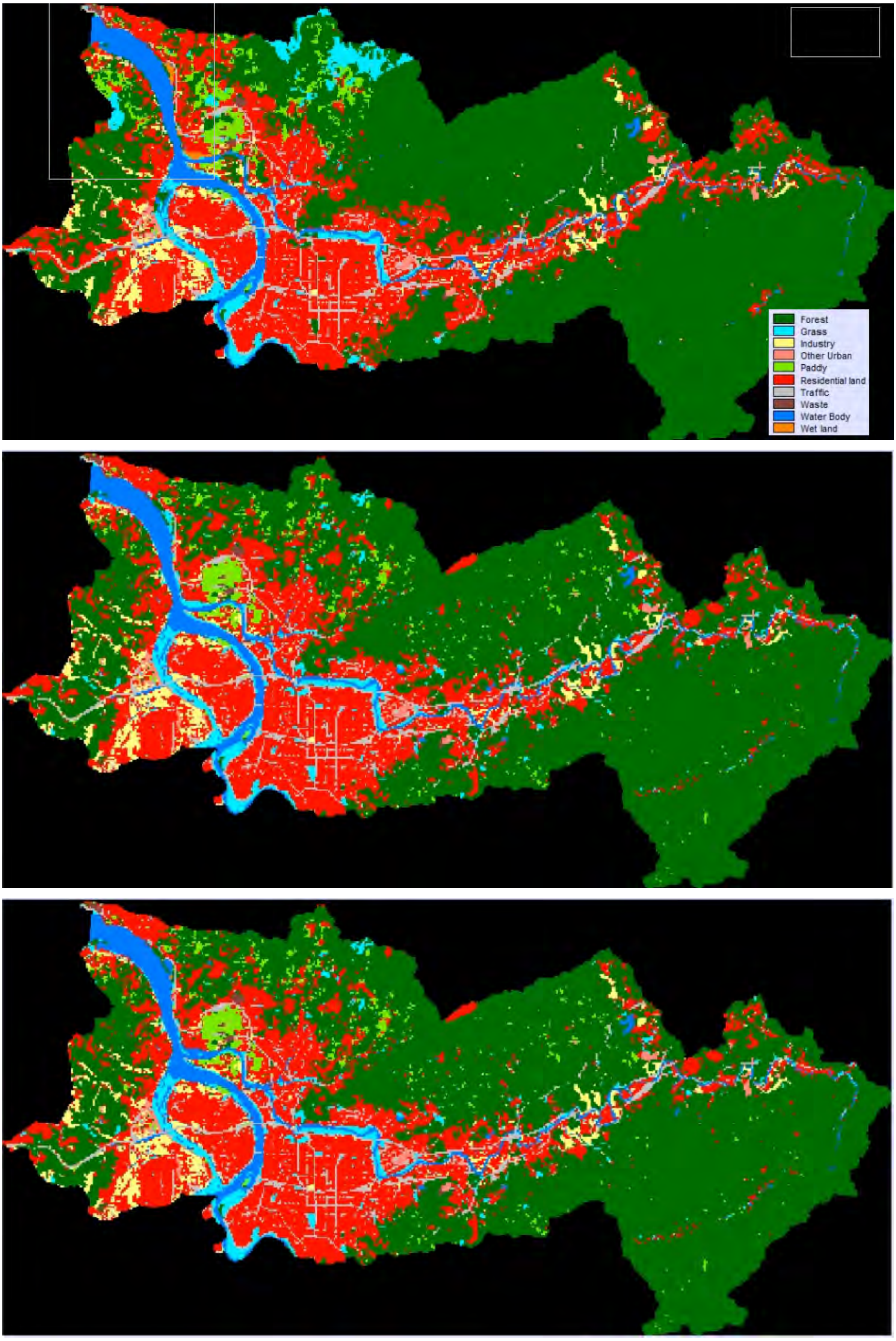

FIGURE 3. Land use scenarios for 2050 for the Tamasui River Basin study area.

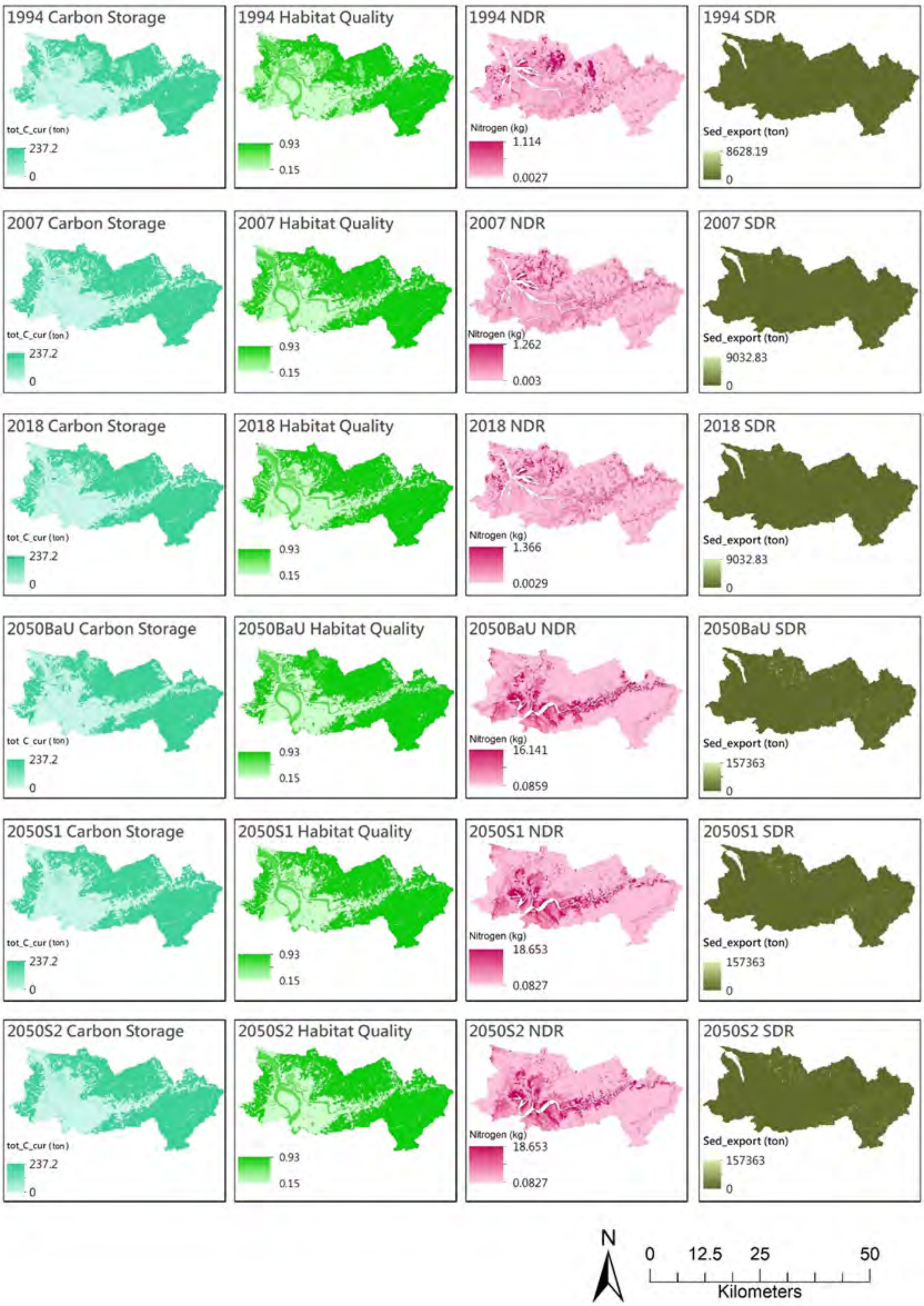

FIGURE 4. Spatio-temporal modelling of vital ecosystem services across three scenarios.

3.5. Policy recommendation

The processes of urbanisation in the Taipei Metropolitan area significantly impact mangrove forests in the Tamsui River Estuary. In the past, the Taiwanese government used urban and regional planning to preserve the land, water and overall

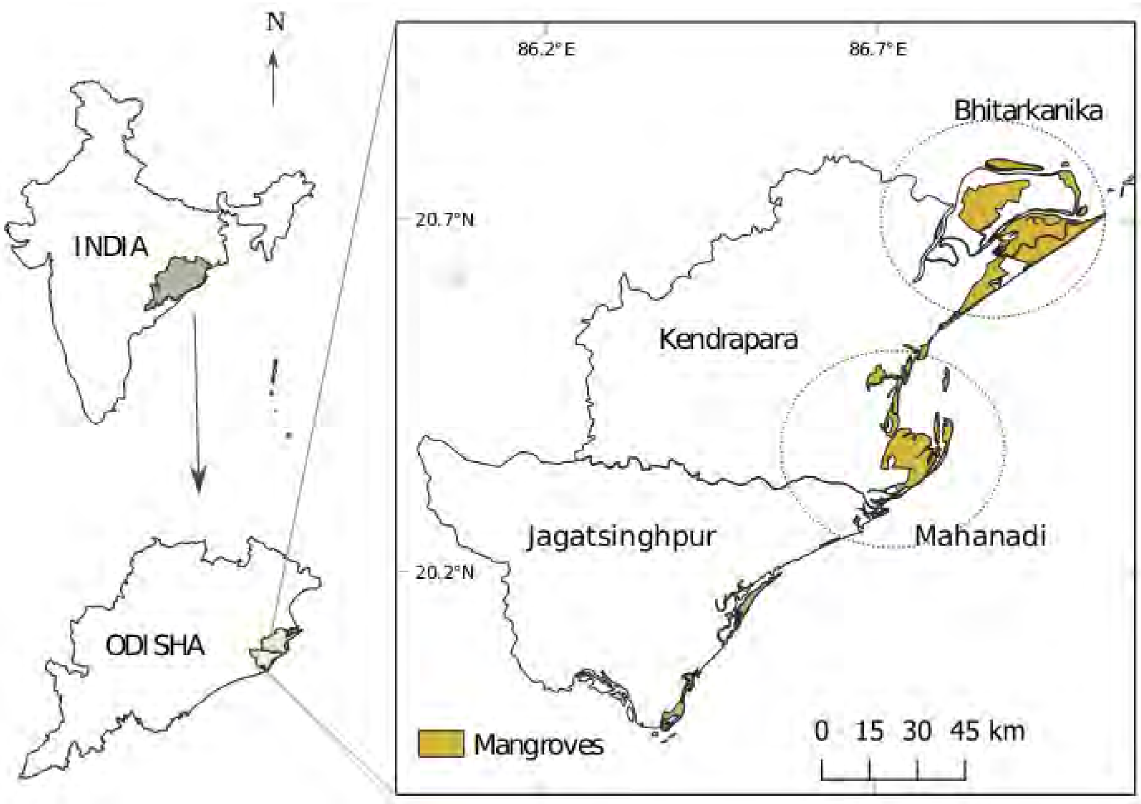

FIGURE 5. Mangroves patches of the Bhitarkanika and Mahanadi delta.

environmental quality in the upper and middle parts of the catchment; however, with limited impacts in the lower catchment. In this research, we looked at the changes in ecosystem services as a function of land use changes over the past and in the future. The key findings include that from 1994 to 2018, these four ecosystem services experienced a decline. However, the BaU land use of 2050 is anticipated to be relatively stable, with increased forest land and decreased agricultural land. As such, the data is helpful for the evaluation of ecosystem services.

4. CASE STUDY 2: QUANTIFICATION OF MANGROVE ECOSYSTEM SERVICES THROUGH EXPLORATORY SCENARIOS IN BHITARKANIKA MANGROVES IN ORISSA, INDIA[3]

4.1. Introduction to the Bhitarkanika Mangroves, Orissa, India

The Bhitarkanika and Paradip mangroves are among the important mangrove habitats on the east coast of India. Over the past decades, it has faced tremendous pressure from industry and other forms of coastal development. As a result, the mangrove extent was reduced significantly. According to the Census of India (2011), approximately 400 villages within the Bhitarkanika National Park and approximately 1,50,000 people living in these directly or indirectly depend on the mangroves. Figure 5 depicts the location of the study area.

4.2. Scenario development from the participatory survey

To determine the plausible alternative futures of mangroves in these two study areas, we ratified the story and simulation approach, a common method used for scenario building. We first conducted a participatory survey to identify the key drivers and uncertainties associated with it.[4] This served as the basis of the storyline development. After providing a summary of the perceptions held by stakeholders regarding the region's future landscape, this study produced three scenarios based on the region's economic development. LCM was used for the first scenario, i.e., Scenario 1, where economic growth gets the highest priority. In other words, the local government prioritises the expansion of the built-up area, agricultural farms and aquaculture. In Scenario 2, the conservation of mangroves is taken care of, although development continues. Lastly, Scenario 3 portrays an ecologically optimistic future characterised by the reverse conservation of

[3]For details, see Kadaverugu et al. (2022).

[4]For details, please see Dhyani et al. (2022).

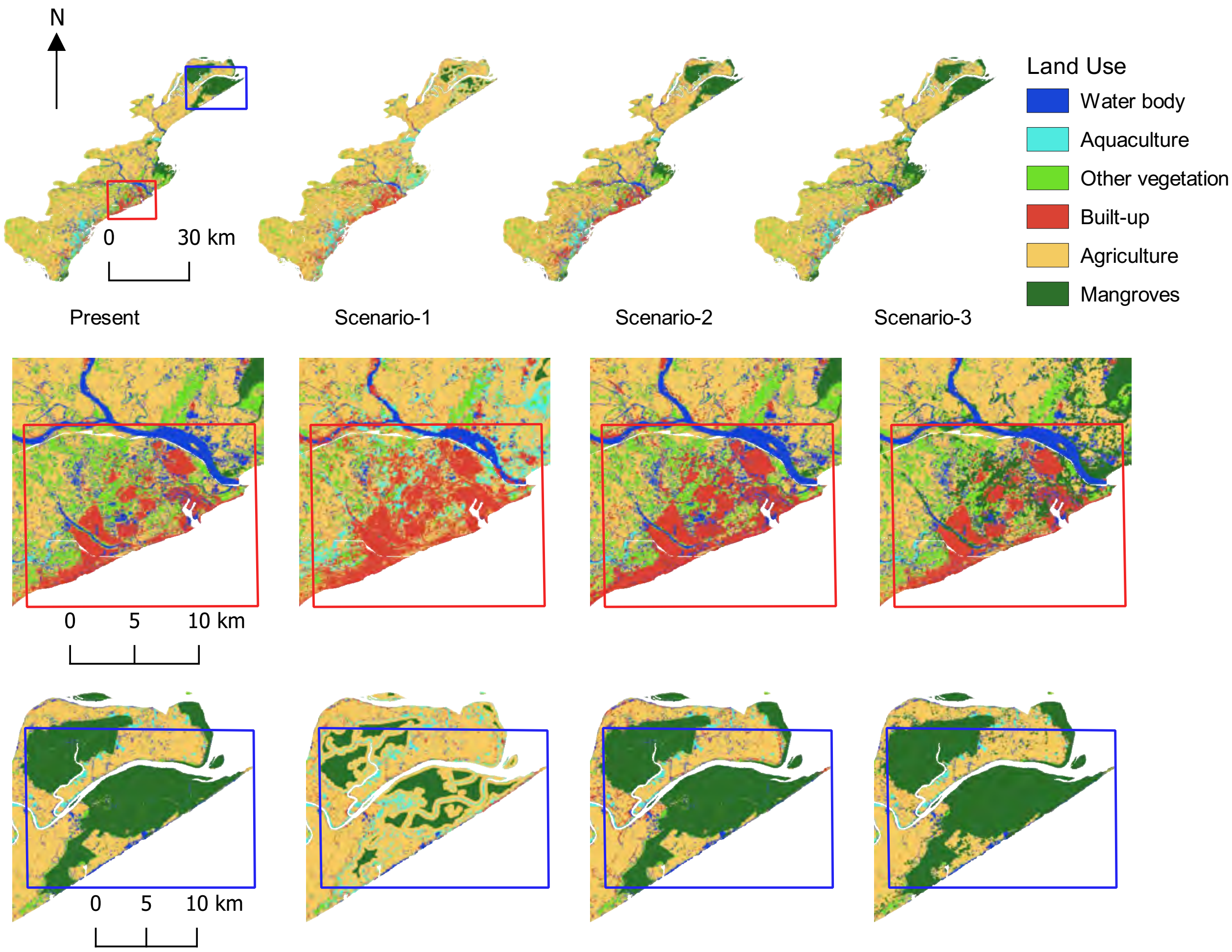

FIGURE 6. The plausible alternative land use for three contrasting Scenarios.

aquaculture, agriculture and other vegetated areas. Under this scenario, it is considered that mangrove conservation and regeneration will be prioritised owing to changed government policy.

4.3. Scenario analysis

Scenario 1 is dominated by agriculture, aquaculture cover and built-up expansion. Expectedly, mangrove cover has decreased by 2.5% in this scenario from the current extent and built-up areas expanded from 4.5% to 9.5%. The land use pattern for Scenario 2 reflects similar changes, with the mangrove cover remaining unchanged at 9.1%. In contrast, the mangrove cover in Scenario 3 rises from 9.1% to 14.1%, owing to extensive plantation-based restoration. Figure 6 provides the alternative land use maps for 2050.

4.4. Scenario analysis for vital ecosystem services

This research focused on four ecosystem services types: blue carbon, nitrogen and phosphorus retention and sediment transport.[5] The findings indicate that the loss of mangroves resulted in a net emission of blue carbon in scenario 1. In scenario 2, changes in mangrove cover are insignificant, while an increased mangrove cover in scenario 3 will boost blue carbon to 6.10 Tg C. Similarly, sediment export will marginally increase to 1.99 Gg/y in Scenario 1, mainly due to the loss of mangroves. On the contrary, sediment transportation will decrease in Scenario 2 and a further decrease in Scenario 3. As mangrove cover loss is also directly proportional to N and P nutrient exports, in Scenario 1, the export is likely to increase to 41.58 and 18.83 Mg/y, respectively. However, in the alternative scenarios (i.e., both Scenarios 2 and 3), it is expected to be even lower than the baseline (see Figure 7).

[5] For details on InVEST modelling, see Kadaverugu et al. (2022).

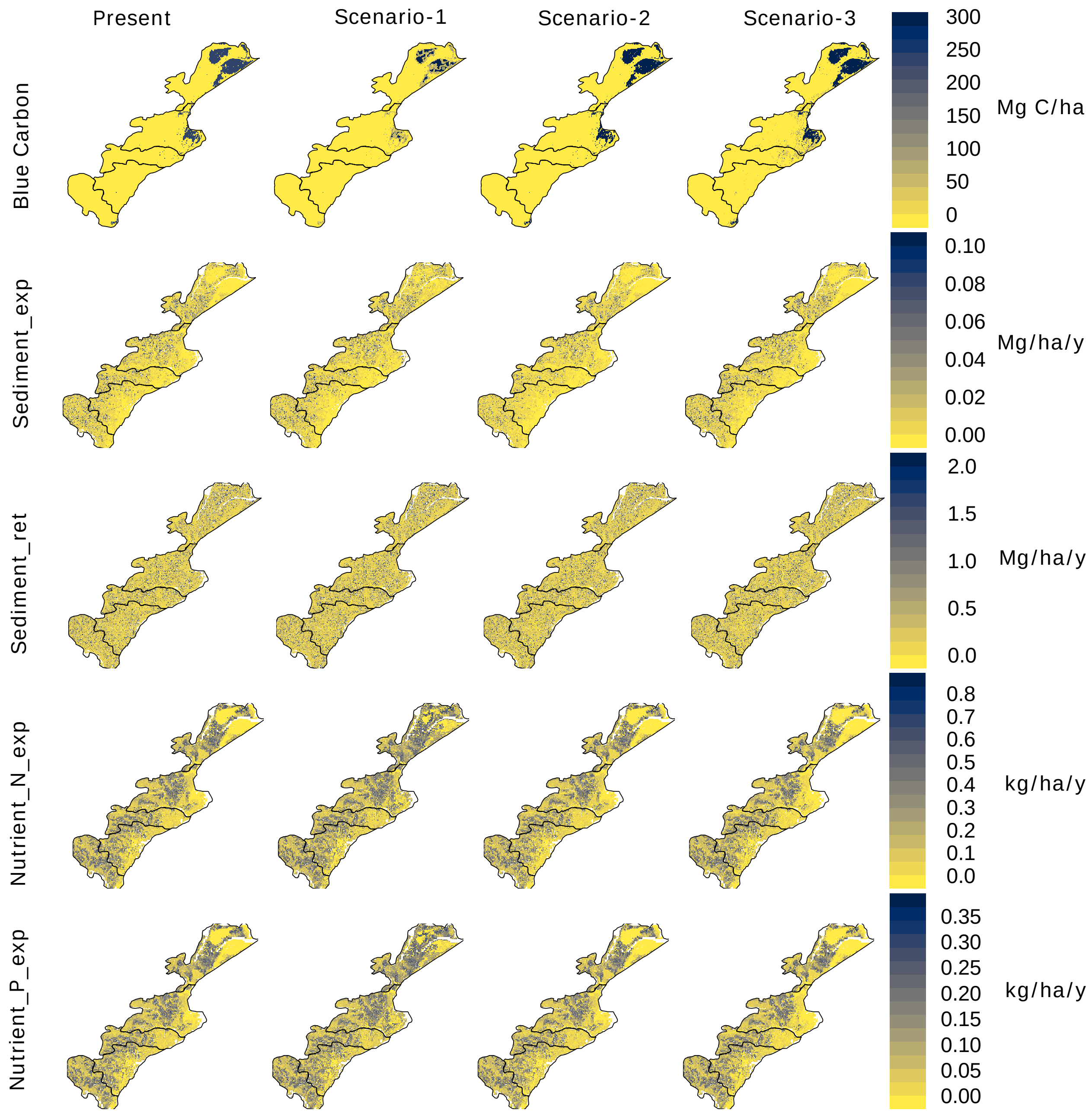

FIGURE 7. Ecosystem Services across three scenarios.

4.5. Policy recommendation

Mangrove ecosystems provide many ecosystem services essential for controlling coastal environments. This study developed three potential alternative scenarios based on which ecosystem services of mangroves were quantified. The research explored that, in the worst case, the state of Odisha is likely to release 2.16 Tg C by 2030, which is undesirable. On the other hand, under the best-case scenario, Mangroves can potentially absorb an additional 1.55 Tg C of carbon dioxide from the atmosphere. Furthermore, conservation co-benefits include lower exports of sediment and nutrients, which are pivotal for an ecosystem-based adaptation in the region.

5. CONCLUSION

Mangroves are finite and fragile resources and there is a global consensus that these forests should be conserved and restored, given that the coastal areas face unprecedented risk from climate change. This paper presented two case studies where we developed landscape-scale scenarios and quantified the state of mangrove ecosystem services across plausible alternative development pathways. The scenarios identified a range of possibilities, including the best and worst-case scenarios. At the local scale, these case studies would be helpful for policy planners to optimise their development plan spatially to balance the synergies and trade-offs in vital ecosystem services. The methods adopted in this study should further inspire researchers to adopt a similar approach to scenario-based quantification of mangrove ecosystem services in Asia and elsewhere. Nonetheless, the study has certain limitations, e.g., the models we used are not conducive to calculating the impacts of sea level rise of the prime determinant for future mangrove ecosystem services. In addition, large-scale natural hazards also alter mangrove habitats drastically; however, such uncertainties were not considered during our simulation.

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Original Article

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Towards sustainable mangrove-shrimp aquaculture through capacity building and partnership in the Mekong River Delta

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ABSTRACT

Vietnam, the world's third-largest shrimp producer, witnessed a surge in shrimp farming when rice fields were converted into ponds, aiming to alleviate poverty in the Mekong River Delta (MRD). However, this growth significantly contributed to the decline of mangrove forests, as indicated by empirical and geospatial data. Local authorities have encouraged the application of "International Principles" to promote sustainable mangrove-shrimp aquaculture in MRD provinces. Tra Vinh, a province with a high rate of mangrove-shrimp farming, faces challenges in applying international standards, particularly for small-scale farmers. Understanding the circumstances in Tra Vinh is crucial not only for local farmers but also for stakeholders in the region. An in-depth review, local needs assessment, and a capacity-building program centred on the Asian Seafood Improvement Collaborative (ASIC) standards were conducted in Tra Vinh. The findings suggest that adhering to ecological/organic shrimp farming based on international standards is the right direction for local shrimp farmers. However, increased awareness alone does not guarantee a shift from traditional to internationally certified sustainable shrimp farming. The study highlights the role of private-private partnerships (PPPs) in facilitating the transition to sustainable mangrove-shrimp farming, emphasising that sustainable practices in the MRD are essential for household income, mangrove forest protection, environmental conservation, and climate resilience.

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KEYWORDS MEKONG RIVER DELTA, MANGROVE FORESTS, SHRIMP FARMING, MANGROVE-SHRIMP AQUACULTURE, SUSTAINABLE AQUACULTURE, LIVELIHOODS

HIGHLIGHTS

- The rise of shrimp farming in MRD was a main driver in the region's decline in mangrove forest area.
- Small-scale farmers in Tra Vinh province face difficulties applying the "International Principles" toward better management of shrimp farming.
- Shrimp farmers in Tra Vinh province expressed their interest in applying the ASIC international standard.
- ASIC capacity building should be provided to local farmers and agencies/companies to support international shrimp management standards implementation.

1. INTRODUCTION

Shrimp is one of the most valuable seafood commodities in the world. Shrimp and prawns dominate aquaculture production in coastal areas, constituting more than 60% of the farmed crustaceans in the world. However, the cultivation of shrimps and other aquatic species, nonetheless, is confronted by manifold sustainability issues, including environmental impacts like mangrove degradation, water quality degradation, salt-water intrusion, disease outbreaks (Sivaraman et al., 2019), water use conflicts, privatisation of natural resources (Primavera, 1997), and food safety. Meeting the needs of buyers, especially in developed countries, certifications were born with increasing numbers and requirements for manufacturers to meet standards, notably Aquaculture Stewardship Council (ASC), Best Aquaculture Practices (BAP), and Global Good Agricultural Practices (GLOBAL G.A.P.) The growing trend of the market for product certification requires seafood exporting countries to make efforts to promulgate regulations for sustainable seafood production and consumption.

Vietnam is the third largest shrimp-production country in the world (FAO, 2020). Shrimp is the second most important aquaculture industry in Vietnam - only after catfish – with an export value of around $3.4 billion in 2017 (Rubel et al., 2019), $3.85 billion in 2020 (Luu et al., 2021), $3.9 billion in 2021, and $4.3 billion in 2022 (Tu Nguyen et al., 2022). Shrimp culture has flourished in Vietnam, especially after the Doi Moi economic reforms in the late 1980s. The government allowed farmers to convert rice fields and salt pans, especially in the Mekong River Delta (MRD), to shrimp ponds to promote poverty reduction. Shrimp farming thus becomes the main livelihood for hundreds of thousands of people.

The MRD is a large flat land area located in southern Vietnam. With a total area of approximately 40,000 km^2 (Phan, Le Toan & Bouvet, 2021), it occupies 12% of the country's total area (Lam, 2020). The MRD is the home of over 17.3 million people, accounting for 17.7% of the total population of the whole country. The MRD is the most important economic region of Vietnam as it has the largest agricultural and aquaculture production in the entire country. In particular, aquaculture production was over 3.1 million tons and occupied 70% of the country (FAO, 2022; GSO, 2021). However, the MRD is also the most vulnerable area of the country when it is facing a series of environmental problems including climate change, rising sea levels, coastal erosion, land subsidence and changes in hydrological regimes. One of the reasons for this phenomenon is deforestation with the reduction of mangrove forests in the coastal areas of the MRD. The area of mangroves in the MRD has decreased by nearly half in the past 48 years, from about 185,800 ha in 1973 to 102,160 ha in 2020 (Phan & Stive, 2022).

One of the reasons for the decline of mangrove forests in the MRD is the development of shrimp farming. From 1953 to 1995, 161,277 ha of mangrove forests were converted to shrimp farming and other uses (Minh et al., 2001). Since 1995, the Vietnamese government has implemented a policy to allocate mangrove forests to households for protection, management, and logging. Under this policy, households could convert part of the contracted mangrove forests to agriculture, aquaculture, and housing, in which shrimp farming was the main driver of forest conversion (Thu & Populus, 2007). As a consequence, the rapid development of shrimp farming in the MRD has contributed to deforestation, erosion and rising salinity levels that are threatening the stability of the entire region (Waugh, 2011). Tra Vinh – a province in the MRD is not an exception. The reduction of mangrove forests has especially occurred in Tra Vinh province, where most natural mangroves have been replaced by shrimp culture areas (Thu & Populus, 2007). This is a worrying trend, as healthy mangroves make important contributions to both climate change adaptation and mitigation, acting as a natural barrier against storms, sea-level rise, and erosion, and have the ability to store and sequester carbon (Salem & Mercer, 2012; SNV, 2019). In addition, mangroves offer important services in maintaining biodiversity and purifying water (Alongi, 2008; Sathirathai & Barbier, 2001). Important as well is that mangrove forests are home to shrimps, crabs, bivalves and fish, among other species, and sustain the livelihoods of coastal communities (Barbier, 2007).

To address the aforementioned situation, in 2017, the Vietnamese Government passed Resolution 120/NQ-CP on Sustainable and Climate-Resilient Development of the MRD, which recognises the challenges of climate change and outlines its vision for a sustainable delta. In terms of development, they state the need to "shift from quantity-based to quality-based development; build new rural areas associated with strong development and application of high technology agriculture, organic agriculture and clean agriculture chain and trademarks". As a result, the trend of mangrove forest protection is highly encouraged to ensure sustainable development in the region. Nguyen et al. (2022) emphasised the triple benefits of mangrove-shrimp farming models from economic, environmental and social aspects. However, the ratio between mangrove forests and water surface in shrimp ponds to bring the maximum profits is often different from the ratio suggested by researchers, varying from 30 to 60% (Bosma et al., 2014; Nguyen et al., 2022; Tuan et al., 1992). In order to meet the growing trend of the international market for product certification, the International Principles for Responsible Shrimp Farming provide the basis upon which stakeholders can collaborate for a more sustainable development of shrimp farming and have been applied in Vietnam. Evidence has shown, however, that local small shrimp farmers found these principles difficult to apply. This is due to the fact that the principle focuses on ecology while the adaptation and social aspects have not received enough attention.

This study investigated how a capacity building programme centred on the sustainable development of shrimp aquaculture based on the Asian Seafood Improvement Collaborative (ASIC) international food standard that aimed to address the challenges of the mangrove social-ecological systems. The area of mangrove cover on each farm, the benefits to the local community and adaptation to climate change have changed the ways in which small shrimp farmers have traditionally farmed shrimp towards sustainable mangrove-shrimp aquaculture in Tra Vinh province. The main objective of the paper is to compare the level of knowledge of stakeholders before and after the training modules and assess their willingness to adopt the Asian Seafood Improvement Collaborative (ASIC) international food standard that has been customised from VietGAP (Vietnamese Good Agricultural Practices) to suit the context of Tra Vinh province. The study results will provide policymakers with the evidence to promote sustainable mangrove forest management through supporting sustainable mangrove-shrimp aquaculture practices in the MRD.

2. METHODOLOGY

2.1. Research site

The research area is in Long Khanh commune and Don Chau commune, Duyen Hai district, Tra Vinh province, where the largest mangrove areas exist (see Figure 1). It had 5,616.09 ha of mangrove forest across the 9,538.74 ha of Tra Vinh province (Tra Vinh Provincial Sub-department of Forest Protection, 2022). The mangroves of Long Khanh commune account for 21.62% of the total mangrove areas of the district and Don Chau commune accounts for 3.07% of the total mangrove areas (Ibid.). Long Khanh commune had the largest areas of mangrove-shrimp farming, with 634 households that practised mangrove-shrimp farming in an area of 1530 ha (Tra Vinh Provincial Sub-department of Fisheries, 2022). Meanwhile, Don Chau commune,

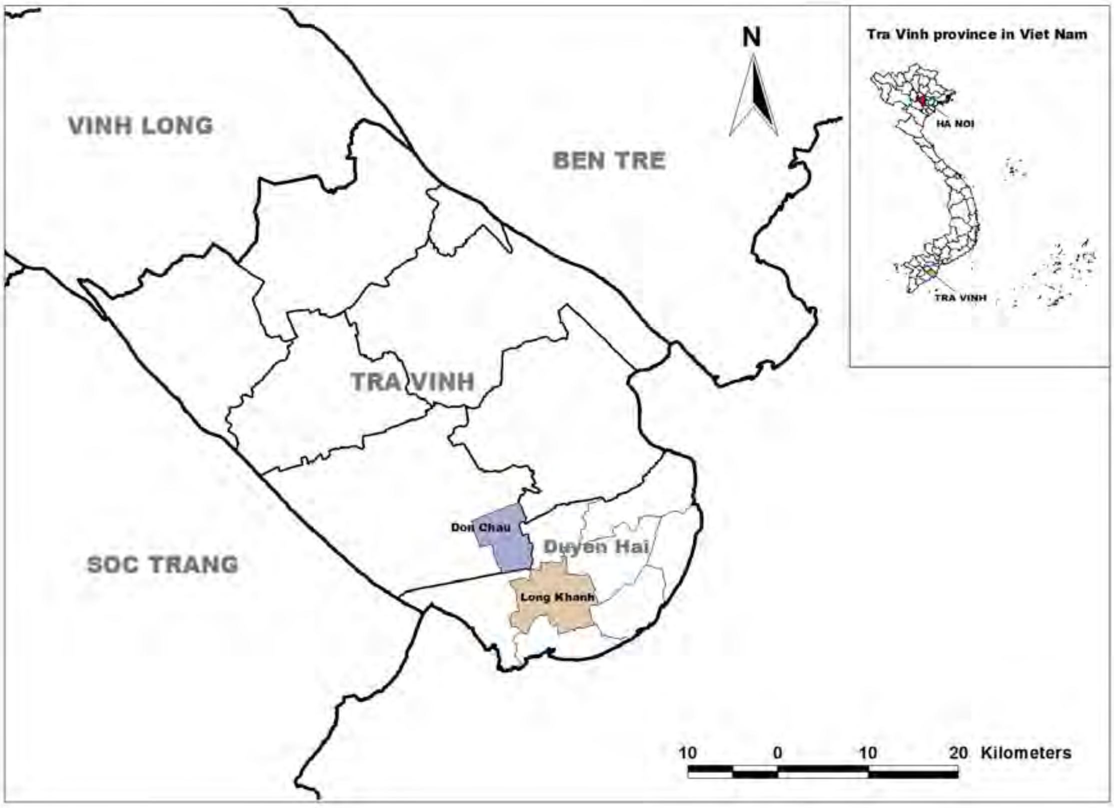

FIGURE 1. Map of Long Khanh and Don Chau commune, Duyen Hai district, Tra Vinh province.

which has the smallest mangrove areas in the district, had well-developed extensive shrimp farming. Many shrimp farmers in Don Chau commune were interested in shrimp farming with certification because they believed that by participating in the project, they would gain better and more effective shrimp farming knowledge and, more importantly, they wanted to aim for certified shrimp farming in their respective area.

2.2. Methodology

2.2.1. Approach

The research used the Knowledge- Attitude and Practice (KAP) assessment along with focus group discussions to understand perceptions, skills, and lessons learned that served as the basis for developing capacity building programs on sustainable mangrove-shrimp aquaculture in accordance with the international standards in the context of climate change for relevant stakeholders in Tra Vinh province.

KAP is a frequently used survey methodology in social research (Vandamme, 2009). The method is used to quantify and analyse human perception and behaviour relating to a certain topic in three aspects: to what extent they know about that topic, how positively or negatively they regard it, and what they would do relating to it (Kaliyaperumal, 2004). The result of the KAP survey is to identify knowledge gaps, attitudinal challenges and the factors influencing the attitudes and behaviour of stakeholders relating to certain issues (WHO, 2008).

In our study, knowledge was referred to understanding sustainable shrimp farming and their training history and lessons learned from those training on shrimp farming. The attitude of the respondents was considered to be the willingness to participate in training and activities on sustainable shrimp farming and international food standard certification - ASIC. Practice was conducted to assess whether the change in awareness and attitudes of local shrimp farmers has led to a change in the ways in which they farm shrimp towards sustainable mangrove-shrimp aquaculture at the community level.

2.2.2. Methodology

The research was organised on two levels: desk study and fieldwork.

- Desk study: We conducted a literature review on shrimp farming practices in Vietnam and certificates that have been applied and are potential for implementation in Vietnam, especially in the Mekong River delta. Socio-economic develop-

FIGURE 2. A mangrove-shrimp farming pond in Long Khanh commune, Duyen Hai district, Tra Vinh province.

ment plans of the research areas and related policies and programs on shrimp farming in the Mekong River delta were also studied.

- Fieldwork: Primary data collection was carried out through key informant interviews and focus group discussions. We conducted key informant interviews with 40 stakeholders, of whom 11 were officials of relevant departments, two were from private shrimp companies, one was an aquaculture lecturer at Tra Vinh University, and 26 were shrimp farmers in Duyen Hai district, Tra Vinh province. A questionnaire was designed to collect information on relevant stakeholders' knowledge and experience related to shrimp farming, their training history and lessons learned, their knowledge gap and training needs, and their suggestions for the training format, duration, and location. Those stakeholders included local shrimp farmers who were members of the cooperative group, policymakers, NGOs active in the region, and the private sector that was engaged in the shrimp. A focus group discussion with eight shrimp farmers was conducted in each commune. The questions covered information about current methods of shrimp farming practised by local farmers, the knowledge and skills that they had gained from previous training courses, what the gaps were and what they would need in order to better manage mangrove-shrimp aquaculture and also improve their household economy.
- Field observations in Duyen Hai district and Bac Lieu province: Field observations were employed while field research was being conducted in Long Khanh commune and Don Chau commune, Duyen Hai district, Tra Vinh province. This helped the research team better understand different methods that local shrimp farmers applied to their shrimp farming as well as the profits and impacts each method brought to local people. Furthermore, field observation was also used during the study tour to Bac Lieu province with heads of households engaged in shrimp farming from the two communes to learn good practices on shrimp farming combined with ecotourism in the study site and draw lessons that can be applied to Tra Vinh upon their return.
- Consultation and policy dialogue workshops: Thirty stakeholders who were policymakers from relevant provincial departments, small-scale shrimp farmers and shrimp private companies in Tra Vinh province participated in the consultation and policy dialogue workshops. Small-scale farmers participated in the survey on training needs on shrimp farming and attended the training courses, which were developed based on the results of the training needs assessment.

3. RESULTS AND DISCUSSION

3.1. Shrimp farming and mangrove forests in Tra Vinh province

Within 30 years, from 1988 to 2018, the area of the mangroves in Tra Vinh province had a dramatic change, decreasing by 70% (10,678.7 ha) from 15,176.2 ha to 4,497.4 ha (Son et al., 2020). The recovery rate of the mangroves in this period was nearly five times lower than the loss rate. The area of mangrove forests lost due to deforestation to construct shrimp ponds and causing coastal erosion was 13,383.7 ha, while the area of newly formed mangrove forest on newly accreted coastal lands, dunes in the river mouth area, as well as the new planting of mangroves in inefficient shrimp ponds, was 2,704.9 ha (ibid). During the time this field research was being conducted, the total area of mangrove-shrimp farming in Tra Vinh was 7,041 ha, concentrated in 5 sub-regions of Duyen Hai district and Duyen Hai town. According to Decision No. 1925/QD-UBND dated September 29, 2022, the area of 7,041 ha of mangrove forests will be maintained until 2050. As stipulated in Plan No. 69/KH-UBND dated August 6, 2021, of the Tra Vinh Provincial People's Committee, by 2030, 5,700 ha (accounting for 80.9% of the total area) of mangrove-shrimp aquaculture will be awarded ecological certification.

During the time this field research was being conducted, there were no farms with ecological certification. According to participants of the focus group discussions, the reasons are twofold. First, there was no difference between the selling price of certified and non-certified shrimp. Second, the procedure and costs to obtain certification were complicated and expensive, and every year, shrimp farmers would have to pay extra costs to evaluate and maintain the certificate. In addition, because the shrimp farming area of the households was small (about one ha/household), if organic shrimp farming was practised, shrimp production would be lower than traditional shrimp farming and, therefore, shrimp farmers' income was lower compared with traditional farming methods. It is also important to note that due to low shrimp yields, with not enough quantity of farmed shrimp needed for each sale, traders did not come to buy local farmers' shrimp. These problems explain why shrimp farmers did not want to own ecological certifications.

According to key informant interviews, mangrove-shrimp farming started 20 years ago in Tra Vinh province and shrimp farmers have been trained in mangrove-shrimp farming techniques. However, local shrimp farmers still farmed shrimp just using traditional methods (see Figure 2). The reasons include (i) the inability of the household to invest in infrastructure for farming; inappropriate infrastructure with no planning, no investment in water supply channels, no separate drainage, and lack of qualified fry, which were only enough to supply 25% of the demand, also with the quality of fry not checked by the Sub-Department of Fisheries. All of this has made local shrimp farmers more interested in traditional farming methods than sustainable mangrove-shrimp aquaculture.

Our observation while in the field showed that traditional shrimp farmers stocked shrimp with high density, used more industrial feed, took advantage of available farming ponds, and did not invest in or plant additional mangrove forest trees in the pond. As a result, the forest cover in the farming pond was way below the required standard of 40%. According to an official at the Tra Vinh Provincial Sub-department of Fisheries, because the farming area has not been planned, there is no separate water supply and drainage canals. In reality, the extensive and intensive farming ponds alternated in the same farming area, the wastewater from the intensive farming pond was the water supply of the extensive farming pond. This is the cause of disease spread, leading to high shrimp mortality keeping the economic efficiency of shrimp farming in the province low.

3.2. Training needs assessment of small-scale shrimp farmers on shrimp farming practices

Interviews were conducted with 40 representatives of the public and private sector and local shrimp farmers, of which 26 participants were small-scale shrimp farmers in Duyen Hai district, Tra Vinh province. Among these 26 farmers, three people (making up 11.5%) raised shrimp for about 30 years since the 1990s, 21 (80.7%) farmed shrimp for 20 years, while only two people farmed shrimp for the last ten years.

Figure 3 shows shrimp farming methods that small-scale farmers used in the Duyen Hai district, Tra Vinh province. The figure demonstrates that the highest percentage of farmers implemented extensive shrimpfarming[1], which accounted for 57.7% (15 people), while 23.1% of interviewees used

[1]Extensive shrimp farming: Shrimp farmed naturally, with limited additional feeding (Phuong et al., 2004) and low initial stocking densities of 1–3 post larvae per square meter (Tran et al., 2012a).

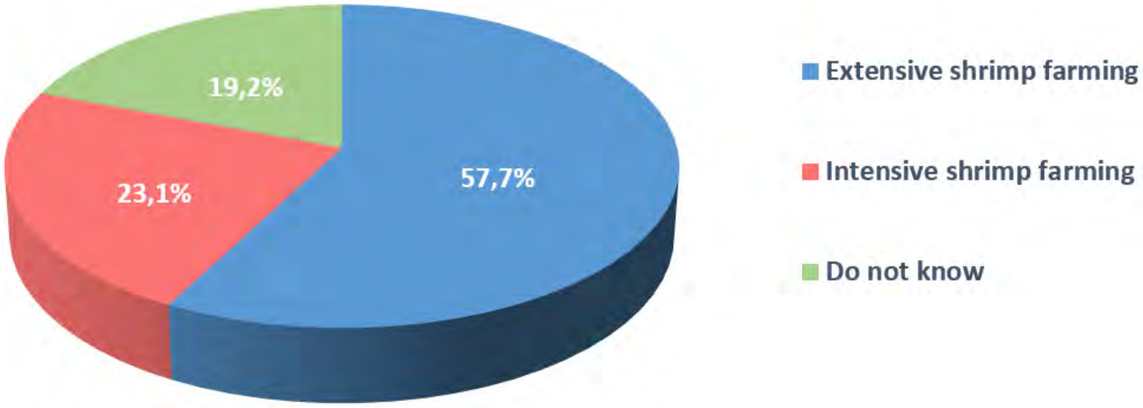

FIGURE 3. Shrimp farming methods practised by sample shrimp farmers in Duyen Hai district, Tra Vinh province in 2022.

intensive shrimp farming[2] (six people) and the remaining 19.2% did not know which methods of shrimp farming they were practising. The findings show that shrimp farmers who used natural shrimp farming methods were more interested in applying sustainable mangrove-shrimp models in their respective areas.

With regard to the level of understanding of sustainable shrimp farming, only one participant (accounting for 3.8%) could describe the benefits this method could bring from social, economic and environmental aspects, while three people (11.5%) stated the economic and environmental benefits. Meanwhile, 14 people (53.8%) explained an aspect or technique in sustainable shrimp farming and they emphasised the importance of fry standards, and 30.9% of the remaining interviewees did not know what sustainable shrimp development was.

As a high percentage of sample shrimp farmers stated that they did not know clearly about sustainable shrimp farming and they had only farmed shrimp based on their experiences, a high number of interviewees expressed their willingness to participate in training on shrimp farming. Specifically, 95% of the sample shrimp farmers' desire was to attend at least a training course related to (a) sustainable mangrove-shrimp farming techniques; (b) lessons learned on sustainable mangrove-shrimp farming, access to markets or a purchasing company engaged in sustainable mangrove-shrimp farming and already awarded ecological certification; (c) International certification in Sustainable Forest Shrimp Farming such as ASIC; and (d) a demonstration model on sustainable mangrove-shrimp farming for local application and replication in the future. The interviewees also said they wanted to have training courses that last three days each.

It is important to also note that a sustainable shrimp farming cooperative group was established in Long Thanh commune before the training courses were conducted. This demonstrated that local shrimp farmers were very much interested in new ways of farming shrimp and were eager to apply sustainable mangrove-shrimp aquaculture in accordance with international standards in their locality.

3.3. Results of training on sustainable shrimp farming

Those who participated in the training needs assessment survey were also invited to attend the training courses on sustainable mangrove-shrimp farming techniques in accordance with international standards and ASIC certification, which was customised from VietGAP (Vietnamese Good Agricultural Practices) to suit the context of Tra Vinh province was introduced to the participants. It is important to note that the Food and Agriculture Organization (FAO) has developed a set of principles called Good Agricultural Practices (GAP) that are geared towards large-scale production households/companies. GAP principles generally focus on creating safe and hygienic products that are economically, socially and environmentally sustainable. Meanwhile, ASIC aims at small-scale shrimp farmers and focuses on principles to improve sustainability, environmental and socioeconomic performance. A study tour was organised for the participants to Bac Lieu province, where there were good practices on mangrove-shrimp

[2]Intensive shrimp farming: Farmers maximize shrimp yields by applying high densities of larvae (EJF, 2003) and strictly managing water quality by preventing the connection with surrounding waterways (Joffre & Bosma, 2009).

farming combined with ecotourism. An assessment was also conducted as part of the training course. The results of the evaluation showed that all participants were interested in the training and were happy with the knowledge that they had been equipped with. They were specifically interested in the mangrove-shrimp combined with ecotourism. They all expressed their willingness to adopt those practices upon their return.

A small shrimp farmer in Duyen Hai district, Tra Vinh province, said:

> *"I realised that the knowledge and skills on mangrove-shrimp farming are very useful for us. We have raised shrimp for years with mangrove stands in the shrimp pond. However, we have not paid much attention to the roles of the mangroves. I have also learned a new model of mangrove-shrimp farming combined with ecotourism, and I think this is a good model that brings profits to farmers. I will try to apply this model upon my return."*

A staff member from a fishery company shared:

> *"Although I have known some other models of sustainable shrimp farming, I did not clearly understand their techniques. Through this training, I have gained more knowledge and skills on better shrimp management combined with ecotourism so that I can support local farmers more effectively."*

A policy dialogue workshop was conducted at the end of the study and served as a forum for policymakers to meet and discuss face-to-face with local shrimp farmers to learn about their problems/challenges as well as problem-solving. The workshop was attended by representatives of the Tra Vinh Provincial Department of Agriculture and Rural Development, Tra Vinh Provincial Agriculture and Fisheries Extension Center, the Duyen Hai District Department of Agriculture, Cuu Long SeaPro Joint Stock Company, Farmers' Association and shrimp farming households in Long Khanh and Don Chau communes.

It is important to note that heads of those shrimp farming households had already participated in the training needs assessment, the training courses and the study tour. It was reported that it was for the very first time shrimp farmers had the opportunity to meet and discuss face-to-face with policymakers about their problems related to shrimp farming. In contrast to the results of the evaluation conducted at the end of the training, almost all shrimp farmers attending the workshop said that they did not want to apply the (ASIC) international food standard, even though the representatives from Tra Vinh Sub-department of Fisheries, Tra Vinh Sub-Department of Forest Protection, and Cuu Long Seaproducts Company were committed to provide them technical support to practice ASIC and buy shrimp from those households.

According to the shrimp farmers, being fully equipped with new knowledge and skills was necessary but not yet sufficient for them to switch to ASIC since there were still too many difficulties and challenges. Many of them said that now, because shrimp disease was so serious ,they were not interested in farming shrimp anymore, despite the fact that they were provided technical training and went on a study tour. They believed that without the active participation of the local government and the private sector, the transition of shrimp farming in Tra Vinh based on the requirements of the ASIC international standard would not happen. According to the head of the Long Thanh Cooperative Group, public and private partnerships (PPP) can be particularly beneficial for the shrimp farming industry in the MRD in the following ways:

- Improved productivity: PPPs can help improve productivity in the shrimp farming industry by providing farmers with access to better technology, training and inputs. This can lead to higher yields and profits for farmers.
- Improved environmental sustainability: PPPs can help to improve the environmental sustainability of the shrimp farming industry by promoting the use of sustainable practices, such as closed-containment systems. This can help to reduce the environmental impact of shrimp farming and protect the environment.
- Increased exports: PPPs can help increase shrimp exports from Vietnam by providing farmers with access to international markets. This can boost the economy and create jobs.

The members of the Long Thanh cooperative group and the shrimp farming households of Don Chau commune also hoped that, in the near future, sustainable mangrove-shrimp aquaculture will become a reality in Tra Vinh with the participation of both the public and private sectors.

4. CONCLUSION

As the case of Tra Vinh province illustrates, moving towards sustainable mangrove-shrimp aquaculture based on ecological/organic shrimp farming requirements in accordance with international standards is the right direction for local shrimp farmers to go. To facilitate this transition, it is crucial to employ capacity building methods tailored to the local context and culture, specifically targeting stakeholders in shrimp farming and PPPs. The findings indicate that workshops and training sessions focusing on mangroves, shrimp-forest farming techniques, ecological certification, cooperative economy and product value chains have played a role in altering perceptions within the local community, fisheries management agencies and local authorities. These sessions empowered local shrimp farmers to recognise the challenges they have faced and offered sustainable solutions. The workshops aimed to align aquaculture practices with ecological certification needs, fostering a more sustainable approach. The ultimate goal is to expand both the domestic product market and seafood exports in the future.

However, the case of Tra Vinh also demonstrates that changes in knowledge and attitudes did not lead to changes in practice. Almost all the shrimp farmers who participated in the training and the study tour did not change the ways in which they farmed shrimp to meet international food standards. This is due to the lack of partnerships between the local government and shrimp exporters that could have been an effective catalyst to facilitate the transition towards sustainable mangrove-shrimp farming in accordance with international food standards.

The research findings also show that with the knowledge and skills that local shrimp farmers have gained, they became aware of the trend of aquaculture development in the new era. It is hoped that the participation of the public and private sector will encourage them to boldly and confidently change their way of thinking and traditional farming practices towards responsible, ecologically certified aquaculture linked with chain partners to increase product value. As such, they will contribute to increasing household income while maintaining and conserving mangrove forests and reducing negative impacts caused by climate change in the near future in Tra Vinh.

Further research should be carried out in the future to provide new insights into the possibilities and constraints of PPPs in facilitating the transition towards compliance with international sustainability requirements and motivating small shrimp farmers to apply for ASIC international food standards in the region.

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Case study

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Climate change research, capacity building and communication on climate extremes over South Asia

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ABSTRACT

Climate change is a global issue that significantly impacts various regions, including South Asia, which is particularly vulnerable to climate extremes. Extensive research is required to address the complex interplay between climate change and extreme weather events in South Asia (Bangladesh, Nepal and Pakistan). This study presents a case study of an Asia-Pacific Network for Global Change Research (APN) project focusing on climate change research, capacity building and science-to-policy communication on climate extremes in South Asia. Climate change research emphasises the importance of research to understand the changing patterns and impacts of climate extremes in the region. It underscores the need for robust scientific methodologies, data collection and analysis to generate reliable evidence for policymakers and stakeholders. The capacity building efforts involve training programmes, workshops and knowledge-sharing platforms, which are critical to enhancing the capabilities of local researchers, institutions and communities in conducting climate change research and developing adaptation and mitigation strategies. The science communication includes disseminating the study's findings to stakeholders, including policymakers, researchers, communities, media and civil society organisations. Overall, collaborative efforts between South Asian countries are important for climate change research, capacity building and science-to-policy communication to build resilience and mitigate the impacts of climate change.

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KEYWORDS CLIMATE CHANGE, SOUTH ASIA, CLIMATE EXTREMES, RESEARCH, CAPACITY BUILDING, SCIENCE-TO-POLICY COMMUNICATION

HIGHLIGHTS

- Generated reliable 5 km reference climate data for Bangladesh, Nepal and Pakistan.
- Selected the best climate models for Coupled Model Intercomparison Project Phase 6 (CMIP6) for Bangladesh, Nepal and Pakistan.
- Downscaled CMIP6 models over Bangladesh, Nepal and Pakistan under different Shared Socioeconomic Pathways (SSPs).
- Capacity building through workshops, training sessions and university courses to empower researchers and students, focusing on promoting female involvement and supporting early career researchers.
- Communicated scientific findings to policymakers, stakeholders and the public through diverse channels, e.g., media.

1. INTRODUCTION

Climate extremes, such as heatwaves, floods, droughts and storms, have become increasingly frequent and severe in recent years, posing significant challenges to human societies, economies and ecosystems (Intergovernmental Panel on Climate Change [IPCC], 2023). These extreme weather events can result in loss of lives, health problems, damage to infrastructure, disruption of essential services, displacement and loss of livelihoods, particularly in vulnerable regions such as South Asia. Understanding the changing patterns and impacts of climate extremes at local scales is crucial for developing effective adaptation plans and reducing vulnerability to these events (Ali et al., 2019; Kundzewicz et al., 2019; Pörtner et al., 2022). The South Asian region has already been experiencing extreme events in recent decades, like floods, heat waves, heavy rainfall, among others. Studies show that the extreme phenomena will change in the future. For instance, Khan et al. (2023) and Ali et al. (2019) suggested that the cold days are decreasing while the warm nights will increase in Pakistan. These studies further suggested that the consecutive wet days (CWD) and consecutive dry days (CDD) will decrease and increase in the future, respectively, under both climate change Representative Concentration Pathways (RCP4.5 and 8.5) over Pakistan. A recent study based on observed data claimed that summer days (SU25) increased during 1991–2019 compared to 1962–1990 in Pakistan (Khan et al., 2022). A study about temperature and rainfall extremes in Bangladesh claimed that the warming has increased. However, the coastal areas have shown a higher rate of warming over the last five decades (Abdullah et al., 2022). A study investigated the trends of climate extremes in Bangladesh and concluded that mean monsoon seasonal rainfall can alter, posing significant challenges to agriculture, hydropower and the ecosystem (Rimi et al., 2022). Nepal has experienced extreme events due to climate extremes in recent decades. Studies claimed that heavy and extreme rainfall will increase under the RCP4.5 and RCP8.5 over Nepal (Chapagain et al., 2021; Pandey & Mishra, 2022). Hence, the importance of research in elucidating the changing patterns and impacts of climate extremes in South Asia cannot be overstated. Robust scientific methodologies, data collection and analysis are essential for generating reliable evidence to inform policymakers and stakeholders in developing effective adaptation and mitigation strategies (Karmakar et al., 2020). Furthermore, capacity-building efforts are critical to enhancing the capabilities of local researchers, institutions and communities in conducting climate change research. This includes training programs, workshops and knowledge-sharing platforms to foster multidisciplinary collaboration, promote scientific literacy and facilitate policy-relevant research (Mbah et al., 2022).

The project "Towards Robust Projections of Climate Extremes and Adaptation Plans over South Asia" addressed this need for high-resolution data on climate extremes in South Asia. The project brought together an interdisciplinary team of researchers from various institutions in South Asia and beyond and utilised state-of-the-art climate modelling techniques, data analysis and stakeholder engagement to achieve its objectives. The study's primary objectives include preparing high-resolution reference and future model data for climate extremes in South Asia, including minimum and maximum temperature and precipitation at 5 km resolution. The validation of Global Climate Models (GCMs) involved in CMIP6 was carried out over the study area, and then GCMs were downscaled to regional and local scales using advanced statistical downscaling techniques. The resulting high-resolution data sets provide a valuable resource for researchers, policymakers and other stakeholders to understand better the current and future trends of climate extremes in South Asia (Ali & Reboita, 2022).

In addition, capacity building and effective communication of climate change research findings and policy recommendations are crucial for creating awareness, influencing policy decisions and fostering public engagement. Science communication efforts that involve various stakeholders, including policymakers, researchers, communities, media and civil society organisations, play a vital role in translating complex scientific information into accessible formats for different audiences (Nisbet, 2018). Clear, accurate and timely communication of climate change research findings is essential for promoting evidence-based decision-making and fostering resilience (Kiani & Kiyani, 2023). The project also emphasised effective communication of climate change research findings and policy recommendations using diverse channels and formats, such as reports, publications, multimedia and social media. A small grant project of APN, which communicated the scientific outputs of the project in a simple way, is outlined in Kiani & Kiyani (2023).

Overall, the project "Towards Robust Projections of Climate Extremes and Adaptation Plans over South Asia," funded by the Asia-Pacific Network for Global Change Research (APN) (CRRP2018-04MY-Ali), has significantly contributed to enhancing our understanding of climate extremes in the region. It provided high-resolution reference and historical future model data, strengthened research capacities and promoted effective science communication. This paper highlights the actions and achievements during the project's execution and information on the project can be accessed at https://doi.org/10.30852/p.4583.

2. METHODOLOGY

2.1. Study area

The study area encompasses three South Asian countries: Bangladesh, Nepaland Pakistan. These countries are geographically diverse, ranging from the fertile river plains of Bangladesh to the high Himalayan mountains of Nepal and the vast arid regions of Pakistan. Climatology in this region is of great significance due to its impact on agriculture, water resources, natural disasters and the overall socioeconomic development of the population. Bangladesh experiences a tropical monsoon climate with high temperatures, heavy rainfall and high humidity (Ali et al., 2023). Bangladesh is vulnerable to climate change due to its low-lying coastal areas. Rising sea levels, increased frequency of cyclones and changes in precipitation patterns pose significant challenges. The country experiences droughts and floods, impacting agriculture, water availability and human settlements. Nepal is highly susceptible to climate change impacts, including glacial melt, altered precipitation patterns and increased frequency of extreme events (Maharjan et al., 2023; Pokharel et al., 2019). Changes in the Himalayan glaciers affect water resources, agriculture and hydropower generation. Pakistan faces various climate challenges, including water scarcity, heatwaves, droughts and floods. The country's agricultural productivity heavily depends on water availability from rivers fed by melting glaciers in the Himalayas.

Understanding climate variability and change in these three countries is crucial for effective adaptation and mitigation strategies. The study area is shown in Figure 1.

2.2. Method

The methodology is divided into three parts: (1) Climate Science, (2) Capacity Building and (3) Communication. Details for each of these parts are outlined below:

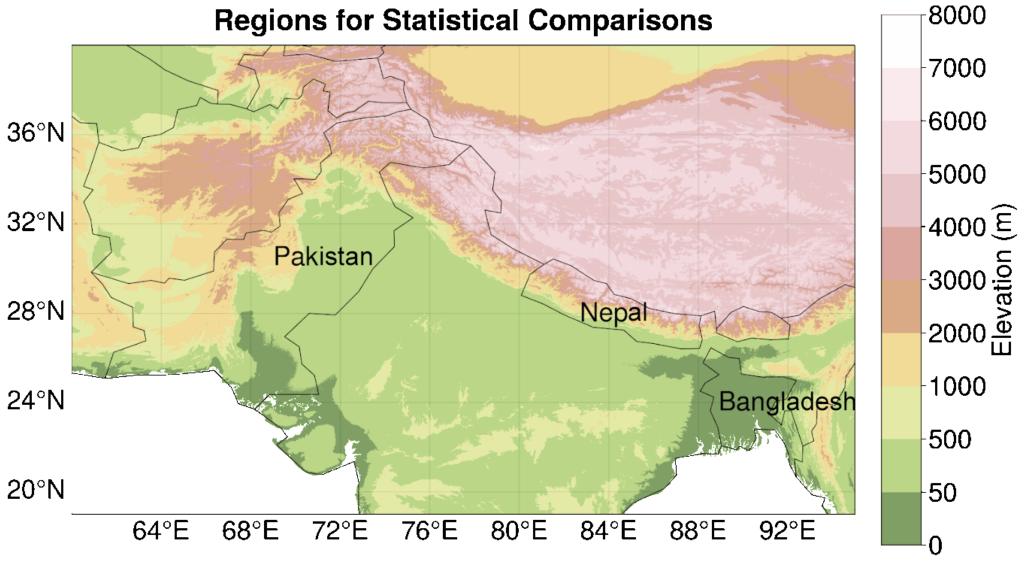

FIGURE 1. Study area including Bangladesh, Nepal and Pakistan.

2.2.1. *Climate science*

In the climate science aspect, the methodology involves three steps: firstly, the preparation of 5 km reference data; secondly, the validation of CMIP6 models over Pakistan, Bangladesh and Nepal; and thirdly, the downscaling of CMIP6 data at 5 km and future projection. Details are below:

- 5 km data results
  Objective and subjective techniques were used to perform quality control on the observed station data (Ali et al., 2023) from 1981 to 2016. The observed data are merged with ERA5 and a higher weight is given to station data during spatial interpolation to 5 km with the Kriging method. For temperature, an additional step was performed: the interpolated data were adjusted using the average Lapse Rate of Temperature (LRT) in mountainous regions using data from the Global 30 Arc-Second Elevation (GTOPO30) provided by the U.S. Geological Survey (USGS).
- Validation
  From CMIP6 (https://esgf-node.llnl.gov/search/cmip6/), we obtained temperature and precipitation data of 48 GCMs for the historical period. The data from GCMs were compared to a novel gridded dataset created in the first step using meteorological station observations for 1994–2014. Three ranking methods were employed for analysis to determine the best models: (1) individual representation of precipitation and air temperature for each country, (2) separate representation of precipitation and air temperature encompassing all three countries and (3) combined representation of both precipitation and air temperature across all three countries.
- Downscaling and Future projection
  We statistically downscaled/bias-corrected the CMIP6 selected models using spatial disaggregation quantile delta mapping (SDQDM) from 2020 to 2100. This method overcomes the stationarity problem in data and preserves the trend in future climate signals (Ali et al., 2019).

2.2.2. *Capacity building*

The project embarked on a comprehensive capacity-building endeavour encompassing various components, including training workshops, lectures, university courses and internships, emphasizing achieving gender balance by actively involving 60% female participants. We also delivered a six-month university course to enhance the capacity of female researchers from South Asia in the field of meteorology. Furthermore, a series of workshops was conducted in China, Pakistan and Nepal. University lectures and participation aim to introduce climate studies concepts to aspiring students. Moreover, the capacity-building initiative extended its reach to the general public through interviews, news coverage and newspaper articles that shed light on the research and its consequential impacts, garnering positive feedback from diverse quarters. A dedicated media training workshop focusing on extreme weather events engaged media organisations and professionals from the health sector, facilitating the widespread dissemination of critical information. The project also provided

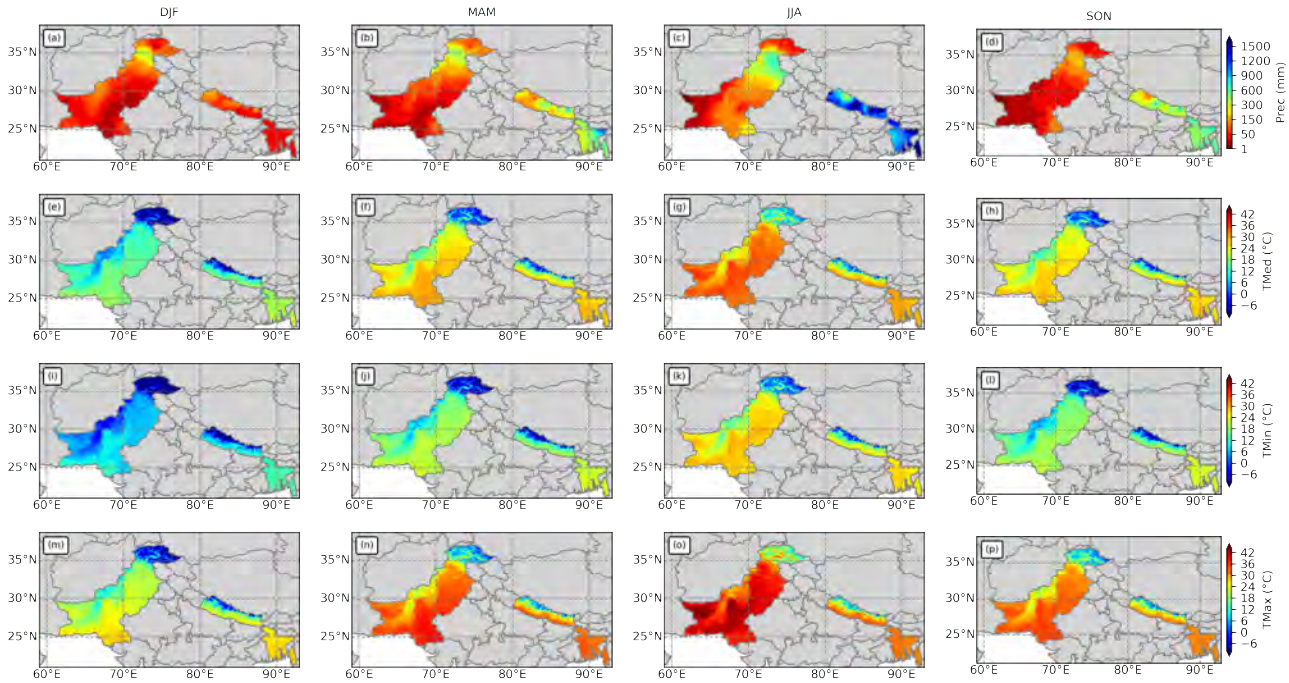

FIGURE 2. Seasonal climatology of precipitation, mean, minimum, maximum temperature.

guidance and supervision to four students as they prepared their university degree theses, enabling them to delve deeper into climate science, climate modelling and data analysis. This internship experience equipped them with essential management skills and paved the way for new opportunities in their future pursuits.

2.2.3. Science to policy communication

A diverse range of communication channels were utilised for communicating scientific discoveries proficiently to policymakers and the broader public. This comprehensive strategy involved electronic and print media, workshops and technical and policy reports. Information derived from our research was disseminated across diverse platforms, including electronic and print media, to bridge the gap between science and policy. Multiple interviews on national channels, conducted in local and national languages, facilitated the spread of climate change awareness, reaching grassroots communities. Additionally, headline news stories and written newspaper articles played a foundational role, educating youth and students and acquainting the general public with these complex concepts. Numerous lectures delivered at universities and participation in international and national workshops and media training programs served as effective avenues for widespread knowledge dissemination. Furthermore, reports and publications were provided to the Ministry of Climate Change and research articles and papers were made available online with open access, further reducing barriers to access.

3. RESULTS AND DISCUSSION

3.1. Climate science

3.1.1. 5-km data results

The study successfully generated high-resolution reference data of 5 km for Pakistan, Nepal and Bangladesh, which provided a reliable and accurate basis for analysing the climate in the region. Figure 2 shows the climatology of precipitation, minimum, mean and maximum temperature over Pakistan, Nepal and Bangladesh using 5 km datasets. Precipitation is highest during the monsoon season and lowest in December to February (DJF). Nepal and Bangladesh receive more rain than Pakistan due to humidity transported by stronger winds (near to sea) and topography effect. Precipitation also exerts an influence on temperature. Pakistan is the warmest country due to less precipitation, while Nepal and Bangladesh have moderate temperatures due to more precipitation. Due to latitude and altitude influences, Pakistan and Nepal's northern parts (NP) show lower temperatures. The annual cycle of mean temperature indicates that NP is the coldest region, while the middle southern is the hottest in Pakistan and Nepal. The increase in temperature due to climate change is observed in all

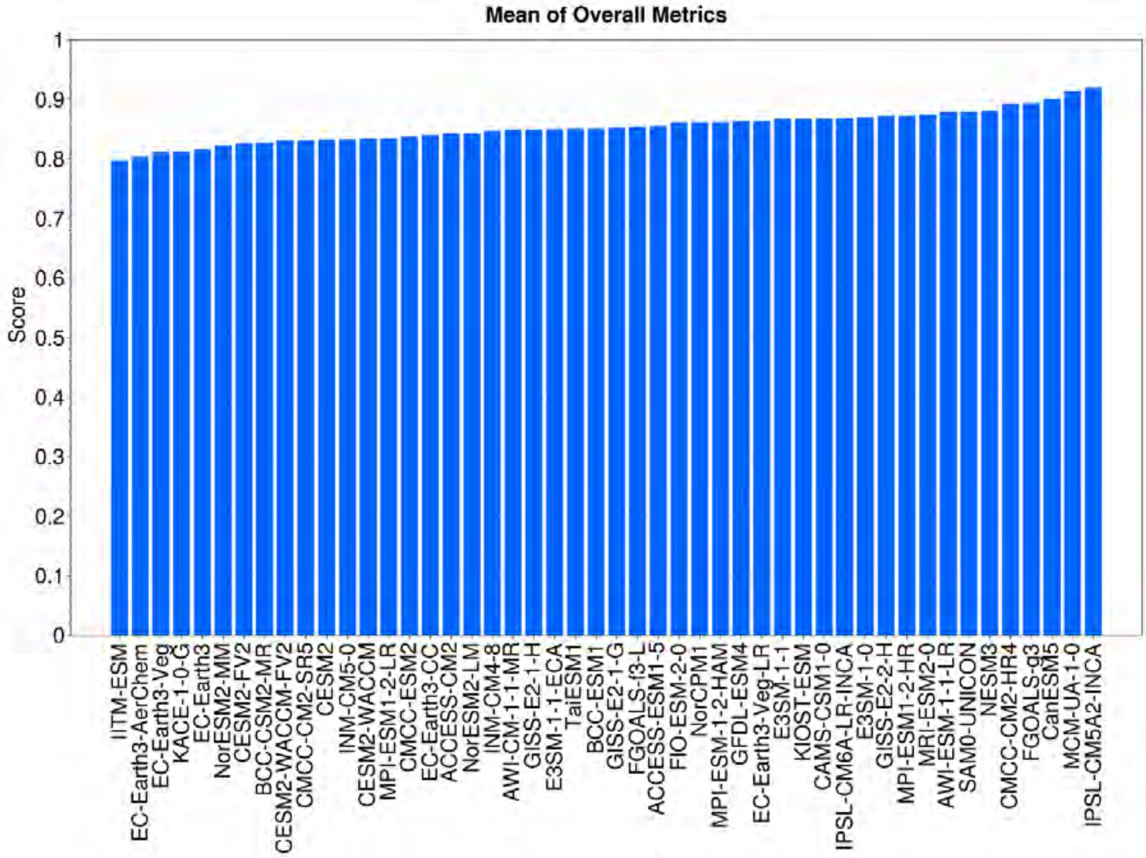

FIGURE 3. Overall raking evolution of CMIP6 GCMs considering precipitation and air temperature in the three countries.

three countries, with the highest increase in Nepal and the lowest in Bangladesh. The temperature rise varies in different regions of Pakistan. Annual precipitation decreases in some regions of all three countries and the seasonal monsoon precipitation from June–July–August increases in Pakistan but decreases in Bangladesh and western Nepal.

3.1.2. Validation

A range of metrics were applied to elucidate the strengths and weaknesses of CMIP6 models. The results show that NorESM2-MM, AWI-CM-1-1-MR, GISS-E2-1-G, GISS-E2-1-H, CMCC-CM2-SR5and KACE-1-0-G were some of the best CMIP6 models for precipitation and air temperature in the individual countries. The results also suggested that IITM-ESM, EC-Earth3-AerChemand EC-Earth3-Veg are the best models for the overall region and variables. These selected models can be used for climate change assessments, impact studies and regional policymaking. Figure 3 presents the validation results.

3.1.3. Downscaling and Future projection

The generated high-resolution reference data were then used to downscale the CMIP6 selected models. The projections were developed for different greenhouse gas emission scenarios, SSPs to capture a range of potential future climate conditions. One example of Nepal's future precipitation projection with SSP2-4.5 is shown in Figure 4 and SSP5-8.5 in Figure 5.

The climate science of the project has published eight research papers in peer-reviewed journals, covering various topics such as spatial monsoon shifts, climate extremes and the impact of climate change on health. These papers have significantly contributed to our understanding of future climate extremes in South Asia and added to the global scientific knowledge on climate change and its impacts. Two of these research papers were cited in the recent Sixth Assessment Report (AR6) by the IPCC, indicating the significance and relevance of the project's findings for global climate change assessments. Furthermore, the high-resolution reference data and future models produced by the project have been valuable sources of information for impact adaptation and vulnerability studies in the region. The monthly mean of reference data is available (Ali & Reboita, 2022).

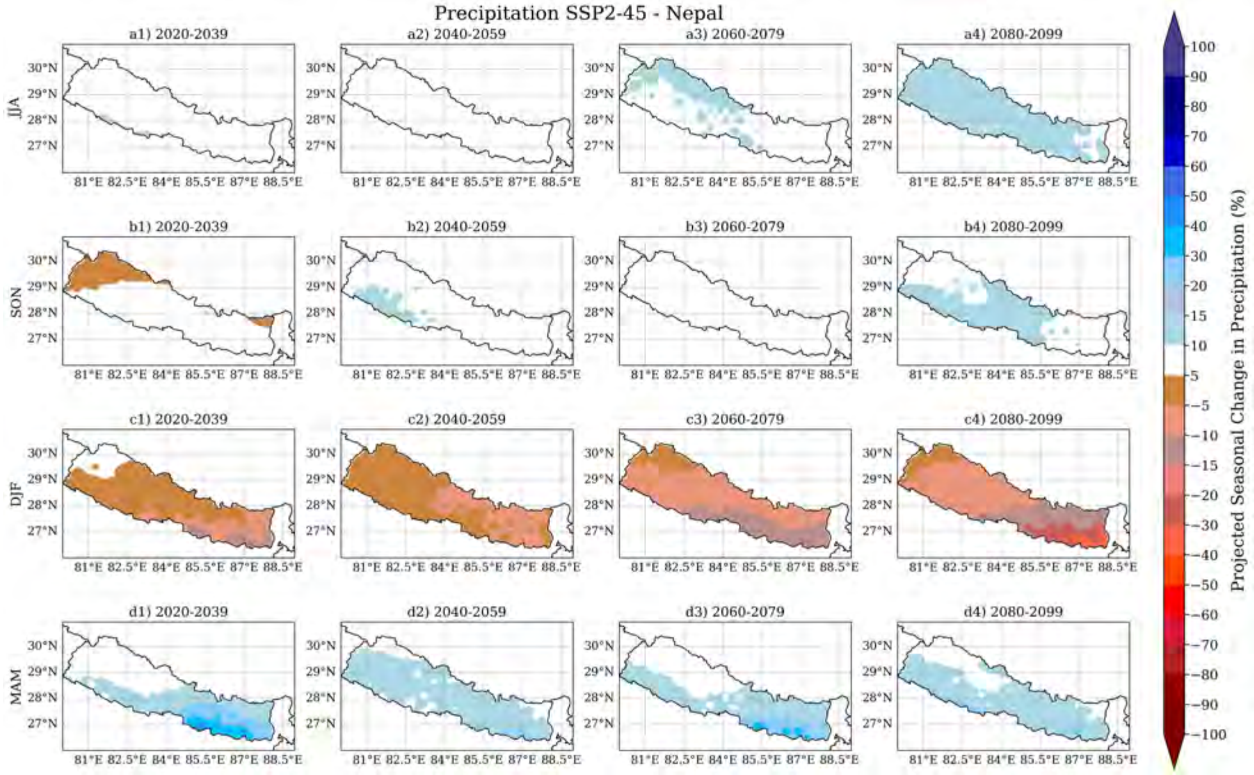

FIGURE 4. Future projection (2020–2099) of precipitation over Nepal for SSP2-4.5 (as an example).

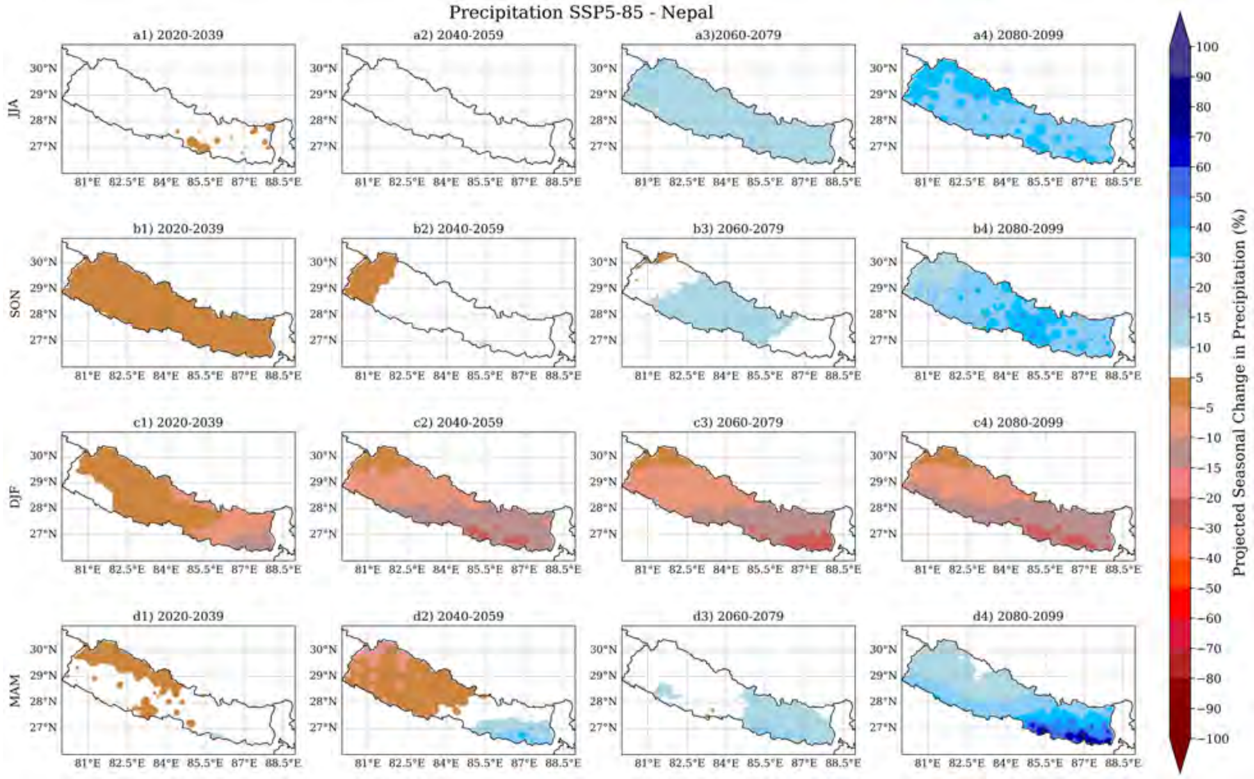

FIGURE 5. Future projection (2020–2099) of precipitation over Nepal for SSP5-8.5 (as an example).

3.2. Capacity building

The study also conducted capacity-building activities to enhance the research capabilities of local researchers and students. This included workshops, training sessions and complete university courses conducted in China, Pakistan and Nepal, which provided hands-on training in climate change modelling, data analysis techniques and downscaling methods. These capacity-building efforts aimed to strengthen the skills and knowledge of local researchers in climate change research and facilitate their active participation in the project. During these activities, 200 students were trained.

Ten lectures were delivered at conferences and workshops in Pakistan, as well as two international presentations at conferences in Malaysia and Austria, which helped disseminate knowledge and raise awareness among local and international stakeholders.

The online courses on atmospheric science and climate modelling titled "Introduction to Atmospheric Science: A Look into the Southern and Northern Hemispheres" and "Climate Modelling and Data Analysis" were launched in 2022 for female students in Pakistan in collaboration with the Universidade Federal de Itajubá (UNIFEI), Brazil. The course has been conducted again this year, with students from Nepal and Bangladesh participating to promote regional and international collaboration and cultural exchange. The course aims to build the capacity of female students and early-career female researchers in the three countries, promoting women's empowerment and gender balance. In the first semester of 2022, 30 Pakistani students were taught the basics of climate science and climate models, while in the first semester of 2023, 30 students from Nepal, Bangladesh and Pakistan combined were taught the technicalities of basic climate science. These efforts collectively contributed to bridging the divide between scientific research and policy communication. The research papers generated vital information that will significantly inform evidence-based policymaking in the field of climate science within the country.

3.3. Science to policy communication & research collaboration

Effective communication of the scientific outputs was emphasised, utilising various channels and formats, such as television, radio, newspapers, workshops and awareness events, to disseminate the research findings to policymakers, stakeholders and the public. Clear and accessible communication of complex scientific information was emphasised to raise awareness about climate extremes and their impacts in the study area and to inform evidence-based decision-making processes.

Five news articles were published. The articles explained the country's vulnerability in terms of future hotspot cities, possible changes in monsoon over the region of Pakistan, climate change and health and discussed the policy implications of the research. Five television interviews and two radio programmes were conducted in different local languages, including English, to promote research under the project.

The project collaborated with national and international organisations to enhance research and collaboration in South Asia (Bangladesh, Nepal and Pakistan). This involved partnerships with local research institutions, government agencies and international organisations to share data, expertise and resources. The collaboration aimed to foster multidisciplinary research, promote knowledge exchange and enhance the relevance and applicability of the project's findings for policy and decision-making processes.

4. CONCLUSION

The study of future climate extremes at small scales with robustness depends on high-resolution reference and model data. The statistical and dynamical downscaling communities aim to improve reference and model data to produce reliable data at the local level, reduce uncertainty and establish policymakers' confidence in future climate extremes. However, there are gaps in finer resolution, scaling issues between reference and model data and insufficient observation data in South Asia. High-resolution regional/local future climate extremes information is urgent for impact adaptation and vulnerability studies. To address this need, the project "Towards robust projections of climate extremes and adaptation plans over South Asia" was undertaken to produce 5 km reference data over Pakistan, Nepal and Bangladesh and fine-resolution climate model data for the future projection of extreme events. These higher-resolution data allowed for the projection of climate extremes in the region. Scientific research conducted under the project has led to the publication of eight research papers in well-reputed impact factor journals, with two cited in the recent AR6 report.

In addition to data preparation, the project has organised significant capacity building activities. Workshops were held in China, Pakistan and Nepal to train young researchers and students in climate change modelling, climate change and media and climate change and health. These workshops were attended by experts from around the world, with technical experts from Brazil and a collaborator from Bangladesh present physically. Gender equality was ensured in the workshops and over 200 students were trained. The workshops received much appreciation and were highlighted in local media channels.

This project employed a variety of media channels to communicate its outcomes to policymakers. Five news articles were published in English newspapers, two radio interviews were conducted and five television interviews were held. Furthermore, the project's findings were presented at ten national and two international conferences. Throughout the project, collaboration was established with several national and international organisations, highlighting APN's crucial role in advancing regional research and cooperation.

Overall, this project has significantly contributed to understanding future climate extremes in South Asia, provided high-resolution data for impact adaptation and vulnerability studies and organised capacity-building activities to train young researchers and students. Communicating the project's outcomes to policymakers through multiple media channels and collaboration with national and international organisations further highlights its importance in promoting regional research and collaboration.

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Original Article

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Assessment on the impact of mining and industrial activities in groundwater quality in Chandrapur, Maharashtra through remote sensing and GIS applications

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ABSTRACT

This study evaluated the quality of groundwater in Chandrapur Taluka, Maharashtra, using geospatial techniques and data from 2014 and 2018. The study assessed various water quality parameters such as chloride, fluoride, pH, residual sodium carbonate (RSC) and sodium adsorption ratio (SAR). The findings showed that chloride concentrations were mostly within acceptable limits, but there was a slight increase in areas near mining and industrial sites, which was statistically significant ($p < 0.05$). Fluoride levels were generally within permissible bounds, but there was a noticeable increase near industrial areas in 2018 compared to 2014, which was statistically significant ($p < 0.05$) and raised environmental concerns. Variations in pH values were also observed, which could impact aquatic ecosystems, with a decrease noted from 2014 to 2018. RSC levels were higher near mining and industrial zones in 2018, exceeding recommended limits, indicating a potential threat to water quality. SAR levels in 2018 were higher, potentially impacting agriculture, but still within acceptable limits. Sulphate levels showed a reduction from 2014 to 2018. These comprehensive findings highlight the specific impacts of mining and industrial activities on groundwater quality and raise broader scientific questions. They can be used to develop evidence-based policies for effective mitigation measures and engage a wider readership.

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KEYWORDS GIS, REMOTE SENSING, WATER QUALITY, LAND USE AND LAND COVER (LULC), SODIUM ADSORPTION RATIO (SAR), RESIDUAL SODIUM CARBONATE (RSC)

HIGHLIGHTS

- Chandrapur's groundwater exhibited stable chloride levels near mining and industrial areas between 2014 and 2018, consistently within Bureau of Indian Standards (BIS) safe limits.
- Fluoride contamination witnessed an increase near industrial sites during the same period, although it remained within permissible limits.
- pH values displayed fluctuations but stayed within acceptable ranges. There was a slight decline from 2014 to 2018, suggesting potential changes in water quality.
- RSC levels near industrial areas rose in 2018, signalling a risk of soil degradation and a potential reduction in agricultural water availability.
- SAR values experienced an increase in 2018 near industrial areas, posing a potential threat to soil fertility and crop growth. However, they remained below BIS standards for irrigation water quality.

1. INTRODUCTION

Groundwater, an essential component of the Earth's hydrological cycle, plays a pivotal role in sustaining biodiversity, maintaining ecosystems and supporting human life (Abijith et al., 2020). Over the last few decades, groundwater quality has become a growing concern due to the immense anthropogenic pressures of industrial development, agricultural activities and mining operations (Bagchi et al., 2002). The burgeoning groundwater contamination problem threatens human health and livelihood and undermines the ecological equilibrium (Becker, 2006).

In India, groundwater is a major source of water for daily requirements of most of the population (Boutroy et al., 2014; Duggal et al., 2017). However, several factors, such as industrial growth, increased agricultural output, poor management and uncontrolled groundwater exploitation, have led to a shortage of potable water (Chilton, 1996). The groundwater potential of an area depends on various factors and fluctuates as conditions change (Costa, 2003). To counteract groundwater deficits, satellite data can be used to define groundwater prospect zones and expand artificial recharge initiatives (Eastmond et al., 2008; Hamilton, 2005).

Remote Sensing and Geographic Information System (GIS) techniques have proven useful in managing aquifer reserves. The reliability of these methods depends on the classification standard and average ranks enforced upon the input parameters (Harris et al., 2022). Ancillary data, such as Toposheets and Landsat images, have enabled the creation of thematic maps using a weighted overlay approach to define potential groundwater zones (Kaur et al., 2021).

Chandrapur, located in Maharashtra, India, is known for its abundant mineral resources and strong industrial sector. The district is rich in coal reserves, making it a major Centre for mining activities. Additionally, various industries, such as thermal power plants, cement factories and chemical processing units, have been established in the region. While these activities have contributed to economic growth and employment opportunities, they also raise concerns about their environmental impact, particularly water quality (Kumar et al., 2020).

Mining activities, by their very nature, involve the extraction of minerals from the Earth, often resulting in the disturbance of natural ecosystems and the release of pollutants into the surrounding environment (Li et al., 2020). Similarly, industrial activities such as manufacturing, processing and waste disposal can introduce chemicals and contaminants into nearby water bodies, leading to water pollution and degradation (Galkate et al., 2022; Gibert et al., 2022). As a result, the water quality in Chandrapur district has become a pressing issue that requires thorough investigation, monitoring and mitigation (Liang et al., 2021).

Understanding the impact of mining and industrial activities on water quality is crucial for sustainable development and the preservation of ecosystem health (Meraj et al., 2021). It helps identify the sources and types of contaminants and facilitates the formulation of effective management strategies to mitigate adverse effects and safeguard water resources (Mishra & Bharagava, 2016).

Despite the economic benefits of mining and industrial activities, the potential negative consequences on water quality cannot be ignored. The discharge of pollutants into water bodies can have far-reaching ecological, economic and public health implications (Mpouras et al., 2021). With its extensive mining and industrial operations, Chandrapur faces the challenge of assessing the extent and severity of water contamination caused by these activities (Okogbue & Ukpai, 2013; Singh & Bhakar, 2021; Upadhyay et al., 2019).

Advanced monitoring and assessment techniques are essential to effectively address this problem. Geospatial techniques, including GIS and remote sensing, provide valuable tools for studying the spatial patterns, changes and associations between mining, industrial activities and water quality parameters (Pradhan, 2009). By integrating these techniques, a holistic understanding of the impact on water quality can be achieved, aiding in developing targeted pollution control and management (Prasad et al., 2008; Raju et al., 2019; Rather et al., 2022).

In the Chandrapur study area, elevated chloride and fluoride concentrations in groundwater warrant geochemical investigation. These elements can be critical indicators of potential contamination sources associated with industrial and mining activities (Rodell & Famiglietti, 2002). Elevated chloride levels may be linked to processes like leaching of salts from industrial effluents or the presence of saline aquifers, while increased fluoride concentrations could be attributed to the release of fluoride-bearing minerals during mining operations or industrial discharges. By examining the geochemical signatures of chloride and fluoride in the groundwater, we aim to identify potential contamination sources and provide a deeper understanding of the specific mechanisms driving groundwater quality degradation in this region, further strengthening the foundation of our study and contributing to effective mitigation strategies.

Our study distinguishes itself from existing literature by comprehensively analysing groundwater quality in Chandrapur, India, where mining and industrial activities coexist. While prior research has typically focused on either mining or industrial impacts on water quality separately, our integrated approach allows us to uncover potential synergistic effects, providing a more holistic understanding of the complex dynamics of groundwater contamination in this region. Additionally, applying advanced geospatial techniques, specifically GIS and remote sensing, enhances our analysis' precision and spatial resolution, enabling a more detailed examination of contaminant distribution. This methodological innovation sets our study apart and contributes to a practical framework for addressing water quality challenges in areas characterised by both mining and industrial activities.

In conclusion, our findings have several implications for sustainable water resource management in regions facing challenges similar to those in Chandrapur. We recommend developing targeted pollution control measures that consider the combined impact of mining and industrial activities on groundwater quality. Additionally, our study underscores the importance of continued monitoring and assessment using geospatial techniques to track changes and implement adaptive management strategies. Finally, the knowledge generated from this research can serve as a valuable resource for policymakers, industry stakeholders and environmentalists, facilitating informed decision-making and contributing to preserving water resources in such critical areas. Future work should focus on expanding the scope of our study to other regions and further refining the integration of geospatial techniques for improved water quality management.

This research utilises GIS and remote sensing techniques to assess the impact of mining and industrial activities on groundwater quality in Chandrapur. GIS integrates, manipulates and analyses geospatial data, while remote sensing captures data across large areas without physical contact, making it an effective method for monitoring environmental changes.

2. METHODOLOGY

2.1. Study area

Chandrapur, a city located in Maharashtra in India, is the study area for this research. Geographically positioned between 19.57°N latitude and 79.18°E longitude, Chandrapur boasts a diverse topography marked by plains, hills and rivers (Figure 1). The city is nestled in the Deccan Plateau region, known for its rich mineral resources, particularly coal, and exhibits a tropical monsoon climate, making it suitable for intensive agricultural activities. With an estimated population of over 3.75 million, the district of Chandrapur spreads over approximately 11,443 km^2. Agriculture remains a dominant economic activity, sustaining a significant proportion of the rural populace. However, the region has seen a growing focus on industrialisation and mining in recent decades, mainly due to vast coal deposits. The city houses many industrial units, including Chandrapur Super Thermal Power Station, one of India's largest coal-based power plants, and various coal mines operated by Western Coalfields Limited. These mining and industrial activities have been central to the region's economic growth but have also raised serious concerns about environmental sustainability and health hazards. Chandrapur's groundwater is a crucial water supply source for domestic and agricultural purposes. The presence of numerous rivers, such as the Wainganga, Wardha and Irai, plays a significant role in replenishing the groundwater levels. However, the extensive extraction of minerals and relentless discharge of industrial effluents have reportedly led to a steady deterioration of groundwater quality over time. The examination of groundwater quality in Chandrapur, with its intricate blend of agriculture, mining and industrialisation, offers a unique setting to understand the impact of anthropogenic activities on water resources. Consequently, it serves as a valuable study area for this research, with its findings likely to provide crucial insights to manage and mitigate the negative effects of industrial activities on groundwater quality.

2.2. Data used

This study used a multifaceted data set to assess the impact of mining and industrial activities on groundwater quality in Chandrapur, Maharashtra, utilising both spatial and non-spatial data sources. Satellite data from the Linear Imaging Self Scanning Sensor (LISS-3) on the Indian Remote sensing satellite was employed to create land use and land cover (LULC) change maps, with data from 2014 and 2018 allowing us to observe changes over these four years. The district administrative boundary of Chandrapur helped define the study area, ensuring a precise geographical focus for our analysis. Groundwater quality data were sourced from India's Water Resources Information System (WRIS) and the Central Pollution Control Board (CPCB), yielding extensive hydrological information about the region and insights into groundwater contamination levels. By examining parameters such as pH, electrical conductivity, total dissolved solids and ion concentrations, this study effectively mapped groundwater quality in Chandrapur and assessed the potential impacts of land use changes on this critical water resource. Details of the data set are given in Table 1 and Table 2.

Building on the collected data, we meticulously prepared the LULC change maps for 2014 and 2018. This enabled a comprehensive understanding of the transformations in the regional landscape over the four years. In addition to the LULC maps, specific maps highlighting the mining areas and industrial zones for both years were created to represent the extent and alterations in these zones visually. Following this, we focused on understanding the potential impacts of these changes on groundwater quality. We compiled the groundwater quality data from the WRIS and CPCB and developed comprehensive groundwater quality maps for 2014 and 2018. These maps were constructed using the Inverse Distance Weighting (IDW) interpolation method. IDW is a deterministic method for multivariate interpolation with a known scattered set of points. This method was chosen because it assumes that the variable being mapped decreases in influence with distance from its sampled location, providing a precise and visually intuitive means to represent spatially distributed data. By overlaying the LULC, mining and industrial zone maps with the groundwater quality maps for respective years, we could visually analyse the spatial correlation between land use changes, especially the expansion of mining and industrial areas, and the shifts in groundwater quality. Through this approach, the study aims to establish a clearer understanding of how mining and industrial activities may have influenced the groundwater quality in Chandrapur over the analysed period.

TABLE 1. GIS and Satellite data source.

Sr. No.	Map data	Data source
1	India political boundary shape file	Indian Space Research Organisation (ISRO)
2	India state boundary shape file	ISRO
3	India district boundary shape file	ISRO
4	India tehsil boundary shape file	ISRO
5	Satellite image - 2014	LISS-III
6	Satellite image - 2018	LISS-III
7	Satellite Image-2018 (For LULC Map)	Sentinel-II

TABLE 2. Statistical data and Ground Water Reports Data source.

Sr. No.	Statistical data	Data source
1	Ground water quality	INDIA -WRIS
2	Type of ground water contamination	INDIA - WRIS
3	Water quality data	CPCB

2.3. Pre-processing of satellite data

The pre-processing of LISS-3 satellite data from 2014 and 2018 was performed using ERDAS Imagine 2014 software to ensure its accuracy and validity. This multifaceted process began with radiometric correction, which adjusted for sensor irregularities and atmospheric distortions, facilitating accurate surface radiation representation. This was followed by a geometric correction, ensuring the data's accurate alignment with the Earth's surface and true geographical positioning. Atmospheric correction was next, accounting for and mitigating atmospheric effects such as scattering and absorption. To further enhance data accuracy, the corrected images were rectified and registered to a common geographical coordinate system, supporting accurate comparison and integration of images from different dates. Finally, image enhancement techniques like contrast stretching and edge enhancement were applied to improve the visual interpretability of satellite images. This comprehensive pre-processing stage, supported by ERDAS Imagine 2014, ensured the data's reliability and comparability, setting a solid base for the subsequent stages of analysis.

2.4. LULC map

This study utilised processed LISS-3 satellite data to create LULC maps for Chandrapur district in 2014 and 2018. These maps highlighted the changes that occurred in the district's mining area over a span of four years. The Maximum Likelihood method, an advanced statistical technique, was used in ERDAS Imagine to classify the satellite data. This method assigns each pixel in the image to the highest probability class, providing a more accurate and efficient classification. The data was divided into seven categories: agriculture land, barren or open land, built-up area, forest, other land use, water bodies and mining and industrial Area. The creation of these LULC maps allowed for an accurate visual representation of land use changes, particularly in the mining and industrial areas, providing a robust base for analysing the impacts of these changes on groundwater quality.

2.5. Ground water quality map

This study delved into an in-depth analysis of groundwater quality in Chandrapur Taluka by identifying the sources and types of pollutants in the region's water bodies. Field observations were complemented with laboratory data from the India-WRIS web portal to provide a robust data set. Statistical techniques were employed to analyse various physicochemical and microbiological parameters, offering a comprehensive view of water quality. Remote sensing techniques allowed for assessing spatial and temporal variations in water quality, with data from 2014 and 2018 serving as key comparative points. An interpolation model was developed to demonstrate the spread of contaminated areas in groundwater quality, visually representing areas of concern. Finally, the

TABLE 3. Ground water contamination in Chandrapur as per CGWB report.

Sr. No.	Ground water contamination in Chandrapur	Level of contamination
1	Salinity (EC above 3000 micro mhos/ cm) (EC: Electrical Conductivity)	4580 μS/cm
2	Fluoride (above 1.5 mg/l)	9.183 mg/l
3	Nitrate (above 45 mg/l)	57 mg/l
4	Arsenic (above 0.01 mg/l)	0.05 mg/L
5	Iron (above 1 mg/l)	3.258 mg/L
6	Heavy metals: Lead (above 0.01 mg/l), Cadmium (above 0.003 mg/l), Chromium (above 0.05 mg/l)	0.08 mg/L

study offered measures to mitigate the impact of contaminant activities on water quality, aiming to provide a roadmap for future conservation efforts in the region. Table 3 shows the ground water contamination in Chandrapur as per the CGWB report.

3. RESULTS AND DISCUSSION

3.1. Water quality assessment

In our water quality evaluation, we employed an interpolation technique to visualise the dispersal of individual contaminants within groundwater, providing a holistic view of regional water quality. We implemented the IDW method to predict the values of each processing cell on the output image based on the surrounding sampled data points. We created two maps for each contaminant to facilitate comparison between the data from 2014 and 2018. The maps were generated using the data provided in the tables appended after the maps. Additionally, to portray the fluctuation in contaminant levels, we prepared bar diagrams from the data.

3.2. Chloride distribution

In our assessment of groundwater samples near mining and industrial operations in Chandrapur, the chloride concentration results appeared within the acceptable range, as showcased by the chloride content chart of various sites within Chandrapur. According to the Bureau of Indian Standards (BIS), chloride levels up to 250 mg/L are deemed safe for consumption. The results show that the chloride content within Chandrapur's water doesn't pose a significant risk. However, a slight increase in chloride levels can be noted in areas close to mining and industrial activities. The distribution of chloride levels for the years 2014 and 2018 are illustrated in Figure 2 and Figure 3, respectively. Table 4 encapsulates the statistical data representing the chloride distribution for the same years, providing a comparative view of the changes that occurred over this period.

TABLE 4. Chloride value.

Sr. No.	Location	2014	2018
1	Agarjhari	46	21.09
2	Ballarsha	ND	ND
3	Chandrapur	64	ND
4	Chichpalli	149	88.09
5	Ghugus	ND	55.83
6	Kothari	163	ND
7	Nandegur	35	23.57
8	Padmapur	ND	26.06
9	Tadali	32	85.61

3.3. Fluoride distribution

The above ground water contamination map analysis and the data say groundwater samples near Chandrapur mining and industrial areas have elevated fluoride levels. Fluoride contamination is a common issue in areas with industrial activities. Excessive fluoride intake through contaminated water can lead to dental and skeletal fluorosis, posing significant health risks to the local population. As per BIS for water, up to 1.5 ppm of fluoride is suitable for drinking. The above results show fluoride content under the permissible limits, but a rise can be seen in areas near mining and industrial activities in the year 2018 compared to year 2014, which is alarming. Table 5 shows Fluoride distribution in study area.

TABLE 5. Fluoride value.

Sr. No.	Location	2014	2018
1	Agarjhari	0.36	0.61
2	Ballarsha	ND	ND
3	Chandrapur	0.1	ND
4	Chichpalli	0.35	4
5	Ghugus	ND	1.58
6	Kothari	0.27	ND
7	Nandegur	0.12	1.59
8	Padmapur	ND	0.38
9	Tadali	0.12	1.02

TABLE 6. pH Value.

Sr. No.	Location	2014	2018
1	Agarjhari	7.7	7.4
2	Ballarsha	ND	ND
3	Chandrapur	8	ND
4	Chichpalli	8	7.6
5	Ghugus	ND	7.8
6	Kothari	8.2	ND
7	Nandegur	7.7	7.7
8	Padmapur	ND	7.2
9	Tadali	8	7.4

TABLE 7. RSC value.

Sr. No.	Location	2014	2018
1	Agarjhari	−2.2	2.19
2	Ballarsha	ND	ND
3	Chandrapur	−5.1	ND
4	Chichpalli	−6.5	7.24
5	Ghugus	ND	2.61
6	Kothari	−7.6	ND
7	Nandegur	−2.2	0.63
8	Padmapur	ND	−1.78
9	Tadali	−2.1	−0.30

TABLE 8. SAR Value.

Sr. No.	Location	2014	2018
1	Agarjhari	0.06	0.26
2	Ballarsha	ND	ND
3	Chandrapur	0.12	ND
4	Chichpalli	0.16	2.55
5	Ghugus	ND	0.81
6	Kothari	0.11	ND
7	Nandegur	0.06	0.23
8	Padmapur	ND	0.19
9	Tadali	0.1	0.52

3.4. pH distribution

The analysis of groundwater pH near mining and industrial areas indicated variations. Mining activities often contribute to acidic mine drainage, while industrial processes can introduce alkaline substances into the water. Such pH variations can adversely affect aquatic ecosystems and the overall water quality. The good quality of water is 6.5pH; less or higher value indicates non-drinkable or poor quality as per BIS [33, 34]. After evaluating the maps and data above, the pH value is under the permitted limits, but some decrease in value can be seen from year 2014 to year 2018 (Table 6).

3.5. RSC distribution

RSC indicates the potential for sodium hazard in water. Groundwater samples near mining and industrial activities in Chandrapur exhibited higher RSC values in 2018 compared to 2014. Elevated RSC levels indicate a higher concentration of sodium carbonate and bicarbonate, which can lead to soil degradation and reduced water availability for agricultural purposes. The presence of RSC highlights the impact of mining and industrial activities on water quality and the subsequent consequences on local agriculture. BIS suggests that an RSC level of 1.25 and lower is safe for irrigation (Table 7).

3.6. SAR distribution

SAR is another important parameter used to assess water quality for irrigation purposes [35]. Groundwater samples near mining and industrial areas in Chandrapur demonstrated higher SAR values in 2018 compared to 2014. Elevated SAR values indicate a higher concentration of sodium ions than other essential cautions, such as calcium and magnesium. High SAR levels can lead to soil degradation, reduced fertility and impaired crop

TABLE 9. Sulphate Value.

Sr. No.	Location	2014	2018
1	Agarjhari	65	20
2	Ballarsha	ND	ND
3	Chandrapur	158	ND
4	Chichpalli	80	18
5	Ghugus	ND	63
6	Kothari	124	ND
7	Nandegur	42	16
8	Padmapur	ND	22
9	Tadali	36	27

growth, further affecting agricultural productivity in the region. As per the standards of BIS, the SAR value below three is considered good for irrigation purposes, and despite a rise in Chandrapur, it still seems to be under control (Table 8).

3.7. Sulphate distribution

Sulphate contamination can occur due to various industrial activities, including mining, smelting and chemical manufacturing. Excessive sulphate levels in water can lead to aesthetic issues such as a bitter taste and potential health effects in high concentrations. By analysing the data above, the sulphate value in the study area of Chandrapur in 2018 is reduced compared to data from 2014. The BIS limit for water's Sulphate content ranges from 200 mg/L to 400 mg/L (Table 9).

4. DISCUSSION

Various statistical values provide a deeper insight into the trends observed over the years in assessing groundwater quality in Chandrapur. The data reveals that chloride levels, while primarily within the permissible range set by the BIS of up to 250 mg/L, exhibited a slight increase in areas proximate to industrial activities from 2014 to 2018. This increase in chloride content may seem subtle, but it underscores the potential impact of industrial processes on local water quality and emphasises the importance of ongoing monitoring to prevent future breaches of the acceptable limits (Vereecken et al., 2022; Wang et al., 2022; Zhang et al., 2021).

Similarly, fluoride contamination levels increased from 2014 to 2018 in areas near mining and industrial sites, although they remained below the BIS permissible limit of 1.5 ppm. This finding is of significant concern as excessive fluoride intake can lead to health risks. Although within acceptable limits, the fluctuations in pH values also suggest potential changes in water quality (Vincent, 2004; Wolf et al., 2007). Furthermore, higher RSC and SAR values near industrial areas in 2018 compared to 2014 indicate the need for vigilance in preventing soil degradation and maintaining agricultural productivity (Meraj, 2021; Shyam et al., 2022). On a positive note, the declining trend in sulphate levels in the region suggests potential improvements in water quality (Zink et al., 2010). These statistical insights collectively emphasise the need for sustained monitoring, remediation efforts and policy interventions to preserve Chandrapur's water quality, public health and the environment.

5. CONCLUSION

The comprehensive assessment of groundwater quality in Chandrapur using the IDW method revealed notable trends and fluctuations in various contaminant levels over the years 2014 to 2018. While chloride concentrations remained within acceptable limits set by the BIS, a subtle increase near industrial activities underscores the potential impact of such operations on local water quality. Elevated fluoride levels in proximity to mining and industrial sites, albeit below the permissible limit, raise concerns due to associated health risks. Variations in pH values and higher RSC and SAR levels near industrial areas semphasise the importance of ongoing monitoring to prevent soil degradation and maintain agricultural productivity. On a positive note, the decreasing trend in sulphate levels suggests potential improvements in water quality. These findings collectively underscore the need for sustained monitoring, remediation efforts and policy interventions to safeguard Chandrapur's water quality, public health and the environment, considering the potential long-term consequences of industrial and mining activities on the region's water resources.

6. ACKNOWLEDGEMENT

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APPENDIX

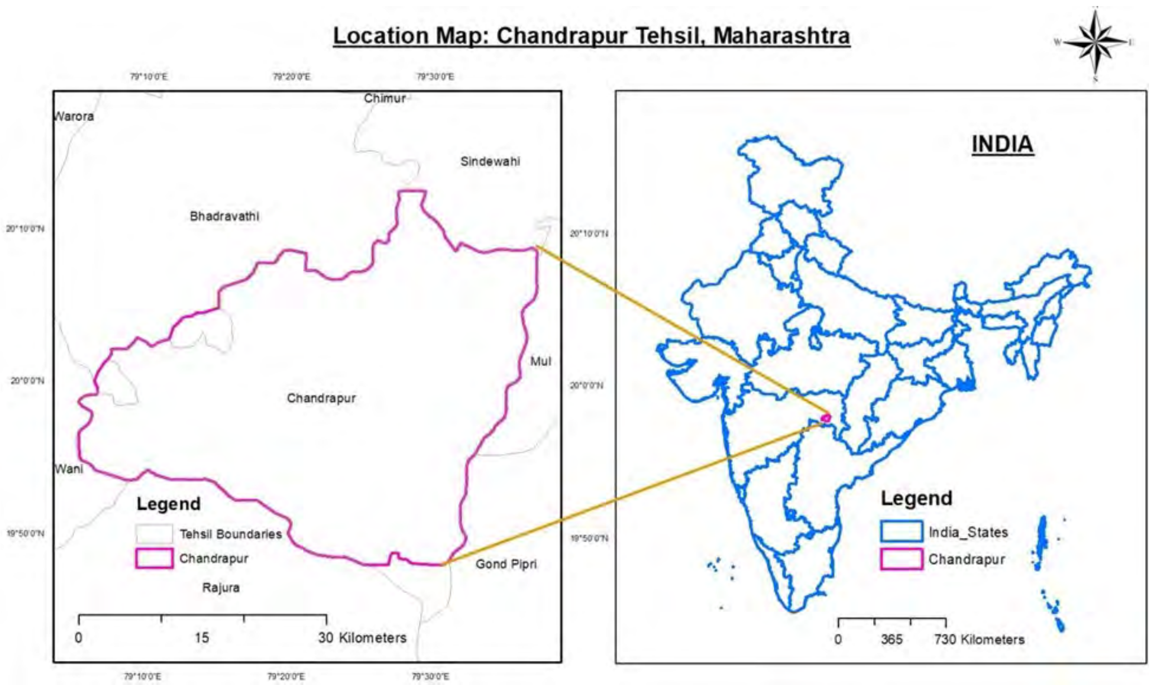

FIGURE 1. Location of the study area.

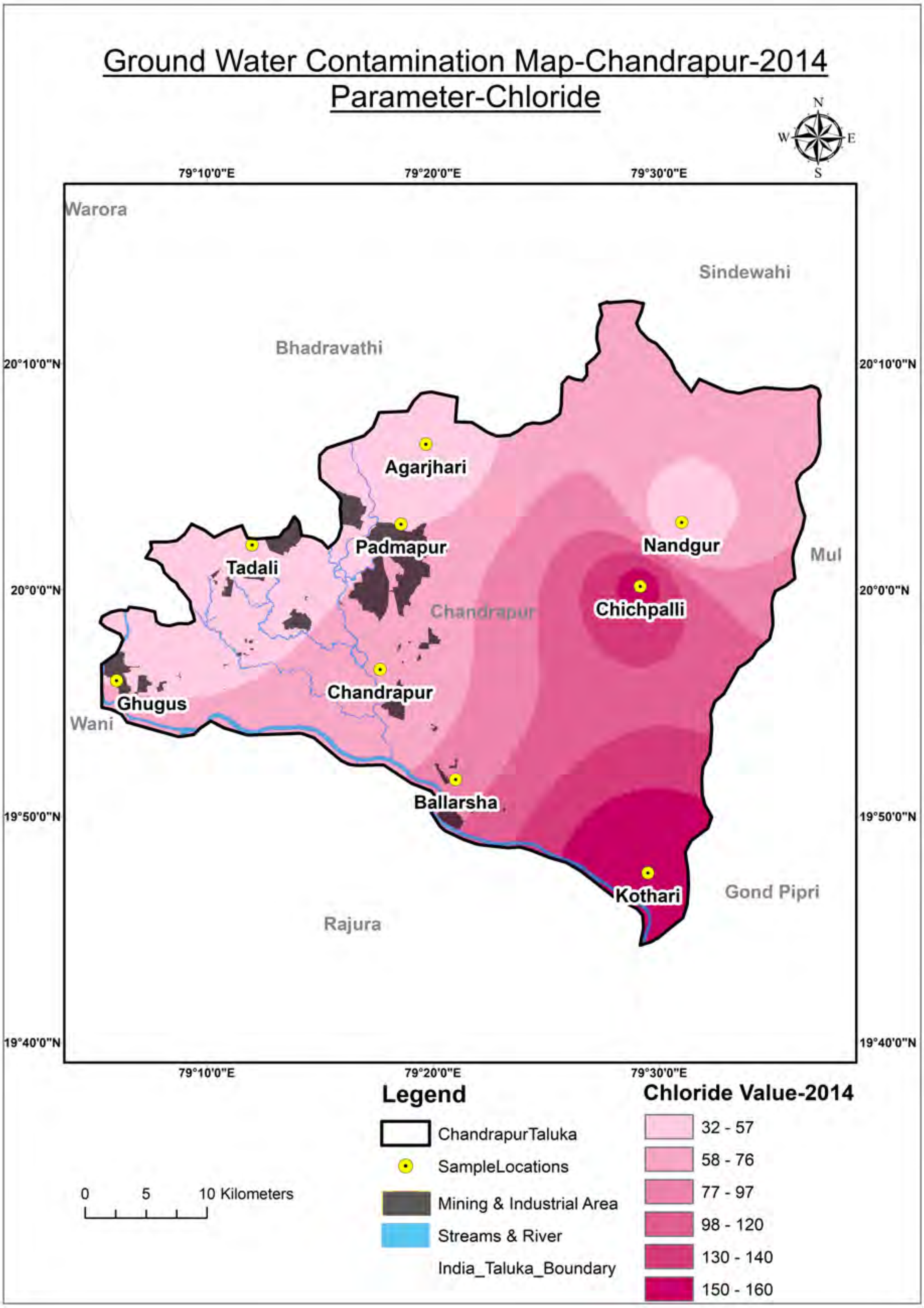

FIGURE 2. Ground water contamination map showing chloride distribution in Chandrapur, 2014.

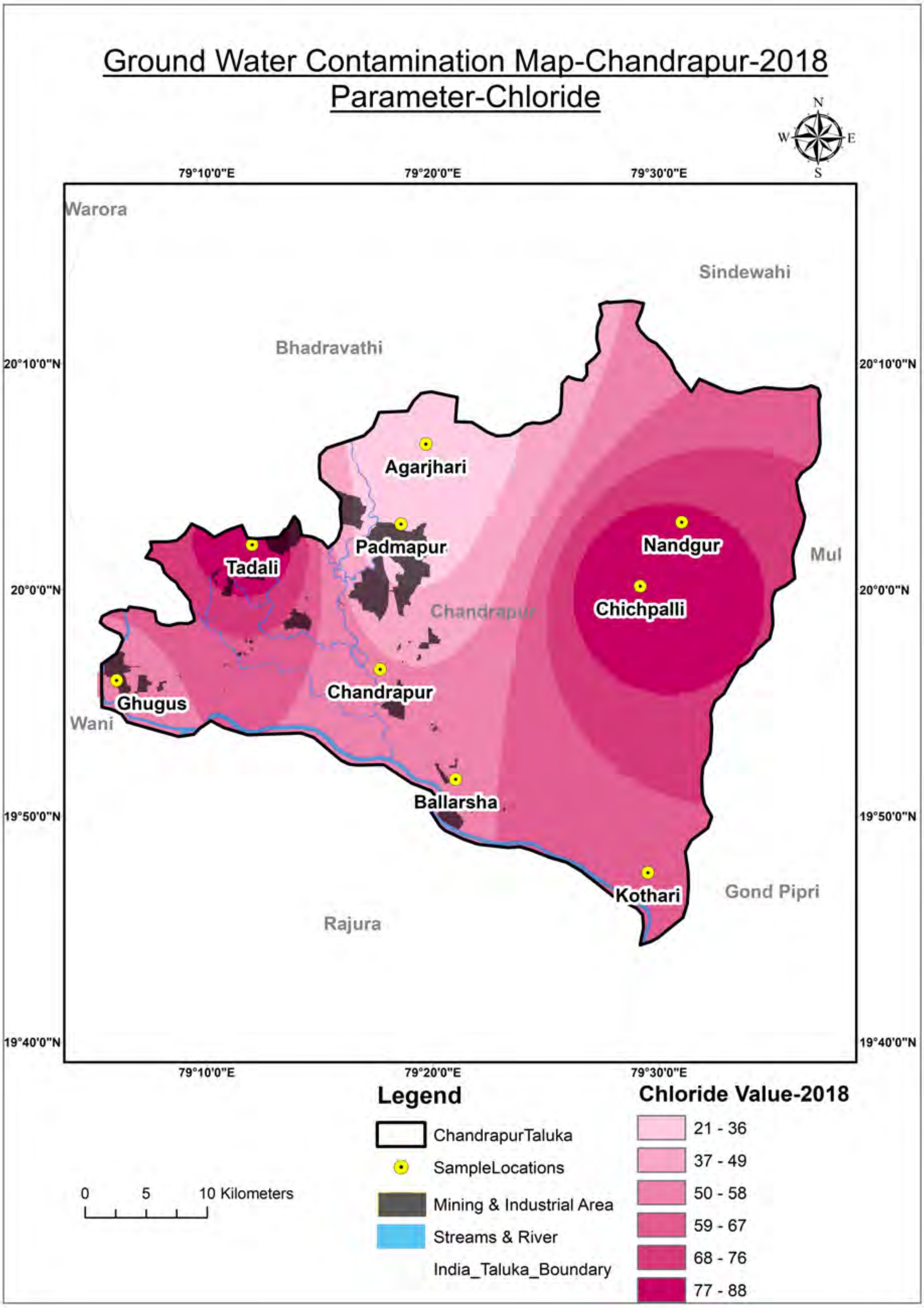

FIGURE 3. Chloride distributions 2018.

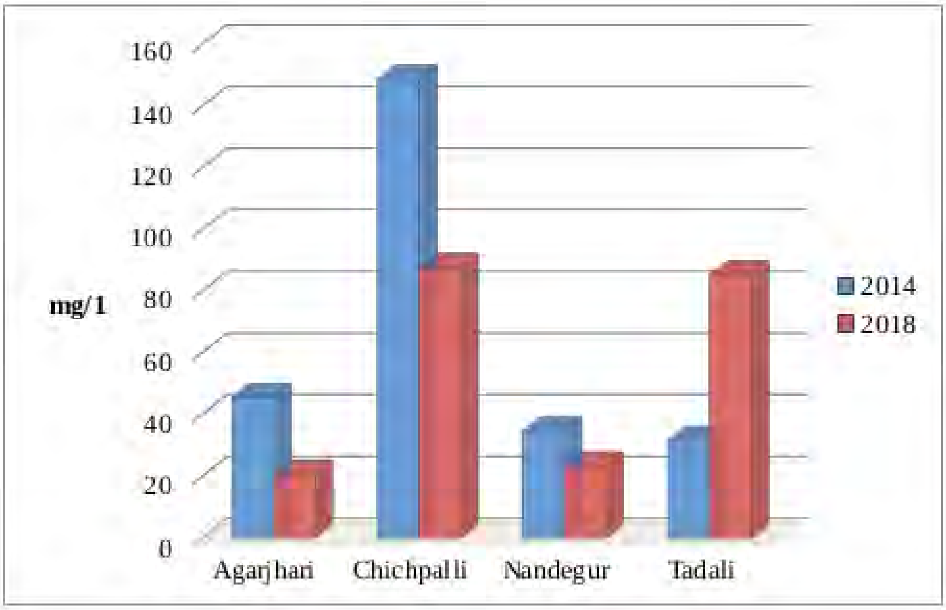

FIGURE 4. Chloride concentration in the study sites between 2014 and 2018.

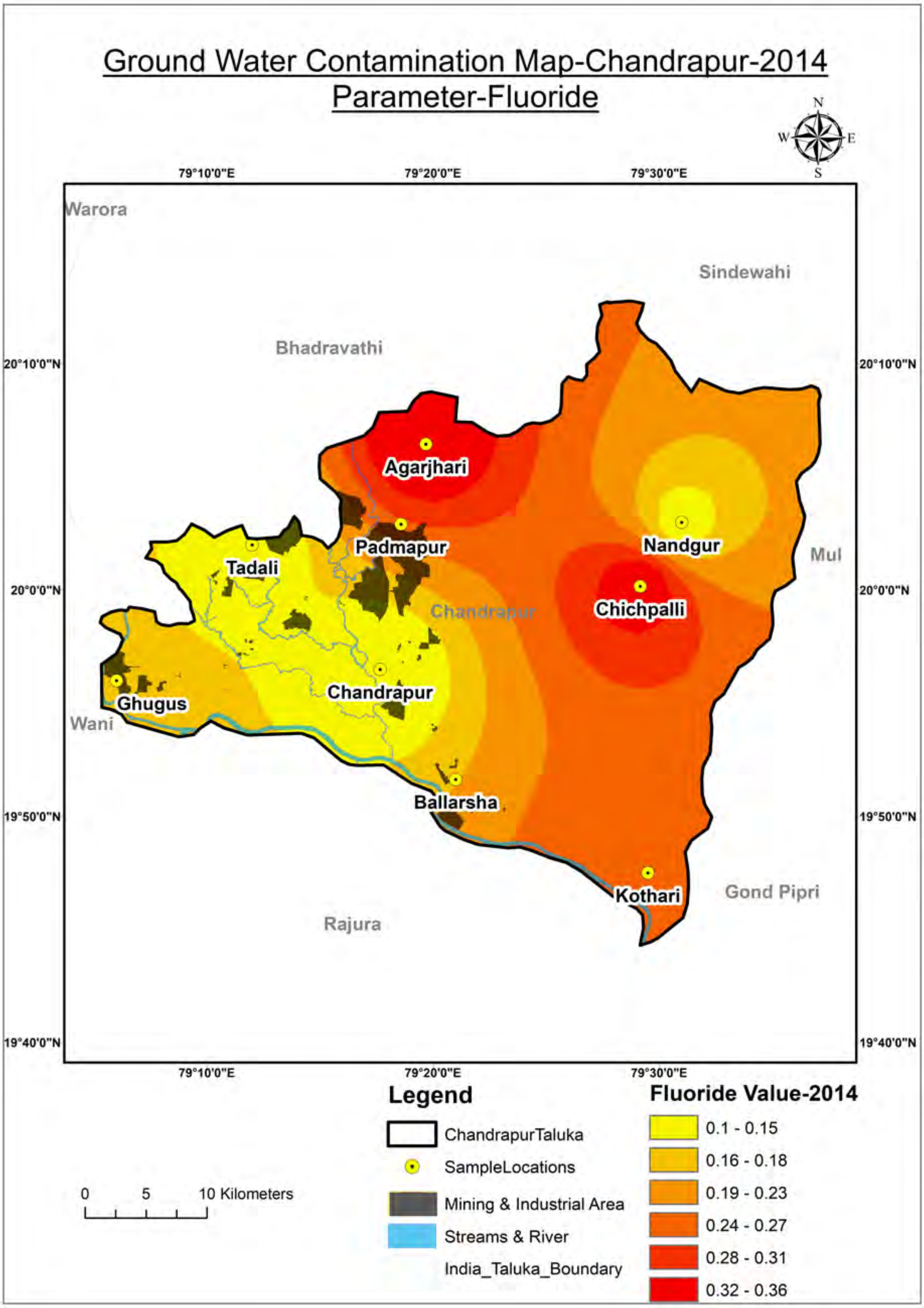

FIGURE 5. Fluoride distributions 2014.

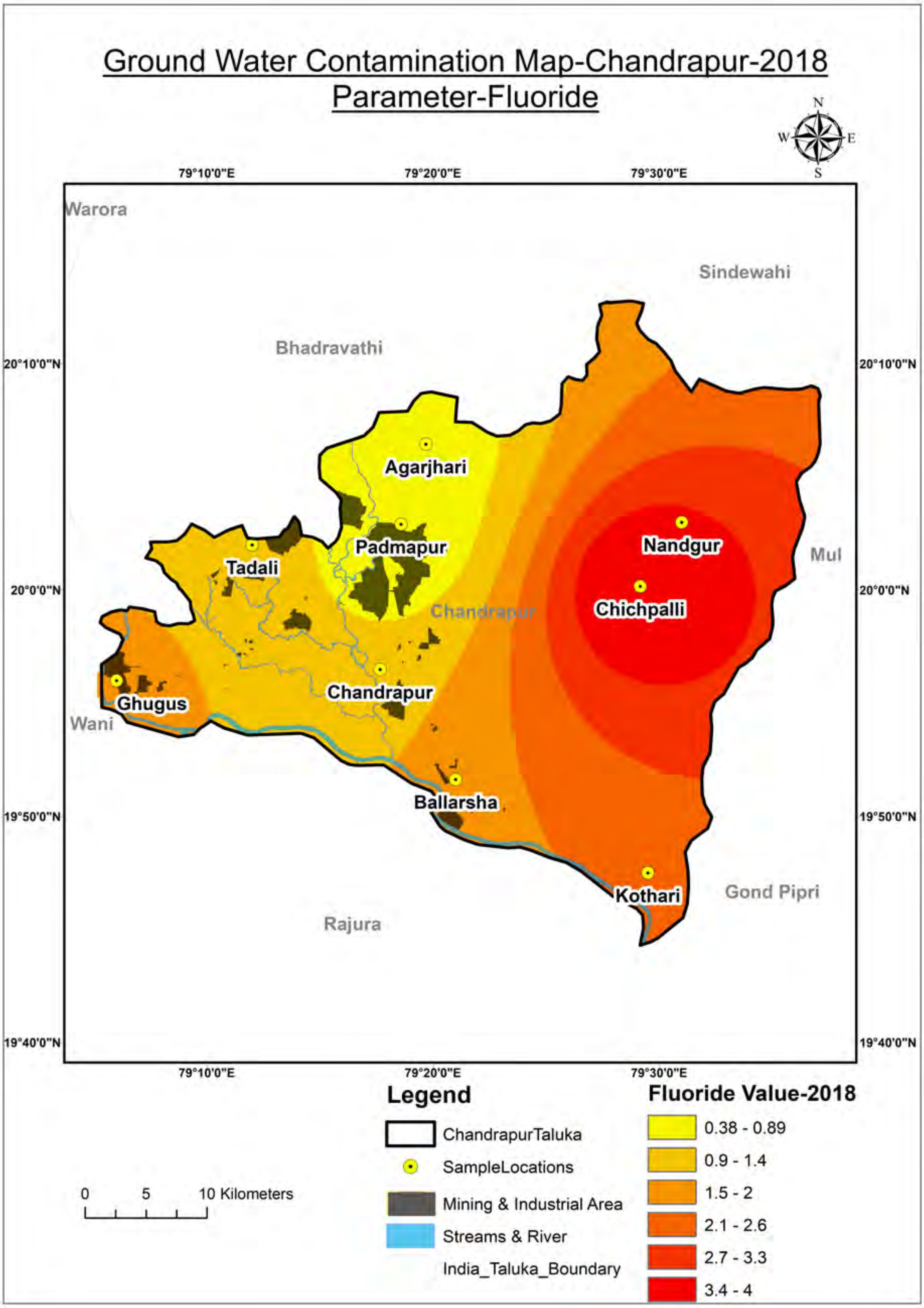

FIGURE 6. Fluoride distributions 2018.

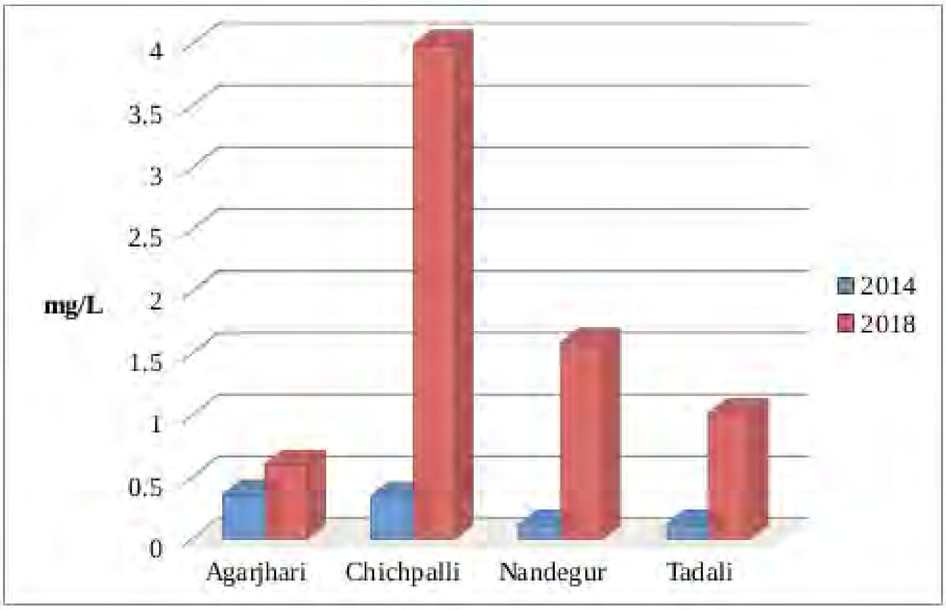

FIGURE 7. Fluoride concentration in the study sites between 2014 and 2018.

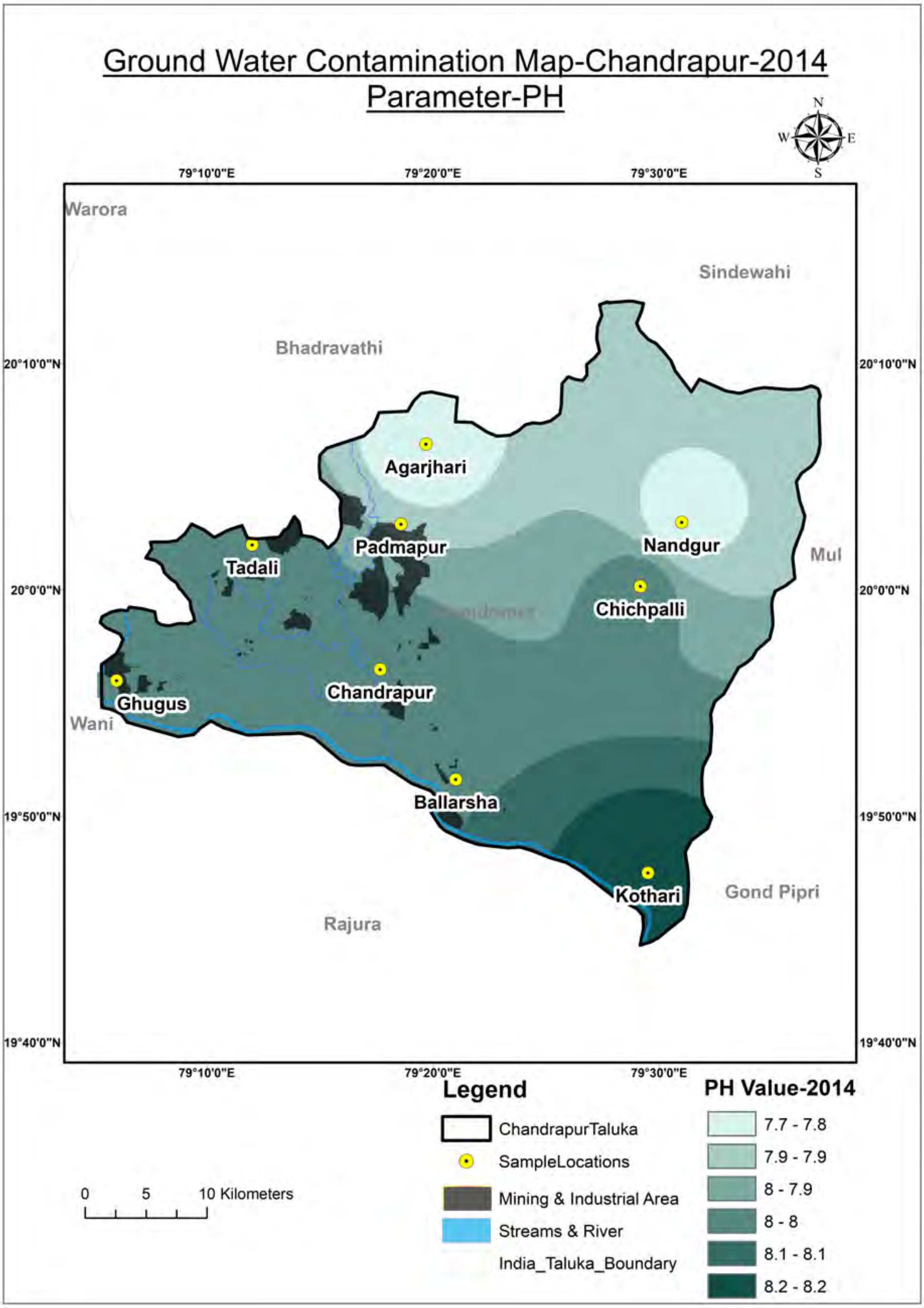

FIGURE 8. pH distributions 2014.

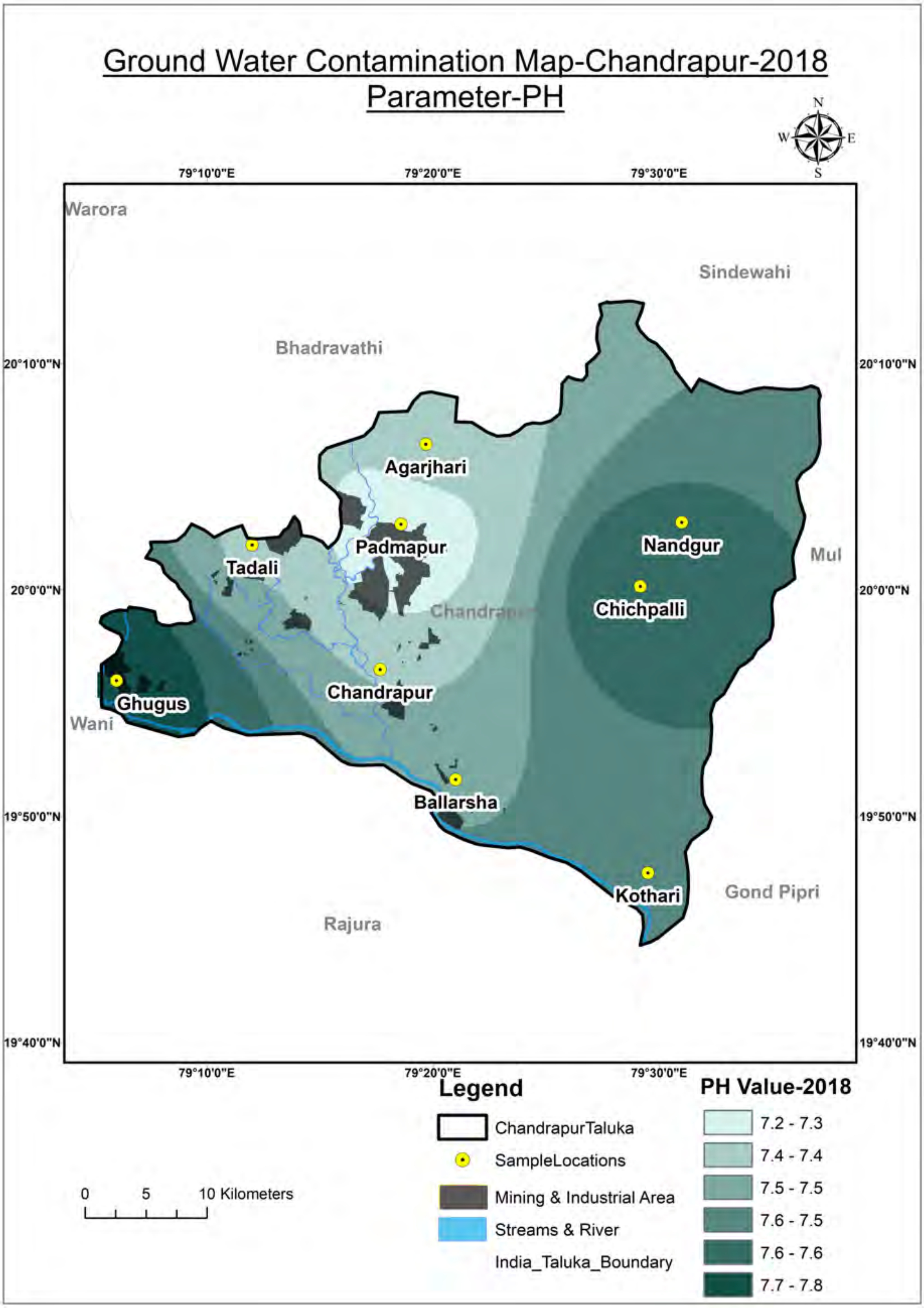

FIGURE 9. pH distributions 2018.

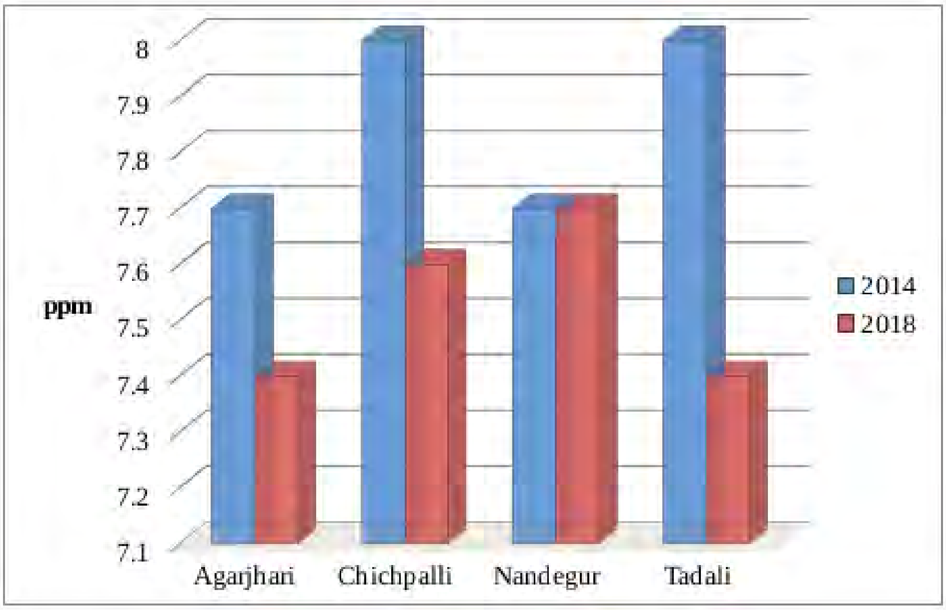

FIGURE 10. Ph in the study sites between 2014 and 2018.

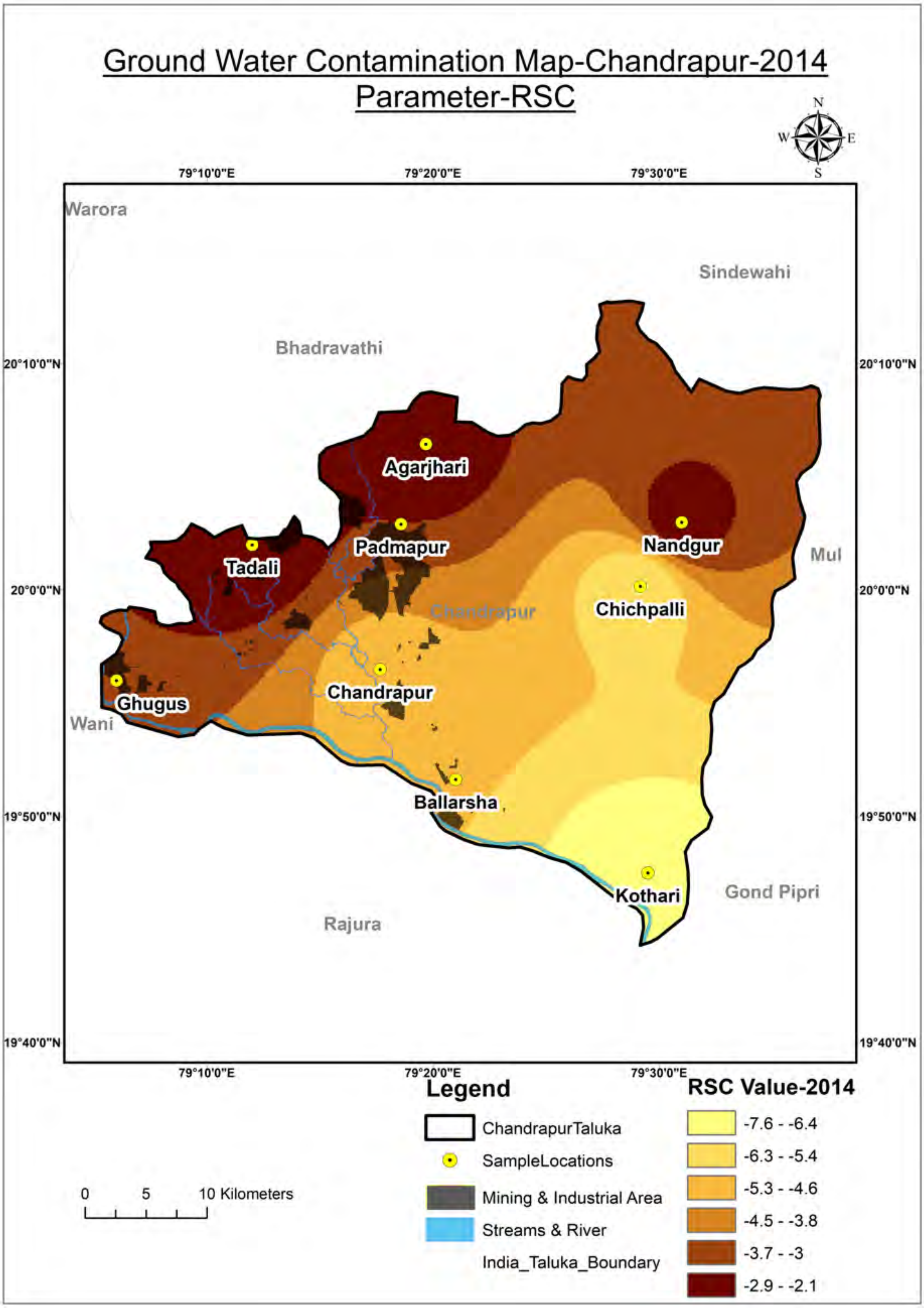

FIGURE 11. RSC distributions 2014.

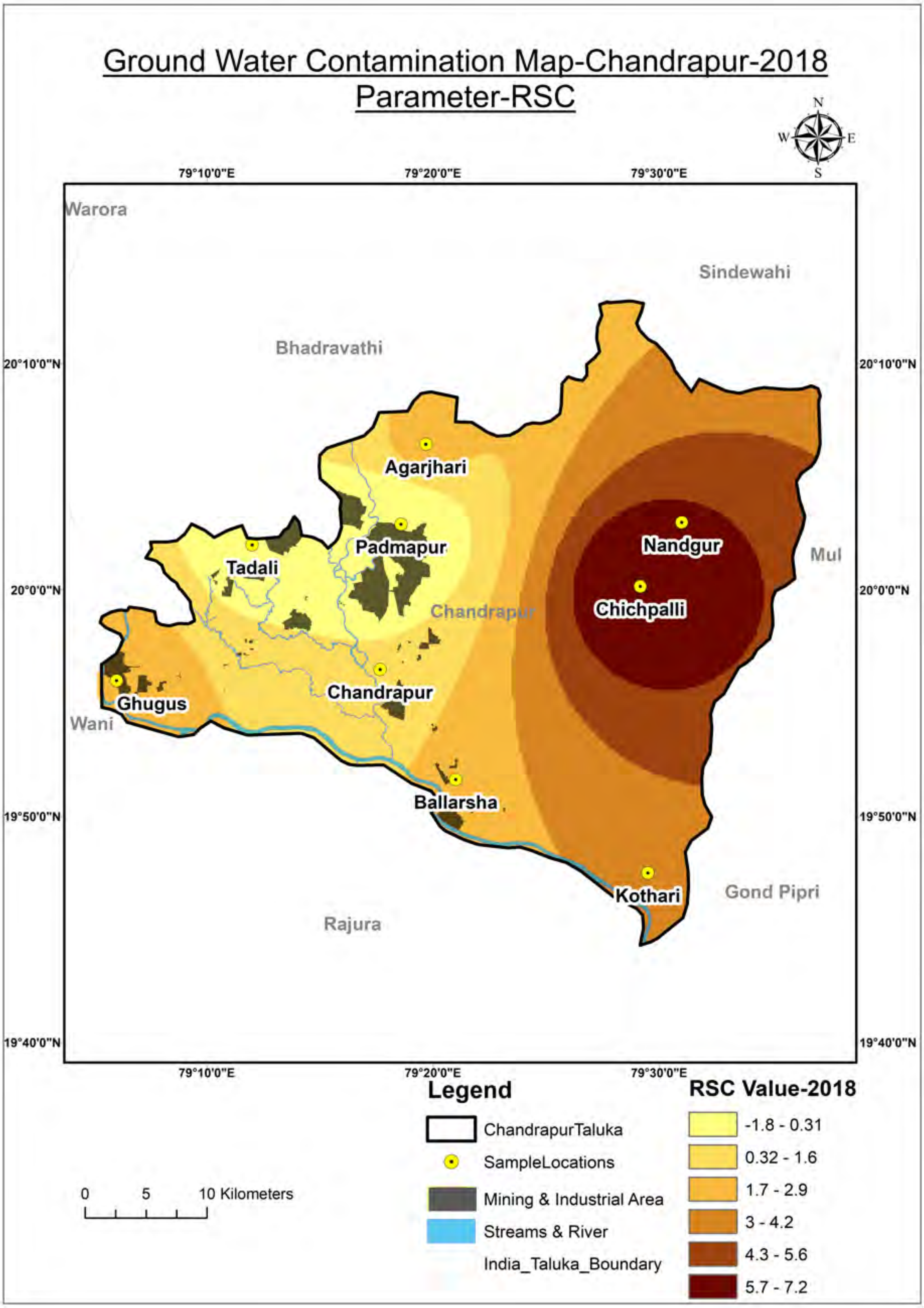

FIGURE 12. RSC distributions 2018.

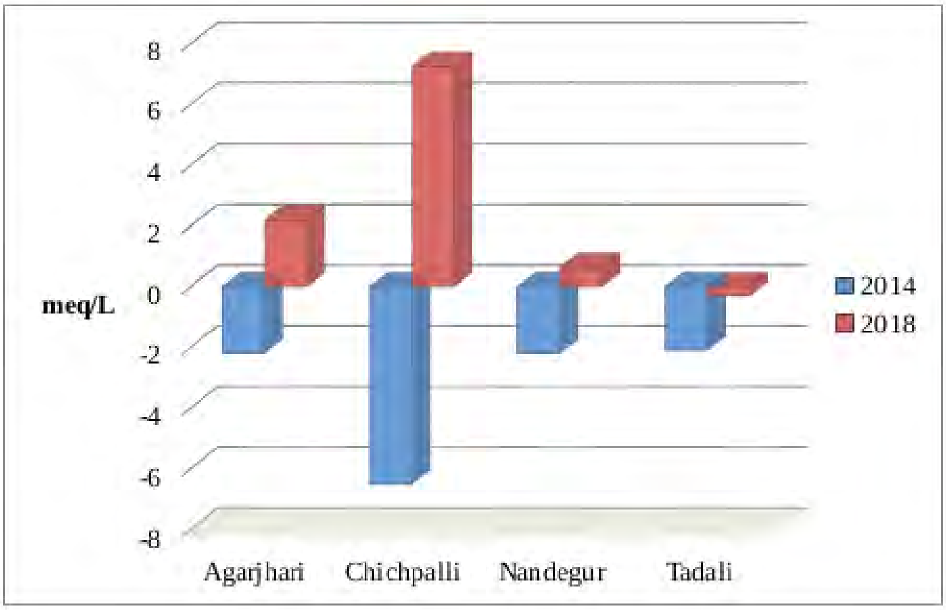

FIGURE 13. RSC concentration in the study sites between 2014 and 2018.

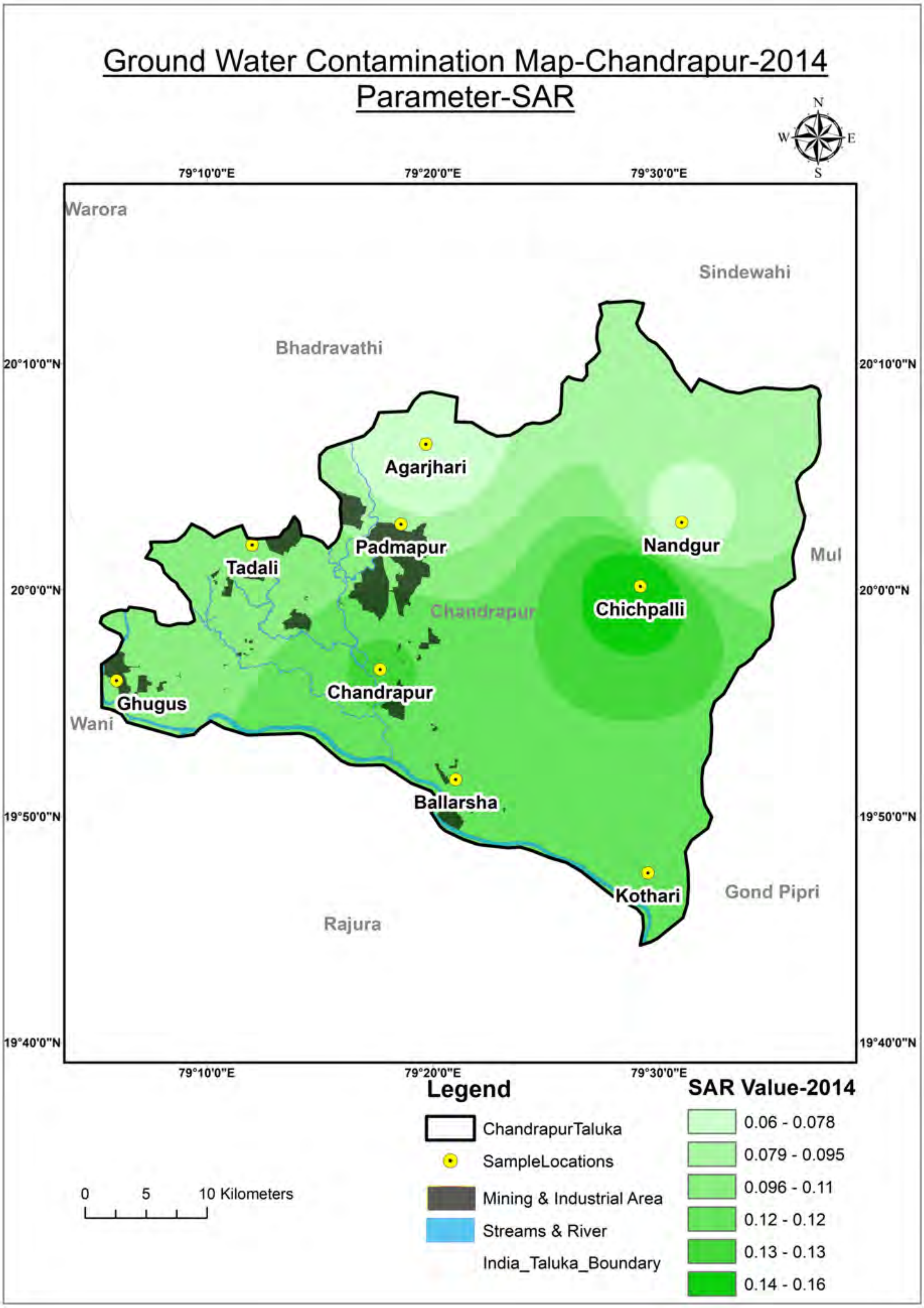

FIGURE 14. SAR distributions 2014.

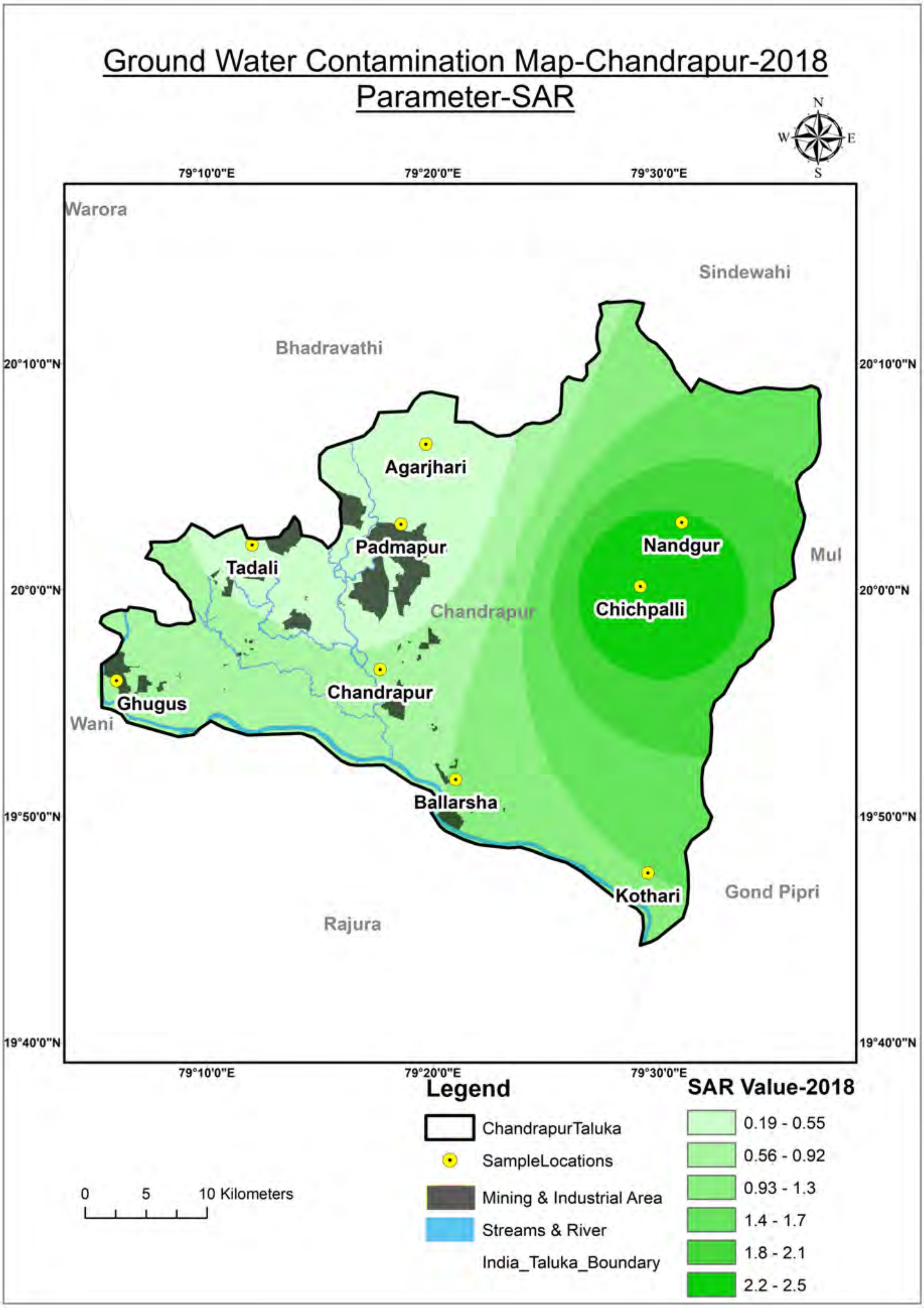

FIGURE 15. SAR distributions 2018.

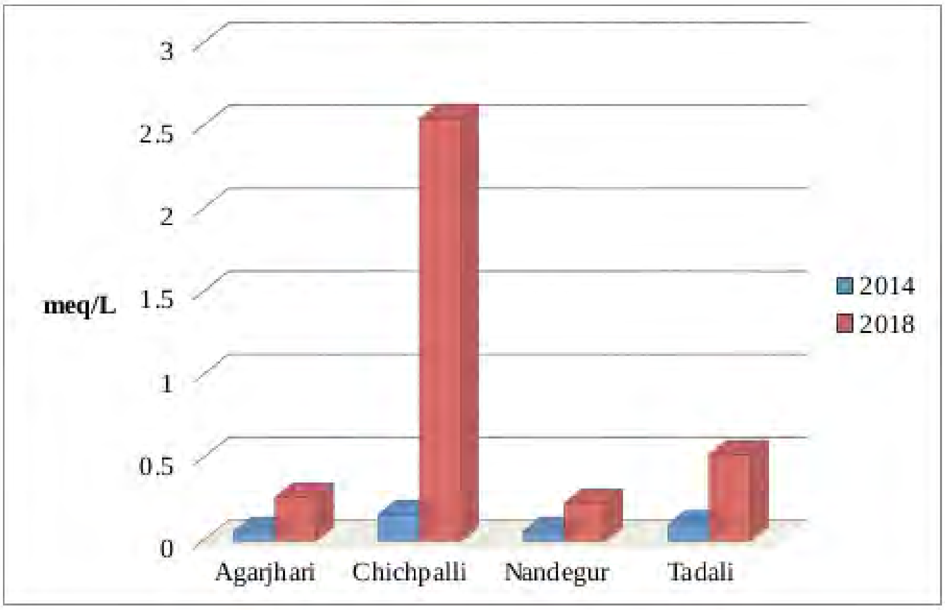

FIGURE 16. SAR concentration in the study sites between 2014 and 2018.

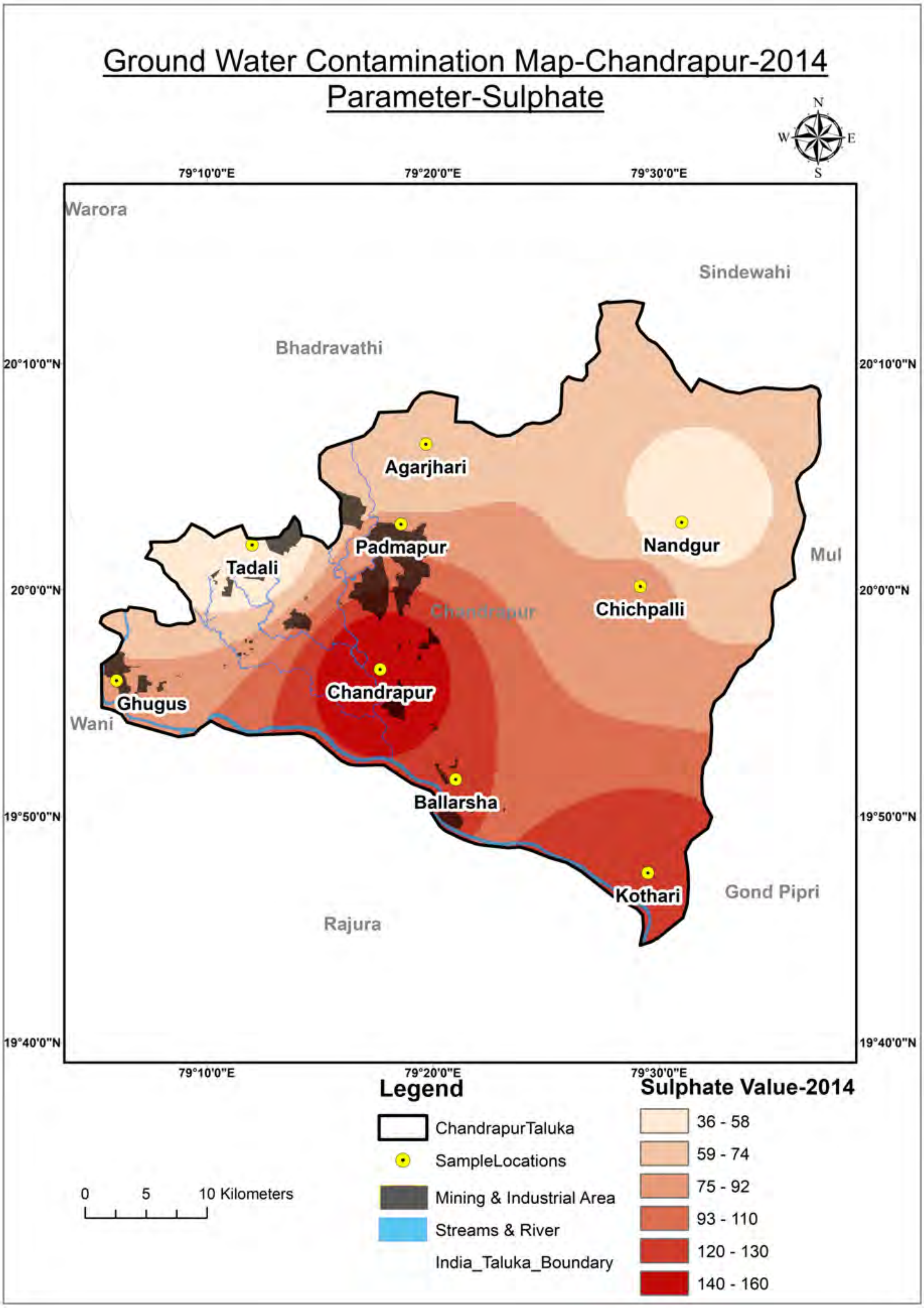

FIGURE 17. Sulphate distributions 2014.

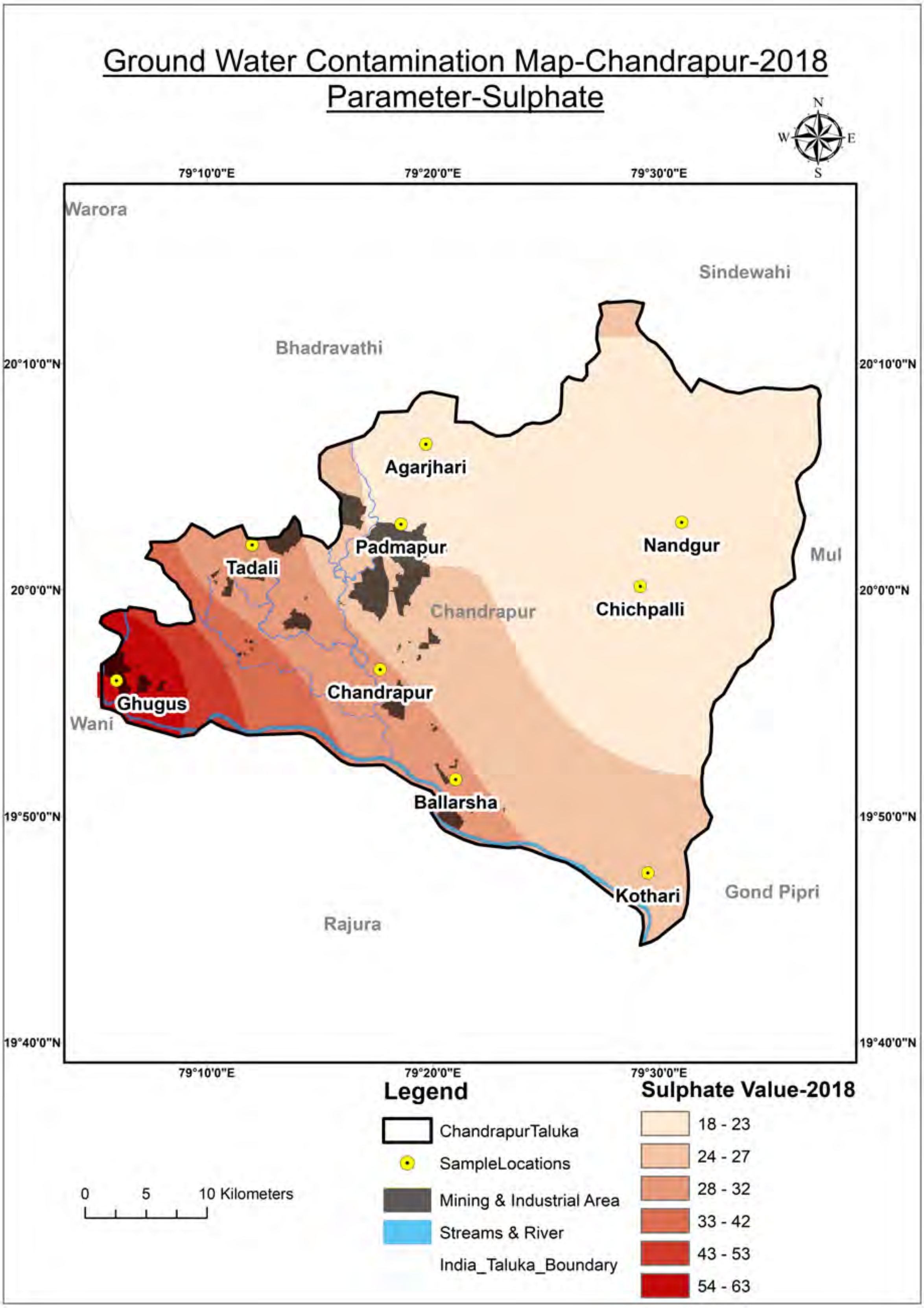

FIGURE 18. Sulphate distributions 2018.

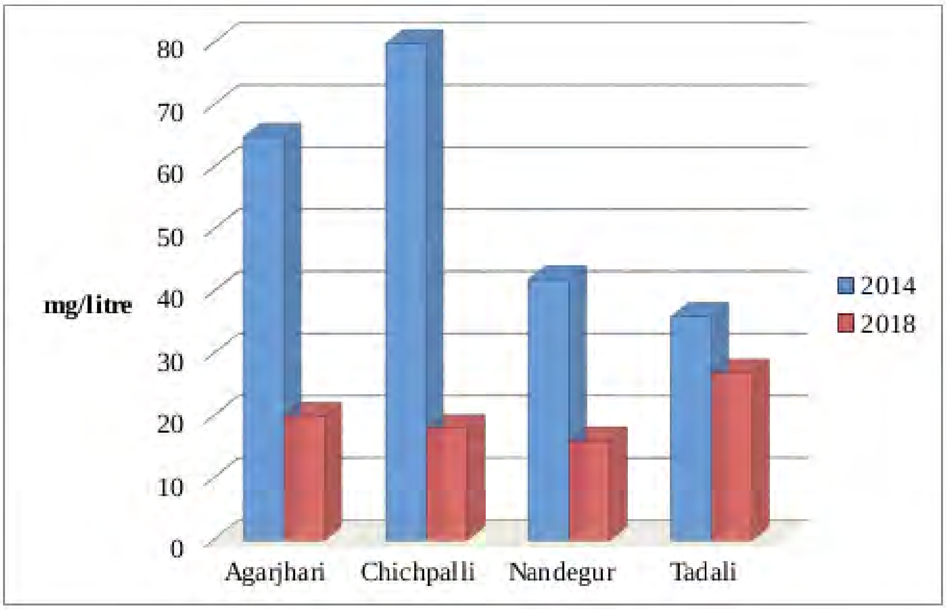

FIGURE 19. Sulphate concentration in the study sites between 2014 and 2018.

Original Article

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Impact of water management on methane and nitrous oxide emission dynamics in Asian paddy ecosystems

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ABSTRACT

With increasing demand for rice productivity linked with intense pressure on water availability in Asia, novel strategies are sought to optimise water management in paddy cultivation without compromising the yield. The conventional submerged paddy ecosystems not only consume water excessively but also constitute a major source of methane (CH_4) and nitrous oxide (N_2O), two highly potent greenhouse gases (GHG). The main objective of this study is to investigate the alternate wetting and draining (AWD) method as an emerging water-saving strategy for Asian countries, which could potentially minimise GHG emissions while maintaining crop productivity. Seasonal CH_4 and N_2O emissions from Sri Lankan and Indian experimental sites under the AWD method were compared with emissions from the conventional completely flooded (CF) method, while Japanese experimental sites were used to examine CH_4 ebullition under CF conditions. Emission measurements were conducted in both wet and dry seasons with no alterations to country-specific applications of fertiliser and soil amendments. Overall results revealed that AWD could potentially suppress CH_4 emissions by 32 to 43% without a significant statistical contrast ($p > 0.05$) in the crop yield. Measurements in Japan revealed that ebullition accounted for 60% of the total methane emissions at the heading stage under CF conditions. Results further emphasise the use of agricultural amendments with caution in paddy cultivation as they may lead to enhanced methane emissions.

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KEYWORDS GREENHOUSE GASES, CONTINUOUS FLOODING, ALTERNATIVE WETTING AND DRAINING, EBULLITION

HIGHLIGHTS

- AWD is a promising strategy to mitigate GHG emissions while sustaining grain yield.
- AWD suppressed CH_4 emissions by 32% to 43%.
- AWD increased N_2O emissions by 7.4% to 23.4%.
- Application of rice straw increased CH_4 emissions via ebullition.

1. INTRODUCTION

More than three billion people worldwide regularly consume rice (Maclean et al., 2002). Particularly in Asia, human civilisations have developed around the cultivation of rice paddies, making it the most socioeconomical and culturally influenced crop. However, paddy ecosystems contribute significantly to GHG emissions, with an estimated 47% of total anthropogenic methane (CH_4) (Smith et al., 2007). In addition, 11% of nitrous Oxide (N_2O) emissions come from rice fields (Zhang et al., 2021). Paddy ecosystems contribute to approximately 20% of human-induced CH_4 emissions within agricultural systems. While the growing population demands expansion of rice production, it inadvertently increases GHG emissions. Nearly 75% of rice is produced under continuously flooded conditions (Van der Hoek et al., 2001) and conventional farmers historically believe that maintaining continuously flooded conditions helps increase soil carbon and suppress soil-borne diseases and weeds (FAO, 2016). Due to an increase in water usage linked with a decrease in availability, paddy cultivation in Asia is likely to suffer from a lack of water in the future, which may challenge the strong hydrological coexistence of Asian paddy ecosystems. Due to the increasing demand for rice productivity under the intense pressure on water availability, the alternative wetting and draining (AWD) method has emerged as a novel strategy for the optimal use of fresh water (Lampayan et al., 2004). The AWD is a water-saving technique in which irrigation water is supplied to the field and then allowed to subside 15 cm below the soil surface through evapotranspiration and percolation, followed by reflooding. In traditional rice cultivation, continuous flooding is used as a water regime, favouring anaerobic conditions for methanogen-originated CH_4 emissions (Qiu, 2009). In contrast, draining-induced aeration of paddy landscapes can effectively reduce CH_4 emissions (Smith & Conen, 2006; Yan et al., 2003).

The produced gases should migrate through soil and be emitted to the atmosphere by diffusion, which can be explained by soil-gas diffusivity, D_p/D_o (where D_p and D_o are gas diffusion coefficients in soil and free air, respectively). Soil-gas diffusivity, in essence, is a function of soil air content and tortuosity of the functional soil-air phase, and becomes a dominant mechanism of gas emission under drained conditions. Under submerged conditions, however, ebullition (i.e., emission through bubble form) and transport through plant aerenchyma play a key role in paddy emissions. Both diffusive soil-gas emissions under drained conditions and ebullition under full flood conditions are sparsely investigated in Asian paddy ecosystems.

This study paves the way for a regional research platform to investigate the feasibility of AWD as an emerging water management practice to reduce GHG emissions without compromising paddy yield. This study further provides policymakers with scientific insight on optimal water management in Asian paddy ecosystems that maintain crop productivity while maintaining a healthy regional environment.

2. METHODOLOGY

2.1. Experimental sites

Field experiments were conducted at three experimental paddy sites in three Asian countries: Sri Lanka, India and Japan. The locations were selected as they contain paddy areas where farmers have been practising intensive farming and have kept records on water management and fertiliser inputs.

The Sri Lankan field study was conducted at an experimental paddy site (7°31′32″ N, 80°26′20″ E) that belongs to the Rice Research Development Institute (RRDI), Bathalagoda, Sri Lanka. The experimental site was located at 161 m above mean sea level. The climate in the area is tropical monsoon, while the mean annual temperature is 27.41 °C, and the mean annual precipitation is 1648.97 mm. The soil texture is loamy sand with 9.75% clay, 5.3% silt and 85.0% sand content. The selected paddy site in India was in the Kaveri River Basin at College of Agriculture, V. C. Farm, Mandya, Karnataka, (12°34′22.8″ N 76°49′34″ E), which is located 695 m above mean seas level. The region's mean annual temperature and precipitation are 27.39 °C and 139.28 mm, respectively. The soil at the experimental site was texturally characterised as a sandy loam with 12.2% clay, 19.47% silt and 68.32% sand content. The Japanese field study was conducted at a rice paddy field of NARO in Tsukubamirai City, Ibaraki Prefecture, Japan (36°00′67″ N 140°02′21″ E) located around 25 m above mean sea level, where mean annual temperature and precipitation in vegetative, reproductive and ripening growth stages are recorded as 21.5, 25.3, 22.7 °C and 283, 67, and 333 mm, respectively. The soil was characterised as sandy clay loam with 25% clay, 23% silt, 52% sand and the average plough layer thickness was 18.1 cm. Physicochemical properties of surface soil are as follows: C: 2.15%, N: 0.19%, pH (H_2O): 6.8, CEC: 17.5 cmol (+)/kg, and dithionite-citrate extractable iron: 12.8 g/kg. The average bulk density ranged between 1.22 and 1.3 g cm^{-3} in Sri Lankan, Indian and Japanese soils.

Notably, the soil-specific application of additional soil amendments, depending on soil quality, differed among the three sites. For example, an episode of vermicompost was applied in the Indian sites while the application of straw was practised at the Japanese site in the experimental stage, while Sri Lankan sites practised regular urea application. We did not alter the country-specific application and sequence of fertiliser and amendments to investigate the effect of water management. Notably, the Japanese paddy sites were only used to investigate methane ebullition under fully flooded conditions as the mid-season draining was not allowed to practice following strict limitations on post-Covid water management.

2.2. Experimental design

Experiments at the RRDI in Bathalagoda, Sri Lanka were conducted in a size 13 m × 7 m experimental site. Field plots representing with plants (P) and without plants (NP), completely flooded (CD) and AWD, each laid out in a randomised block design (RBD) with three replications. The same experimental sites were used during wet (WS) and dry (DS) seasons. Prior to transplant, the entire field was ploughed, puddled to the top 20 cm of soil and levelled. A popular midterm rice variety, *BG 300*, was used in with-plant (P) plots. Twelve days after seedlings emerged from rice seeds produced in a nursery, they were pulled and planted on puddled and levelled fields. Manual transplantation was carried out to preserve regular spacing between plants in straight rows.

In completely flooded (CF) plots, a water level 3 to 5 cm above the soil surface was maintained throughout the season. The AWD plots involved flooding whenever the surface water level dropped 15 cm below the soil. A polythene sheet (250 μm) was placed around the plot beds under completely flooded conditions to prevent seepage. All treatments received an equal amount of fertiliser according to traditional agricultural methods. Figure 1 shows the cultivation practice calendars and the detailed timing for both seasons in Bathalagoda, Sri Lanka.

All plots were continuously flooded during the wet season from 0 to 12 days after transplant (DAT) and then allowed to drain at 77 DAT in preparation for harvest. In the dry season, the field was allowed to drain starting at 77 DAT, the same as the wet season, and was kept completely flooded from the beginning to 23 DAT. The AWD cycle initiated and continued at 24 and 13 DAT in the dry and wet seasons, respectively, while the plots were kept entirely submerged during the flowering period of the rice growth cycle. Maintaining AWD conditions was difficult due to the elevated water table with the onset of the southwest monsoon during the wet season, although two AWD periods could be maintained. Due to a nutrient issue, there was an additional (fourth) fertiliser treatment event during the dry season, which was not uncommon in the selected area.

Similar to Sri Lankan practice, Indian sites maintained a completely randomised design (CRD) with three replications with 3 m × 3 m plot sizes for wet and dry seasons. However, due to the lack of fertility in paddy soil, additional amendments

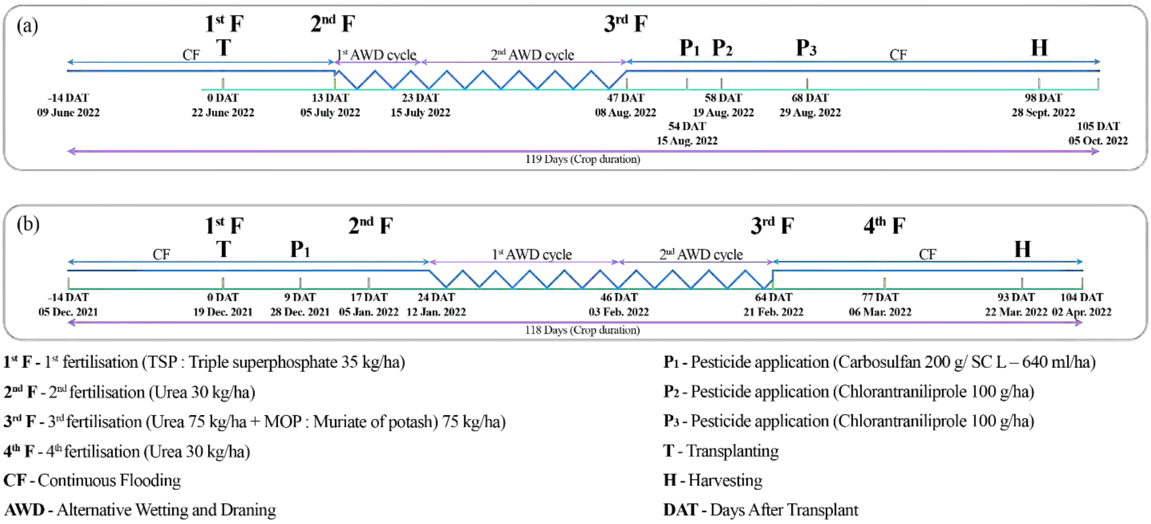


FIGURE 1. Cultivation practice calendar for (a) wet and (b) dry season at the Bathalagoda/Sri Lanka site.

(e.g., vermicompost) were added as a common practice in this area. A recommended fertiliser dose was applied, including basal Single Super Phosphate (SSP) and Muriate of Potash (MOP), as well as split urea doses during active tillering and flowering. A 10 tonne/ha application of vermicompost was made to the treatment-designated plot 15 days before the plots were flooded for puddling. The 21-day-old paddy seedlings were transplanted, two per hill, at 15 to 20 cm spacing. The treatment details for the Indian field experiment were as follows (see Table 1).

Figure 2 shows the cultivation practice calendars in Mandya, India with detailed times for both seasons.

In India, CF and AWD plots were maintained in the wet season. On the 57 DAT, water was drained for eight days until the water level reached 15 cm in the AWD plots and then reflooded again until the end of the cropping period. During the dry season, aerobic plots replaced the AWD plots to maintain the moisture level at field capacity.

In Japan, each plot size was 0.3 m × 0.6 m, and various treatments were adopted to include with and without rice plants, with and without straw application (P_S: plots with plant and straw, P_NS: plots with plant and without straw, NP_S: plots without plant with straw, NP_NS: plots without plant and straw). All experiments were triplicated. A leading cultivar in Japan, *Oryza sativa* L. cv. Koshihikari was used for the plots with rice plants (in total, six plots), and four rice hills (three rice plants for one hill) were transplanted at a spacing of 15 cm × 30 cm. The paddy field was continuously flooded from transplanting until the middle of the grain-filling stage, and for the plots with rice straw application, the 100 g of dried straw cut into around 10 cm was mixed into the plots. Figure 3 shows the cropping details and timing for rice cultivation in Tsukubamirai/Japan.

2.3. Measurements and calculations

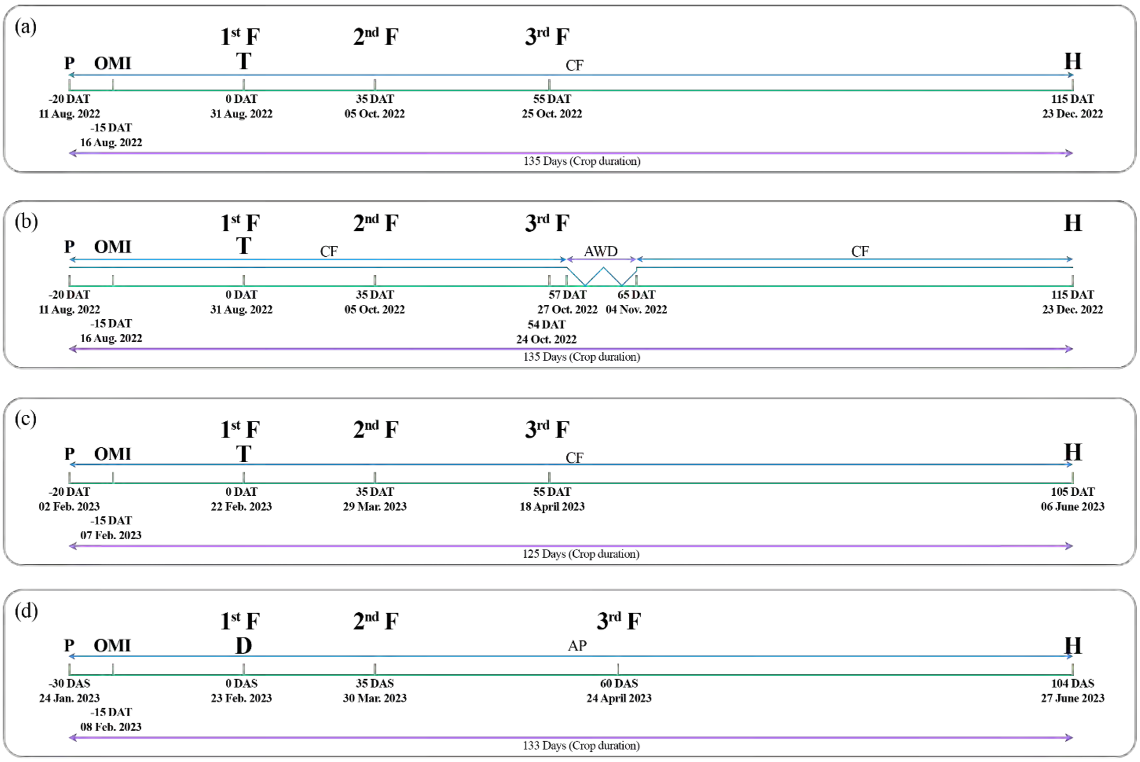
2.3.1. *Field measurements*

Gas samples were collected to evaluate CH_4 and N_2O for daily and seasonal variations using a closed chamber technique. Following the recommendations provided by Minamikawa et al. (2015), rectangular chambers were employed so that the area it covers is equal to that occupied by ten rice plants at the Sri Lankan paddy site. To maintain roughly the same head space between the plant and the top of the chamber and prevent the suppression of rice development, chambers 35 cm wide and 75 cm length were constructed using acrylic and transparent polythene in three different height stages (250 cm, 500 cm and 950 cm). A small, battery-powered fan was fixed inside the chamber's top to mix the inside gases and maintain a constant target gas concentration (Prinn et al., 1994). Additionally, the chamber had a separate gas sampling port, vent hole, and rubber stopper to avoid any drastic inside pressure changes that the chamber deployment could cause. Throughout the entire paddy season, chamber bases were firmly pressed to the soil at each experimental plot at a depth of around 5 to 10 cm, and gas samples were collected by placing the chamber on the base and ensuring a gas-tight closure using a water seal. In temperate regions of Asia, Minamikawa et al. (2012) suggested that daily mean CH_4 flow measurements be carried

TABLE 1. Treatment details for both seasons in the experimental site at Mandya, India.

Wet Season (WS)		Dry Season (DS)	
T1	CF + without plants + control	T1	Without plants + control
T2	CF + without plants + RDF	T2	Without plants + RDF
T3	CF + without plants + RDF+ VC	T3	Without plants + RDF+ vermicompost
T4	CF + with plants + control	T4	With plants + control
T5	CF + with plants + RDF	T5	With plants + RDF
T6	CF + with plants + RDF+ VC	T6	With plants + RDF+ vermicompost
T7	AWD + without plants + control		
T8	AWD + without plants + RDF		
T9	AWD + without plants + RDF+ VC		
T10	AWD + with plants + control		
T11	AWD + with plants + RDF		
T12	AWD + with plants + RDF+ VC		

RDF: Recommended Dose of Fertiliser, VC: Vermicompost.



1st F - 1st fertilisation (Urea 104 kg/ha + SSP : Single super phosphate 312 kg/ha + MOP : Muriate of potash 83 kg/ha)
2nd F - 2nd fertilisation (Urea 52 kg/ha)
3rd F - 3rd fertilisation (Urea 52 kg/ha)
P - Ploughing
OMI - Organic Matter Incorporation
T - Transplanting
CF - Continuous flooding
AWD - Alternative Wetting Draining
AP - Aerobic paddy (moisture was maintained at field capacity)
DAT - Days After Transplant
DAS - Days After Sowing
H - Harvesting
D - Direct seed sowing

FIGURE 2. Cultivation practice calendars for (a) WS/CF, (b) WS/AWD, (c) DS/CF and (d) DS/ Aerobic paddy at the Mandya/India site. WS: wet season, CF: continuous flooding, DS: dry season, AWD: alternative wetting and draining.

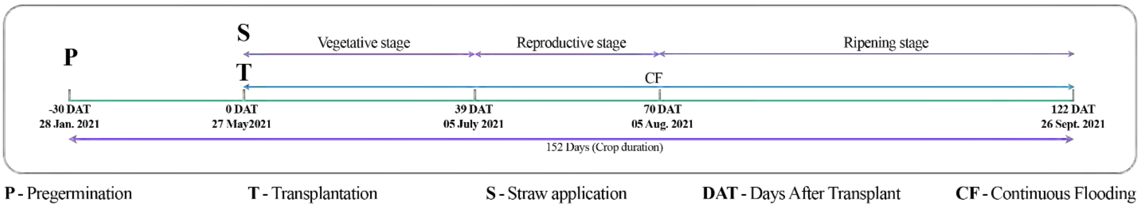


FIGURE 3. Crop practice calendar for seasonal cultivation in Tsukubamirai, Japan.

out once per day during mid-morning, roughly 10:00 (09:00–11:00) since these measurements resulted in acceptable estimates (i.e., 10%). Emissions during this period are assumed to be typical of the daily average emission rate, which is then used to calculate the total seasonal emissions (Cai et al., 1997; Zou et al., 2005). In Sri Lanka, gas samples were collected during 9–11 am local time at 0, 15, and 30 min intervals with a 60 ml syringe fitted with a stopcock valve and stored in 6 ml evacuated glass vials.

Chambers of similar dimensions were used in the Indian experimental sites. Gas samples were drawn from the chambers in the same manner as described above, using a 50 ml syringe. Gas samples were transferred to vacuum-sealed 135 ml vials with rubber stoppers, and analyses were completed within three days of sampling.

In both Sri Lankan and Indian experimental sites, weekly gas sampling was done, along with additional measurements regarding the N fertiliser event and the transition of the AWD season. Water depth inside the base and base height above the soil surface were measured on each gas sampling day. Piezometers installed at each plot were used to guarantee the water depth using the AWD approach. Soil redox potential was recorded in Sri Lanka and India using a portable battery-operated Eh meter by inserting the electrode into the soil under investigation to a root-zone depth of 5 cm. Grain yield was measured at the harvest stage at each plot under both treatments. The concentration measurements of CH_4 and N_2O were completed using a gas chromatograph equipped with a thermal conductivity detector (TCD) using helium as the carrier gas. The Indian team calculated fluxes as per the standardised protocols (Goldenfum, 2009; Venterea, 2010). Further, Ly et al. (2013) noted that cumulative emissions were computed by integrating the area under the curve of adjacent measurement points.

In the Japanese experimental site, seasonal measurements were conducted weekly for seasonal variation and a campaign was conducted for diurnal variation only for CH_4. Measurements were taken four times each during the panicle heading and formation stages and seven times during the ripening stage. Measurements of CH_4 emissions were performed during the hours of 7:00 am to 11:00 am local time. Chambers (30 cm × 60 cm × 60 cm) were placed on each plot and an additional acrylic frame with 60 cm height was placed below the chamber to extend the chamber height after the middle of July to accommodate the growth of rice plants.

The CH_4 concentration inside the chamber was continuously measured by using a high-precision portable gas analyser (G4301, Picarro Inc, Santa Clara, CA, USA) at intervals of 0.9 s. When ebullition did not occur to get a steady linear increase in CH_4 concentration in the chamber, the monitoring period was around 6 min, resulting in a continuous linear increase in the chamber's CH_4 content. The monitoring period was approximately 10–15 min when frequent ebullitions were noticed. Sensors (TEROS-12, METER) were inserted at 5 cm and 10 cm soil depth to measure soil temperature and volumetric water content where ±3 cm of the inserted depths were contained in the measured region. All data were recorded using a logger (ZL6 Basic, METER) at 1 h intervals. After monitoring, intact soil core samples were extracted from each plot at 5 and 10 cm depths. Sensor calibration for volumetric water content was done using the volumetric water content determined by oven-drying the intact soil cores. Ebullition and CH_4 fluxes through the rice plants were separately computed in accordance with Kajiura and Tokida (2021). In a kernel density distribution of the flux, the lowest flux showing local maxima was considered as the diffusive CH_4 flux (i.e., plant-mediated flux and molecular diffusion of dissolved CH_4 across the water–atmosphere interface). The difference between the total and plant-mediated CH_4 fluxes was then used to compute the ebullition CH_4 flux.

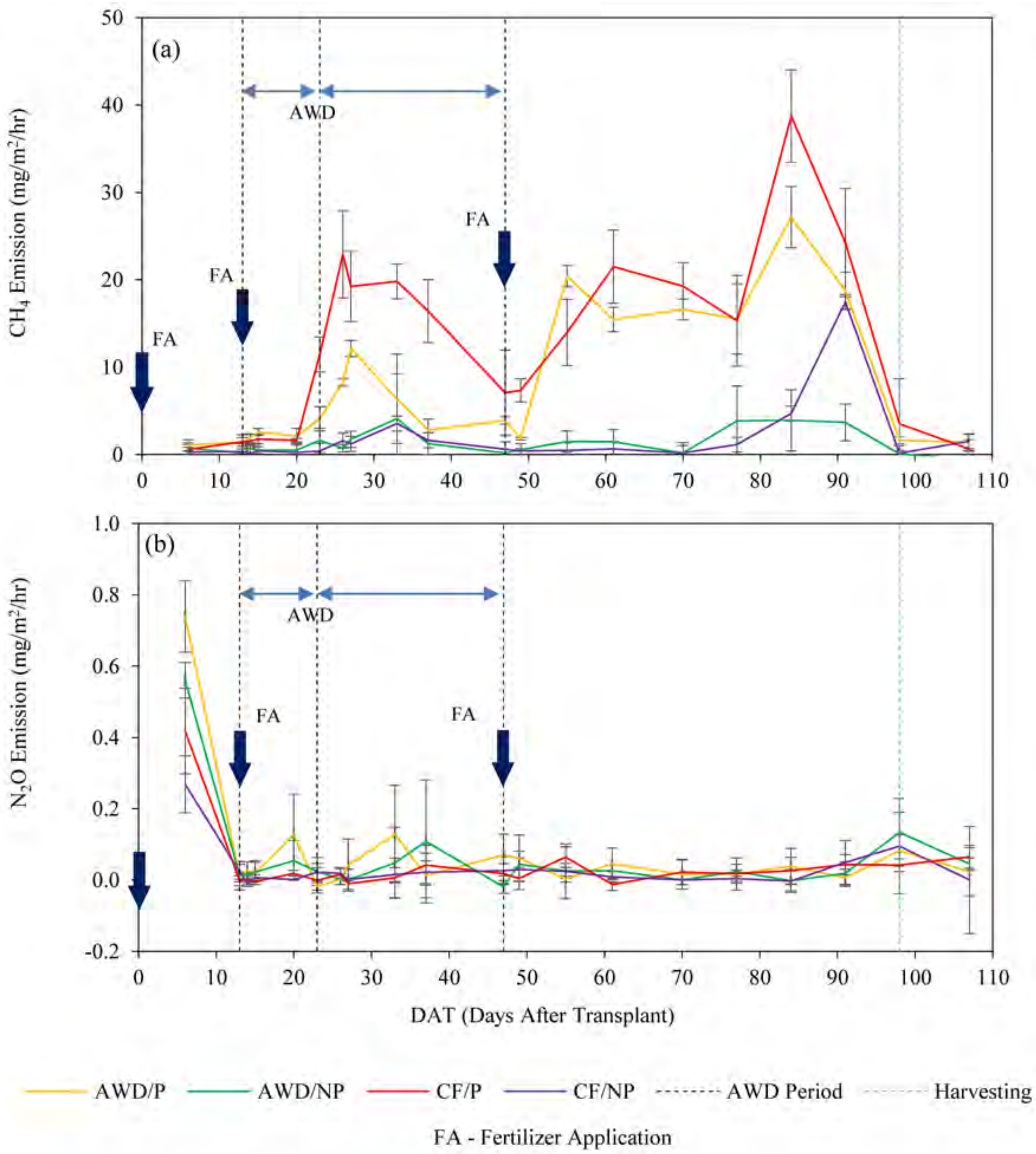


FIGURE 4. Seasonal variation of (a) CH_4 emissions and (b) N_2O emissions during the wet season. Error bars for CH_4 and N_2O fluxes indicate the standard error (n = 3). AWD/P: Alternative wetting and draining with plants, AWD/NP: Alternative wetting and draining without plants, CF/P: continuous flooding with plants, CF/NP: continuous flooding without plants.

It should be emphasised that due to the poor solubility of the CH_4, the diffusive flow of dissolved CH_4 was neglected.

2.3.2. Statistical analysis

All statistical analyses were performed using Minitab® 17.1.0. One-way analysis of variance (ANOVA) and paired *t*-test were used to analyse statistical significance in seasonal emissions and grain yield, respectively. To test differences among treatments, Tukey's HSD (Honest Significant Difference) test was performed with a significance level of 0.05.

3. RESULTS AND DISCUSSION

3.1. Field experiments

3.1.1. Seasonal emissions in Sri Lanka

The seasonal CH_4 and N_2O emissions from the Bathelegoda, Sri Lanka experimental site under both CF and AWD, with and without plants, are shown in Figure 4. Note that they are shown for both the wet and dry seasons.

Figures 4a and 5a indicate the seasonal dynamics of CH_4, demonstrating the complex interplay between methane generation, oxidation and transportation. Due to the constant anaerobic conditions

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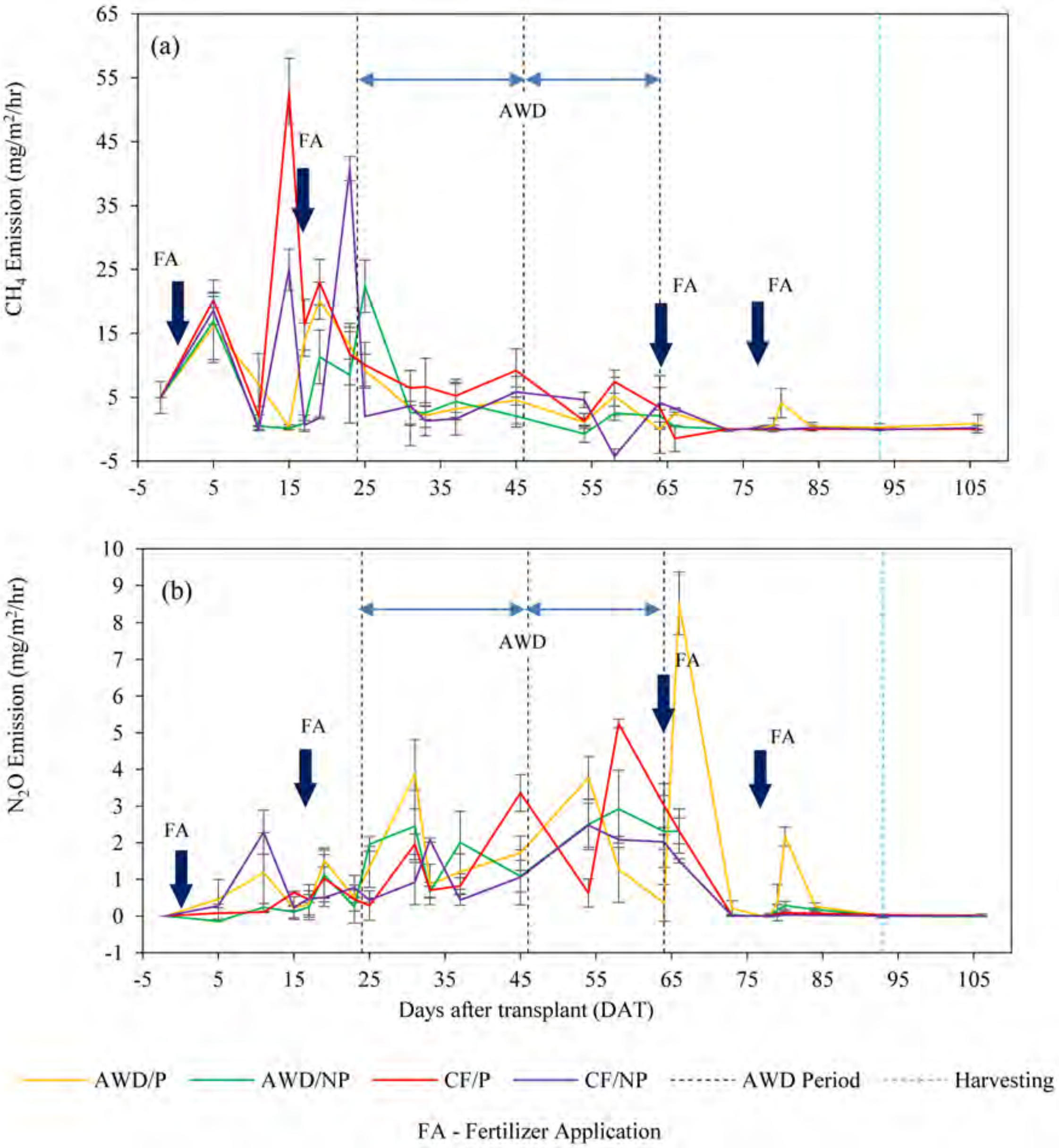

FIGURE 5. Seasonal variation in (a) CH_4 emissions and (b) N_2O emissions during the dry season. Error bars for CH_4 and N_2O fluxes indicate the standard error (n = 3). AWD/P: Alternative wetting and draining with plants, AWD/NP: Alternative wetting and draining without plants, CF/P: continuous flooding with plants, CF/NP: continuous flooding without plants.

present in CF/P as opposed to the intermittent aeration in AWD/P, emissions rates of CF/P were higher than those of AWD/P, as was expected. The large error bars show the spatial variability in the fluxes. Throughout the whole season, as discussed by Pandey et al. (2014) and Oo et al. (2018), three peaks were noticed under with-plant (P) treatments (Figure 4a). Generally, high CH_4 flux is caused by the favourable oxygen status and C availability in the paddy soil due to the release of more plant-borne carbon sources, such as root exudation continuing at high levels or decaying roots. Soil-redox (Eh) ranged from −100 to −200 mV during the CF in WS, as also evidenced by Yagi and Minami (1990) and Wang et al. (2017), who mentioned that the production of CH_4 starts at a redox potential of −150 to −160 mV. Lower CH_4 emissions under drainage have been consistently reported in many past studies, indicating a negative correlation between CH_4 emission and soil Eh (Corton et al., 2000; Wassmann & Aulakh, 2000). In this study, a reduction in CH_4 emission was observed under enhanced redox conditions in AWD, which ranged between (−125) mV – (+510) mV. Decrement of CH_4 emissions from AWD/P was caused by less developed aerenchyma of rice plants that have previously undergone AWD treatment, as compared to those under anaerobic conditions permanently.

With the transition from aerobic to anaerobic conditions due to the AWD episode ceasing, a rapid increment of CH_4 emission was detected under the AWD/P combination. Generally, in paddy systems, transportation and atmospheric emission of methane occurs mainly via three channels: diffusion of dissolved gas through water-air and soil-water interfaces, ebullition as gas bubbles, and plant transport (i.e., by diffusion and conversion to gaseous CH_4 in the aerenchyma and cortex) and subsequent release to the atmosphere (Davamani et al., 2020; Le Mer & Roger, 2001). Literature studies have concluded that more than 90% of CH_4 is emitted through rice plants under normal CF conditions (Xie & Li, 2002). In comparison, 70.3% of emissions occurred through the plants during the wet season, while 29.6% occurred through the soil surface (Figure 1a), suggesting that soil-dominant diffusive emissions are instrumental in alternative wetting and drying periods. Both CF/NP and AWD/NP treatments showed very low emissions, around 15%, in comparison to CF/P and AWD/P (see Table 2), thus corroborating the literature observations. This is primarily due to the fact that methane tends to oxidise in the suboxic zone (i.e., at the interface between oxic and anoxic regimes) where the concentration gradients of methane and oxygen essentially overlap, for instance at the surface of flooded rice soils and in the rhizosphere of rice plants. Therefore, as reported in many studies (Conrad & Rothfuss, 1991; Inubushi et al., 1992), 65–80% of generated methane becomes oxidised en route in NP plots.

In contrast to the wet season, CH_4 flux shows high emissions at the beginning of the dry season, as indicated by Figure 5a, and gradually declined to approximately zero towards the end due to the limited presence of soil organic matter with the reduction of carbon supply because of the ageing of plants. Low Eh values in the field, ranging from −150 mV to −200 mV, have enhanced CH_4 formation by methanogenic bacteria under flooded conditions while at −75 mV to +550 mV under drained conditions. Contrary to Li et al. (2009a,b), CH_4 emissions under AWD treatments were not observed to be zero due to the emission of trapped methane in soil pores (Bubier & Moore, 1994).

Recognisable N_2O emissions were not detected during the wet season (Figure 4b) and the rice growing period fluctuated near zero. High emissions were detected for all four treatments at the start of the wet season as a result of the unexpected drying situation at the field (water level = −15 cm below the surface).

Seasonal N_2O emission increased in the dry season compared with the wet season in numerals (Figure 5b) and is strongly influenced by water regime and fertilisation (Aung et al., 2018). However, no significant difference ($p > 0.05$) in cumulative emission for the dry season was observed among the treatments. Besides, N_2O emission during the dry season (Figure 5b) varies throughout the season in such a way that shows a gradual increment, then peaking at the reproductive phase and followed by a gradual decrease to zero emission. However, a considerable increment of N_2O emission could be observed after first flood irrigation and puddling with the application of basal fertiliser to increase soil biological fertility and concentration of mineral elements and lack nutrients prior to planting.

After the first peak, emissions fluctuated near zero and the second fertilisation was done at 17 DAT under flooded conditions. A temporal peak of N_2O emission was observed at 20 DAT, although it lasted only a few days. It is worth noting that although nitrification and denitrification processes are influenced by soil moisture (Davidson et al., 1986), N_2O production is suppressed under very high moisture content in soil (Tirol-Padre et al., 2017). In this study, continuously irrigated rice paddies have shown quite small N_2O emissions than that of AWD treatment under proper application of N fertiliser, as mentioned by Furukawa et al. (2007) and Tirol-Padre et al. (2017). Brentrup et al. (2000) have documented that N_2O emission increases under moisture alternations such as successive moist and dry episodes. In agreement with the literature, during the alternative wetting and drying period, N_2O fluxes peaked when the water table dropped below the soil surface under high soil redox conditions and during the transition from aerobic to anaerobic just after fertilisation. Hence, throughout the dry season, peaks from AWD/P treatment have increased, as reported in previous studies (Hou et al., 2012; Tirol-Padre et al., 2017).

Statistical details for both wet and dry seasons for the Sri Lankan site are mentioned in Table 2.

3.1.2. Emission dynamics in Indian paddy plots

CH_4 and N_2O emissions measurements in Indian paddy sites for the wet season are shown in Figures 6 and 7, respectively.

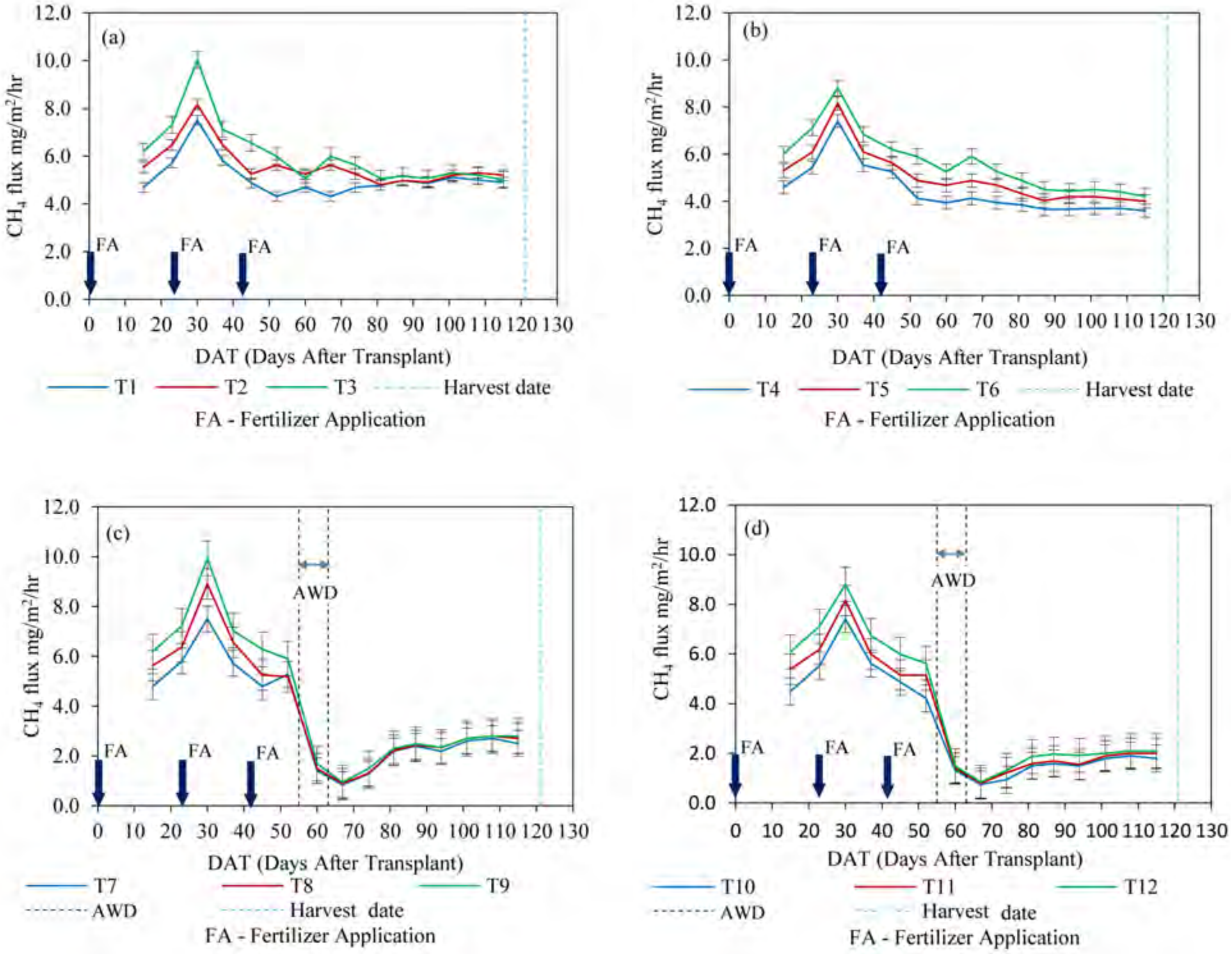

FIGURE 6. Methane flux from paddy plots under continuous flooding (a) without crop and (b) with crop, AWD (c) without crop and (d) with crop in wet season. T1: CF + without plants + control, T2: CF + without plants + RDF, T3: CF + without plants + RDF+ VC, T4: CF + with plants + control, T5: CF + with plants + RDF, T6: CF + with plants + RDF+ VC, T7: MSD + without plants + control, T8: MSD + without plants + RDF, T9: MSD + without plants + RDF+ VC, T10: MSD + with plants + control, T11: MSD + with plants + RDF, T12: MSD + with plants + RDF+ VC.

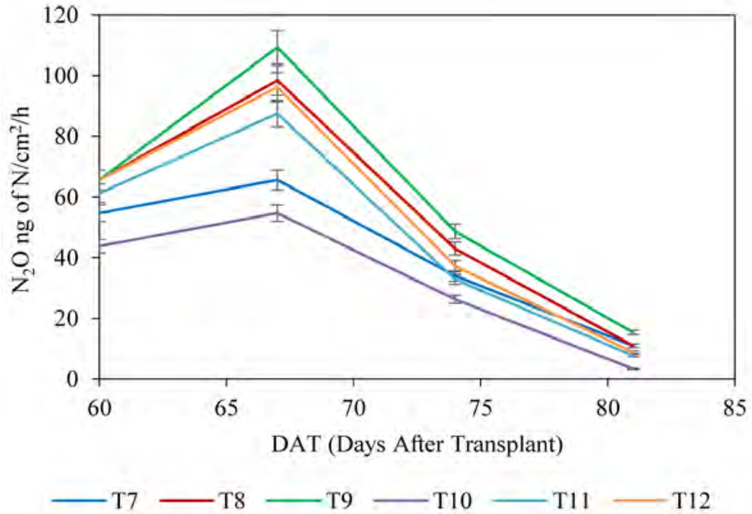

FIGURE 7. Nitrous oxide emissions from paddy plots under AWD condition in wet season. T7: MSD + without plants + control, T8: MSD + without plants + RDF, T9: MSD + without plants + RDF+ VC, T10: MSD + with plants + control, T11: MSD + with plants + RDF, T12: MSD + with plants + RDF + VC.

TABLE 2. Statistical analysis results for dry and wet seasons in Sri Lanka.

	Seasonal CH_4[a] emission (kg/ha)	Seasonal N_2O emission (kg/ha)	Grain yield (Mg/ha)
Wet season			
CF/P	517.0 a	1.24	3.71
AWD/P	349.6 ab	1.34	3.79
CF/NP	57.0 b	1.03	
AWD/NP	36.1 b	1.19	
Dry season			
CF/P	125.0 A	20.9	3.34
AWD/P	71.2 AB	27.3	3.12
CF/NP	74.6 AB	13.7	
AWD/NP	48.4 B	18.0	
Source of variation treatment		***p* value**	
Wet Season	**	0.837	0.851
Dry Season	*	0.117	0.844

Notes: CF/P, continuous flooding with plants; AWD/P, alternative wetting and draining with plants; CF/NP, continuous flooding without plants; AWD/NP, alternative wetting and draining without plants. The asterisks * and ** represent significant at $p < 0.1$ and $p < 0.05$, respectively.

[a] The letters indicate significant difference at the 5% level (lowercase letters) and 10% level (uppercase letters).

Regardless of treatments, the methane emissions observed at 30 DAT peak can be attributed to the interaction between microbial biomass dynamics and organic matter decomposition under shifting soil redox conditions (ranging between −153 to −159 mV). Mid-season drainage substantially reduced methane emissions, while CF without plant plots emitted high methane emissions due to the organic matter accumulation and absence of plant-mediated processes such as oxygen transportation, allowing methanogenic microorganisms to dominate and increase methane production (Conrad, 2007; Khalil & Rasmussen, 1992).

Although measurements of N_2O emissions yielded negative results under CF plots, with the onset of the AWD period, emissions peaked ten days after drainage. Notably, plots without plants exhibited higher N_2O emissions than plots with plants. Furthermore, in terms of supplementation, plots enriched with vermicompost and the recommended dose of fertiliser (RDF) experienced elevated N_2O emissions, followed by plots supplemented solely with RDF, and the control plots exhibited the lowest N_2O emissions. A large number of denitrifying bacteria in the earthworm gut and the surrounding vermicompost substrates is generally attributed to the increased N_2O emissions in vermicompost-amended soils (Wang et al., 2014).

Figures 8 and 9 show the CH_4 and N_2O emission variation in the dry season for Indian paddy plots, respectively.

Figures 8a and b, which exhibit CH_4 emissions data in the dry season, showed the trend around 30 DAT; emissions gradually approached zero. Differences between the plots with and without plants were negligible, demonstrating that the introduction of vermicompost did not exhibit any statistically significant impact on methane emissions (Sharma et al., 2016).

The results demonstrated a noticeable increase in N_2O emissions following fertilisers applied in divided dosages. All treatments show a similar pattern in N_2O fluctuations, while the highest N_2O dynamics belongs to the vermicompost amendment plot when compared to synthetic fertiliser and control plots. As mentioned by Sharma et al. (2016), applying vermicompost increases the soil's physical properties, like soil aggregates and structure, thus enhancing the aeration in the soil profile. Intriguingly, the N_2O emissions rates of the plots without

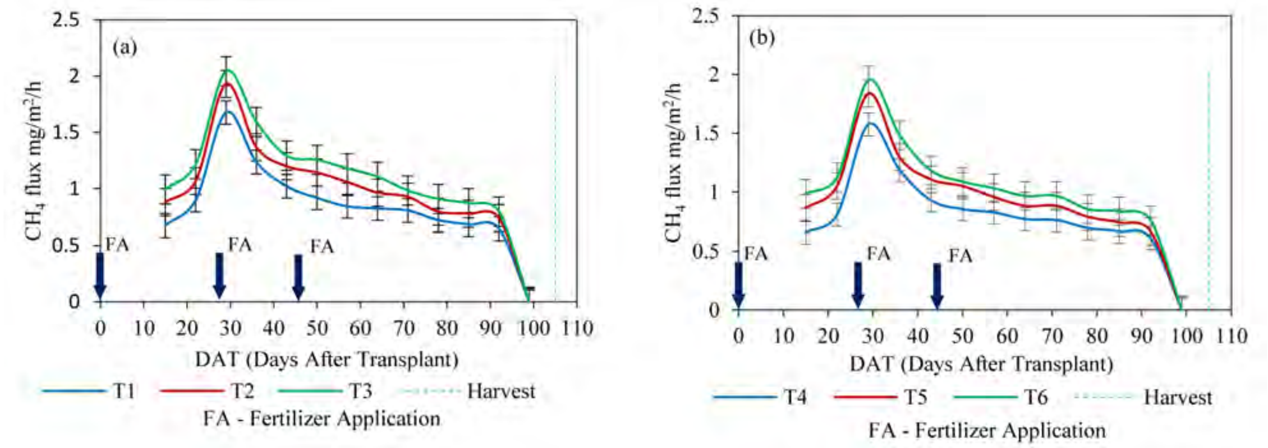

FIGURE 8. CH_4 flux from paddy plots under CF condition (a) without crop and (b) with crop in dry season. T1: without plants + control, T2: without plants + RDF, T3: without plants + RDF+ vermicompost, T4: with plants + control, T5: with plants + RDF, T6: with plants + RDF+ vermicompost.

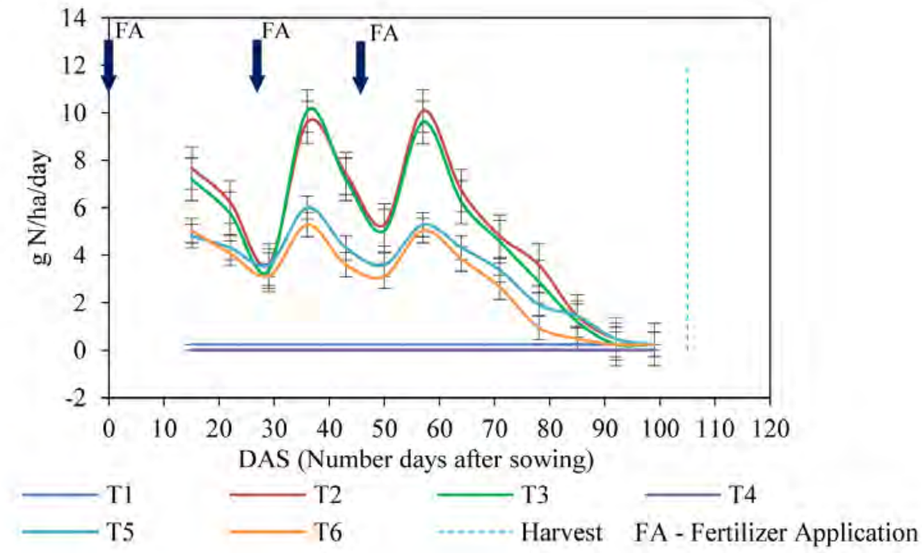

FIGURE 9. N_2O flux variation from aerobic paddy plots in dry season under aerobic conditions. T1: without plants + control, T2: without plants + RDF, T3: without plants + RDF+ vermicompost, T4: with plants + control, T5: with plants + RDF, T6: with plants + RDF+ vermicompost.

plants were higher than those with plant plots, while control plots without any supplementation showed the least emissions, almost nil (Figure 5). This observation underscores the interplay between nutrient availability, fertilisation strategies, and the subsequent manifestation of N_2O emissions.

Comparison between results from Sri Lankan and Indian paddy sites regarding seasonal emissions under CF and AWD and grain yield are shown in Table 3.

3.1.3. Methane emission dynamics of Japanese rice paddies

The Japanese experimental sites were used in this study to closely monitor methane ebullition under fully flooded site conditions, with and without the effect of straw incorporation. The seasonal and diurnal CH_4 flux for the plots containing plants is depicted in Figure 10.

The plots with straw treatment showed higher fluxes via both plant-mediated and ebullition during the heading stage than without straw (Figure 10a); the decomposition of applied rice straw enhanced CH_4 production during the earlier part of the growth period. During the ripening stage, there were high CH_4 emissions via ebullition (Figures 10a and 10b) and the proportion of CH_4 flux as ebullition to the overall flux was greater than 60%. There are two possible reasons for this behaviour. First, there was an increase in the supply of organic matter because

TABLE 3. Emissions and yield data in two countries.

	Sri Lanka		India	
	CF	AWD	CF	AWD
Seasonal CH_4 emissions (kg/ha)	125.0–517.0	71.2–349.6	107.38–136.20	73.5–90.7
Seasonal N_2O emissions (kg/ha)	1.2–20.9	1.3–27.3	NM	0.25–2.86
Grain yield (Mg/ha)	3.3–3.7	3.1–3.8	3.16–5.5	3.15–5.5
Reduction in CH_4 emissions under AWD (%)	NA	32.0–43.0	NA	31.6–33.4

NA: Not Applicable, NM: Not Measured.

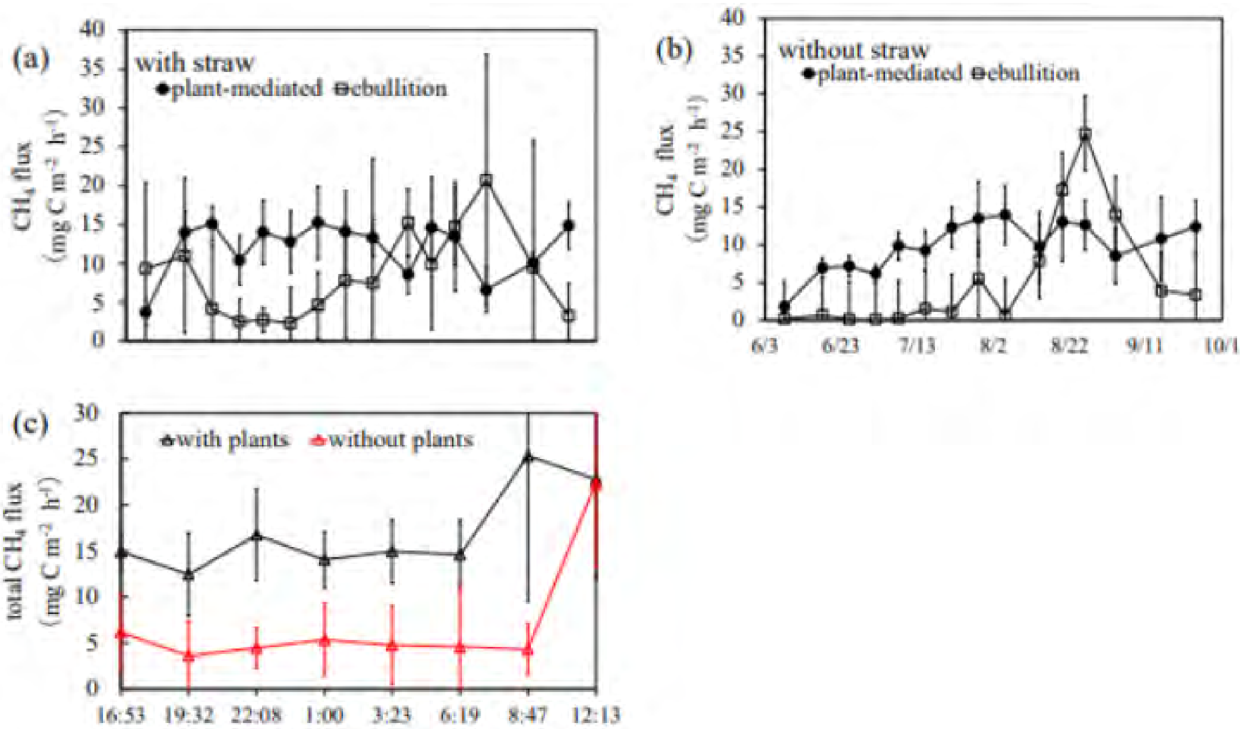

FIGURE 10. CH_4 fluxes via rice plants and ebullition for plots (a) with plants and straws and (b) with plants and without straws. (c) Diurnal variations of total CH_4 flux in the plots without straws.

of the plant roots. Second, there was a dysfunction of aerenchyma in the paddy rice, causing a reduction of plant-mediated emissions. Total flux and ebullition tended to rise in the early morning and fall in the late afternoon throughout the diurnal variation (Figure 10c). Within the day, the CH_4 flux through the plant was essentially constant (data not shown). The magnitude of the ebullition CH_4 flux at all growth stages was not explained by any of the factors considered in this study: soil temperature, atmospheric pressure and average volumetric air content, according to the results of the multiple regression analysis. Figure 11 shows the correlation between the plant-mediated flux for the plots with plants and volumetric air content averaged in 0–10 cm depth at heading and panicle formation stages. The average volumetric air content was positively correlated with both with-straw and without-straw plots. This implies that the increase in the contact area between rice roots and CH_4 bubbles in the soil enhanced CH_4 transport through the plant.

3.2. Practical implications and limitations

The experimental sites in Sri Lanka and India were selected in the intermediate zones (i.e., the transition zone between dry and wet zones) due to the more suitable geographical conditions to maintain the AWD. Due to the practical difficulty of maintaining AWD under monsoons in the wet

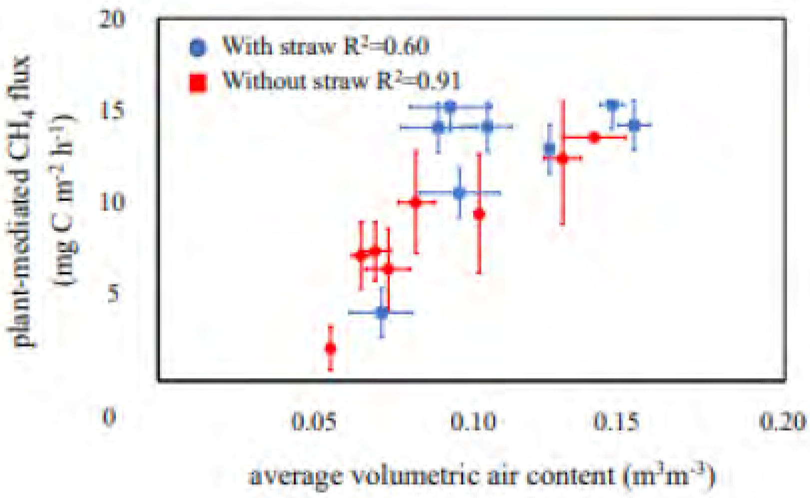

FIGURE 11. The correlation between CH_4 flux via plants and average volumetric air content.

zones due to the saturated ground condition, the AWD method could be easily applicable in dry and intermediate zones where farmers use stored water for cultivation, and it will act as an effective method of conserving water while sustaining paddy emissions. In the wet zones, where farmers depend strongly on rainfall and water is not a critical factor, the application of AWD, and hence achieving its associated benefits on GHG emissions, has become a distant goal.

The country-specific practices and regulations make it difficult to maintain consistency in water management strategies across the region. Some practices are essentially site-specific and vary considerably within the same country, making it difficult to provide conclusive recommendations without detailed studies on the unique responses in each ecosystem. The variations of climate (e.g., temperature, humidity), soil (e.g., texture, structure, and the status of organic matter), plant (e.g., rice cultivar), management (e.g., tillage, time of fertiliser application, agricultural amendments) in different sites bring additional complexity when selecting the optimal AWD windows to sustain agricultural emissions. Further research studies focusing on site-specific parameters are important to make more realistic estimates from the application of AWD to mitigate paddy emissions.

4. CONCLUSIONS

This study examined AWD as a promising water-saving strategy for reducing CH_4 and N_2O emissions while sustaining rice yields compared to conventional CF paddy cultivation. Emissions of CH_4 and N_2O in wet and dry seasons in Sri Lanka and India were studied under country-specific supplemental variations while using measurements in a Japanese site for close observation of methane ebullition under CF conditions.

Sri Lankan experiments show that AWD treatment suppressed CH_4 emissions by about 32–43% without a significant statistical contrast ($p > 0.05$) in the crop yield. Plants were found to be responsible for emitting 70.3% of CH_4. Cumulative N_2O emissions, however, were raised by 7–23% due to the AWD treatment.

In Indian experimental sites, CH_4 emissions under the AWD treatment were 31–33% lower than the CF conditions. Plots supplemented with vermicompost exhibited significantly higher methane emissions, followed by the plots supplemented with regular fertiliser, as compared to the lowest emissions in control treatments.

The application of rice straw at the Japanese experimental site increased CH_4 emissions via ebullition in the heading stage. Methane emissions as ebullition accounted for 60% of total emissions during the heading stage. Total and ebullition CH_4 fluxes were lower at night and higher from the morning to early afternoon.

Overall, the results show that the AWD is a promising water management approach to reduce methane emissions, nearly 31–43%, from paddy fields while sustaining the crop yield. Care should be taken when supplements such as vermicompost or straw are introduced, as they can potentially enhance methane emissions.

Continuing research that puts further emphasis on specific parameters related to climate, soil, plant, and management is essential to making innovative strategies to optimise mitigation efforts from paddy ecosystems in Asian countries.

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Review

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Artificial recharge initiatives in India: Challenges and future scope

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ABSTRACT

Artificial recharge of aquifers is regarded as a fundamental supply-side strategy in India to address the prevalent issue of groundwater over-exploitation. Rainwater harvesting and artificial recharge are often implemented as cohesive sets of interventions because of the significant collateral benefits of rainwater harvesting. Central and state governments have implemented various schemes that incorporate rainwater harvesting and artificial recharge. Several studies are underway to investigate the optimal selection of construction sites, structural types, and designs based on local hydrogeology, groundwater flow patterns, terrain conditions, and water demand. These investigations aimed to assess the impact of these factors on resource replenishment and water quality enhancement. Studies have been conducted to determine the extent to which such initiatives yield socio-economic advantages. The discourse has encompassed crucial concerns, such as the accessibility of source water for recharge, conflicts between upstream and downstream stakeholders, and the increasing recognition of various demand-side measures for the sustainable administration of groundwater reservoirs. The paper highlights that there has been a rise in the number of studies regarding artificial recharge post-2020. Overall, this paper showcases the challenges for the implementation of artificial recharge structures with special focus on aspects such as site suitability, water quality concerns, operational problems and governance. The study also sheds light on the future scope of artificial recharge for the sustainable use of groundwater resources. More studies should be performed considering large-scale implications of artificial recharge structures considering resilience towards climate change and water quality and quality concerns.

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KEYWORDS GROUNDWATER RECHARGE, ARTIFICIAL RECHARGE, MANAGED AQUIFER RECHARGE, RAINWATER HARVESTING

HIGHLIGHTS

- The paper reviews the artificial recharge (AR) strategy of aquifers in India as a primary measure to combat the over-exploitation of groundwater.
- The review focuses on major issues: site suitability, water quality, post-construction challenges, and watershed-level impact assessment.
- The study focusses on the future scope and present development of artificial recharge for the sustainable use of groundwater resources.

1. INTRODUCTION

The expeditious and unregulated utilisation of groundwater has led to numerous challenges. The unrestrained exploitation of groundwater resources in various regions of the country has led to a depletion in groundwater levels and availability. Furthermore, the pristine quality of groundwater has been compromised. While the abundance of groundwater resources may appear ample at the state level, localised areas manifest adverse consequences from undue groundwater extraction. Artificial recharge mechanisms are employed to safeguard the sustainability of groundwater supplies. India's reliance on groundwater is unparalleled and highly significant in ensuring food and potable water security. According to recent estimations by the Indian Government, the nation extracted 248.7 km^3 of water from its aquifers in 2017. This quantity is the world's highest, exceeding the collective extraction of the United States and China (Saha et al., 2018). According to recent studies conducted by Malakar et al. (2021) and Singh et al. (2019), approximately 17% of the assessment units in India are characterised by over-exploitation, which occurs when the annual extraction of water surpasses the amount that is replenished to aquifers. The number of wells utilised for irrigation in the country increased from 62 lakh in 1986–87 to 205 lakh in the period of 2013–14. The extensive exploitation of groundwater has significantly reduced water levels and exhausted groundwater reserves in numerous regions in India (Saha et al., 2018). Rodell et al. (2009) conducted an international study utilising GRACE Tellus satellite data to evaluate the depletion of groundwater in the northwestern region of India, encompassing the states of western Uttar Pradesh, Haryana, and Punjab, as well as the adjacent Punjab province of Pakistan. According to Saha et al. (2018), most of the total extractions are attributed to irrigation, accounting for over 90%. Asoka et al. (2017) contended that the escalation in groundwater extraction in the nation could be attributed to the surge in demand and the irregularity of precipitation patterns resulting from climate change. The depletion of this crucial resource has necessitated the development of groundwater resilience by implementing strategies such as enhanced recharge and reduced extraction via water demand management. Such interventions are imperative for the preservation of Indian agriculture and the security of drinking water (Alam et al., 2020).

Artificial recharge has gained global recognition as a significant measure for enhancing groundwater reserves. The above-mentioned process augments the infiltration capacity by accelerating the infiltration rates or extending the source water's temporal availability. The primary water source for recharge is precipitation, specifically rainwater collected from surface runoff. Alternatively, they may also be sourced from canals or treated wastewater. The supplementary recharge process contributes to the overall availability of groundwater in both spatial and temporal dimensions. According to Scanlon et al. (2006), the natural recharge process is characterised by a slow rate. It typically ranges between 0.15 and 5% of the long-term average yearly precipitation worldwide in arid and semi-arid regions. Regions such as the Indus-Ganga-Brahmaputra plains exhibit a greater replenishment rate primarily due to increased rainfall, improved permeability, and enhanced aquifer storage potential (Bhanja et al., 2019). Empirical data suggests that adopting flood irrigation-based agricultural practices has increased natural recharge.

Nonetheless, these regions frequently exhibit a reduction in water levels due to unfettered agricultural groundwater extraction (Scanlon et al., 2006). This study aims to comprehensively analyse the existing literature, executed projects, relevant policies, and other pertinent documents pertaining to diverse facets of India's artificial recharge, its challenges and future scope. This study will help assess the past developments in artificial recharge and how the technology has advanced, integrating the multifunctional aspects of watersheds for overall ecosystem development.

1.1. Trends in the development of artificial recharge in India

The escalating significance of the artificial recharge may be ascribed to the mounting withdrawal of water from the aquifers and, therefore, has been categorised into four distinct phases within the Indian context. Phase I pertains to the period preceding the mid-1960s when groundwater use was restricted. Indigenous communities were engaged in conventional water-harvesting methods funded or endorsed by regional monarchs or affluent individuals. Phase II, from the mid-1960s to 1990, was characterised by a significant surge in the utilisation of groundwater for various purposes such as irrigation, domestic and industrial applications. The fundamental cause of the increase in overexploitation may be traced to the development of cost-effective drilling and pumping technology and the government's supply of energy subsidies to customers (Saha et al., 2022). During this time, there was growing recognition of the significance of replenishing aquifers, which was subsequently incorporated into policy documentation. In 1987, the National Water Policy was framed, the first document that recognised water as a resource of national importance that requires perspective for management (Geethanjali & Rao, 2021). The period from 1990 to 2010, commonly referred to as Phase III, was characterised by a significant surge in the rate of groundwater extraction. Recently, there has been a substantial increase in the exploitation of groundwater resources, leading to the depletion of water levels and a decline in water quality across India (Saha et al., 2022).

In recent years, there has been a notable escalation in attention toward artificial recharge. Governmental bodies have undertaken pilot studies on artificial recharge to underscore its efficacy, enhance public awareness and foster proficiency within the populace. The impetus behind the government's emphasis on promoting artificial recharge infrastructures stems from the heightened strain on India's groundwater resources, as evidenced by the data presented in Table 1 and Figure 1, which is particularly prevalent in various regions across the country. The Indian government launched the National Watershed Development Programme in 1987 to optimise the utilisation of natural and social capital such as land, water, vegetation, livestock, and human resources (Sikka et al., 2014). Over time, these programs have increasingly prioritised artificial recharge to enhance groundwater levels and agricultural productivity. Several state governments have implemented water conservation programs, such as Mission Kakatia of Telangana, which aims to clean and remove silt from numerous tanks, thereby revitalising aquifers (Shah & Verma, 2018). Government agencies recognise the importance of sensitising, including society, the implementation and maintenance of artificial recharge structures, as noted by Shah et al. (1998). The central and state governments established groundwater authorities intended to regulate groundwater extraction. Singh et al. (2019) reported that the authorities had placed significant emphasis on the mandatory requirement of artificial recharge for issuing no-objection certificates (NOCs) for extracting groundwater to various sectors, including industrial units, infrastructure development projects, and mines. Lastly, phase IV denotes the time following 2012, as in this period, a notable transformation in attitude, strategy, and implementation towards addressing overexploitation was observed, wherein the government now accords equal emphasis to measures targeting both the supply and demand sides (Saha et al., 2022).

TABLE 1. Annual groundwater recharge and extraction for India (CGWB, 2022).

1.	Total Annual Ground Water Recharge	437.60 km^3
2.	Annual Extractable Ground Water Resources	398.08 km^3
3.	Annual Ground Water Extraction	239.16 km^3
4.	Stage of Ground Water Extraction	60.08%

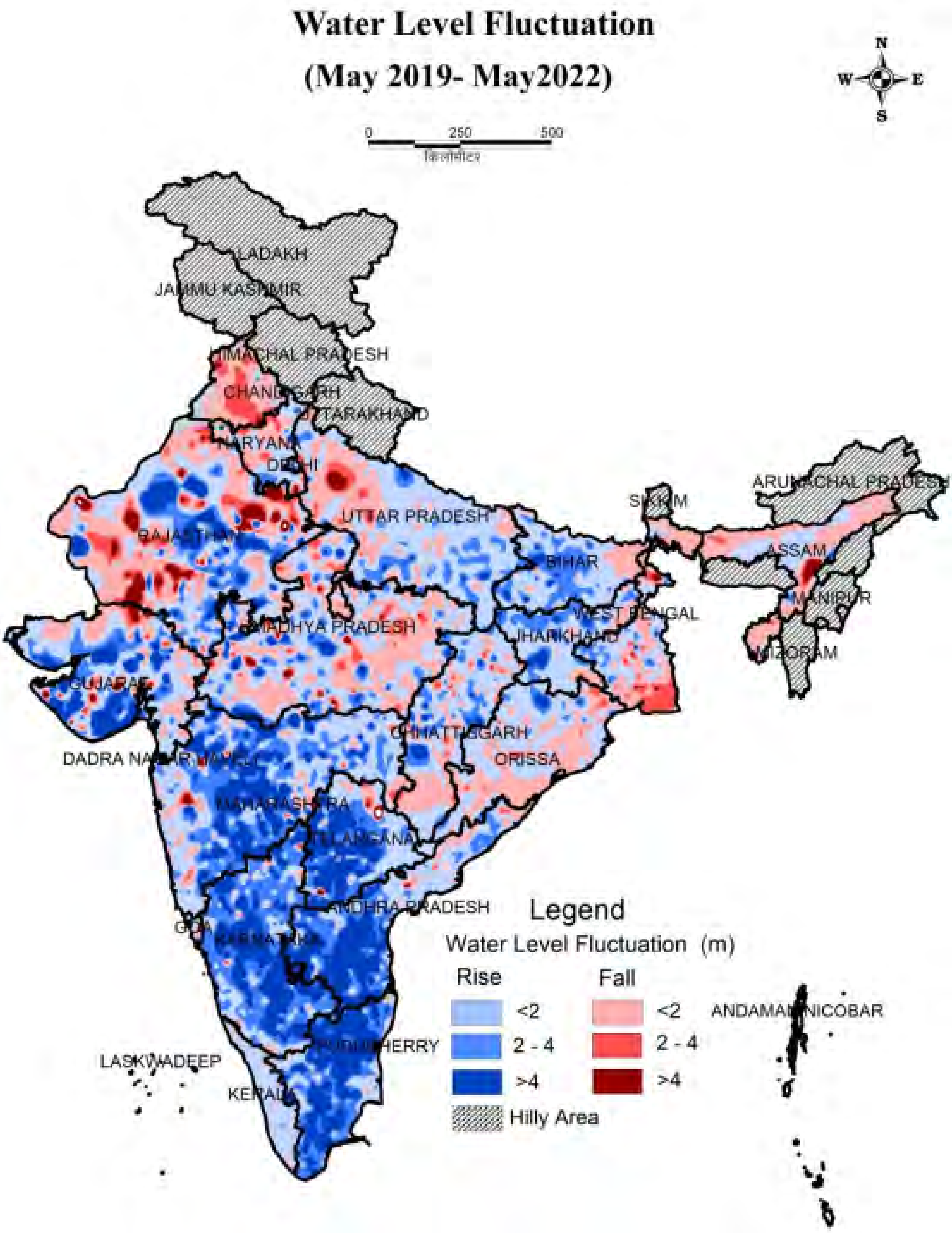

FIGURE 1. Water level fluctuation for India for the period 2019 to 2022 (CGWB, 2022).

The Central Ground Water Board (CGWB) launched the National Aquifer Mapping and Management Program (NAQUIM) in 2012, which aimed to map an area of 25.9 lakh km² that is hydrogeologically mappable to promote the sustainable management of groundwater resources (Saha & Ray, 2019). The primary aim of NAQUIM is to create a three-dimensional representation of aquifers and to develop a thorough understanding of their geometry, hydraulic properties, resource availability and chemical quality of groundwater in a specific aquifer setting. The program's output will aid in delineating appropriate regions that can be utilised for agricultural reclamation, determining the optimal structures to be implemented and specifying their designs. Apart from CGWB's initiatives, other Government of India schemes have primarily focused on water conservation practices. These schemes are namely Catch the Rain campaign (National Water Mission's campaign initiated by Ministry of Jal Shakti, Government of India), Jal Jeevan Mission (JJM) (an initiative of Ministry of Jal Shakti, Government of India) and Mission Amrit Sarovar (an initiative of Ministry of Rural Development, Government of India). These government initiatives primarily create awareness among the masses to conserve water and provide the rural population with access to clean and safe drinking water. There has been a significant increase in studies related to artificial recharge and rainwater harvesting. A rainwater harvesting system is one method of diversifying water resources and increasing water security (Marlow et al., 2013). Rainwater harvesting systems in cities and urban areas can contribute to mitigating the environmental impact of buildings and towns. Additionally, they can enhance urban sustainability and help alleviate water stress caused by over-extraction in urban areas (de Sá Silva et al., 2022). A rainwater harvesting system for urban areas includes capturing and storing rainwater while preventing runoff, including collecting, storing, treating and distributing rainwater from roofs, terraces and other impermeable surfaces to be used on-site (Campisano et al., 2017; Lee et al., 2016). Figure 2 shows the number of research articles published from 2008 to 2022, indicating a substantial surge in artificial recharge-related studies from 2020 onwards. Figure 3 depicts the overall approach followed in this paper for selecting and reviewing the most relevant research papers on artificial recharge.

2. RESEARCH, REPORTS, AND DOCUMENTS ON ARTIFICIAL RECHARGE

The literature on aquifer recharge can be broadly classified into three categories: (i) site suitability for artificial recharge, (ii) water quality concerns for artificial recharge, (iii) operational problems and challenges, and (iv) impact assessment of recharge structures. Figure 4 shows the co-occurrence of keywords from articles published from 2017 to 2022. For this diagram, 311 papers were filtered on Scopus with primary search keywords such as "rainwater harvesting", "aquifer recharge" and "India", with a publication year limit from 2017 to 2022. The duration from 2017 to 2022 was selected to understand the recent trends in research as the number of research publications on artificial recharge has increased significantly from 2020 onwards. The keywords in Figure 4 indicate the dominance of rainwater harvesting, groundwater, groundwater quality, remote sensing, geographical information systems (GIS), climate change and aquifer properties. Further, a few studies also focussed on groundwater vulnerability, sustainability, water scarcity, water productivity and mitigation. However, the consideration of socio-economic aspects, indigenous knowledge about artificial recharge and multi-use services has been lacking.

2.1. Site suitability for artificial recharge

The Central Ground Water Board (CGWB) has formulated a comprehensive plan for artificial recharge (CGWB, 2007) covering the entire nation. The project identified an area of 0.9415×10^5 km^2 appropriate for artificial groundwater recharge. The plan was formulated considering various factors such as the type and characteristics of aquifers, the decadal average of post-monsoon water levels and the ease of access to non-committed surface water sources. As per the Master Plan, a total of 111 lakh structures of various types, such as recharge shafts and wells, check dams, contour bunds, and sub-surface dykes, can facilitate the recharge and storage of approximately 85.6 km^3 of water. These structures are designed to be compatible with local hydrogeology and groundwater regimes. The assessment of these structures in terms of their site suitability has also been done in the past. Anbazhagan and Ramasamy (1997) used geophysical surveys, such as electrical resistivity and water level maps, to identify fractures and determine appropriate locations for aquifer recharge in the hard-rock regions of Tamil Nadu.

The fractures were overlaid onto groundwater level maps to demarcate suitable sites for aquifer recharge. Further, Wada et al. (2012) applied quantitative morphometry and hydrogeological analysis to identify suitable locations for artificial recharge in the Almorah region of Uttarakhand. Using remote sensing data in conjunction with geoinformatics analysis can evaluate the magnitude of runoff and site selection in diverse terrains encompassing soft and hard rock regions (Sharma & Thakur, 2007). Sahu et al. (2022) employed hydrogeological, geospatial and multi-criteria decision analysis methodologies in their research to identify groundwater recharge potential zones and appropriate recharge structures for the Tapi River basin in north Maharashtra. Moharir et al. (2023) recently employed GIS and Analytical Hierarchy Process (AHP) methodologies to identify potential

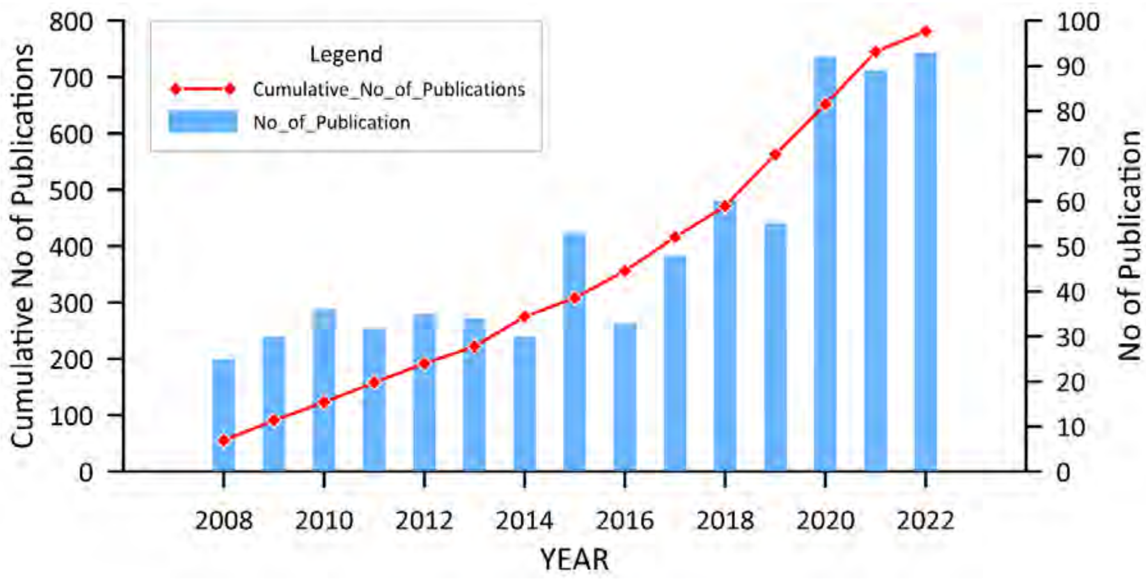

FIGURE 2. The number of peer-reviewed publications on artificial recharge year-wise for the period 2008–2022.

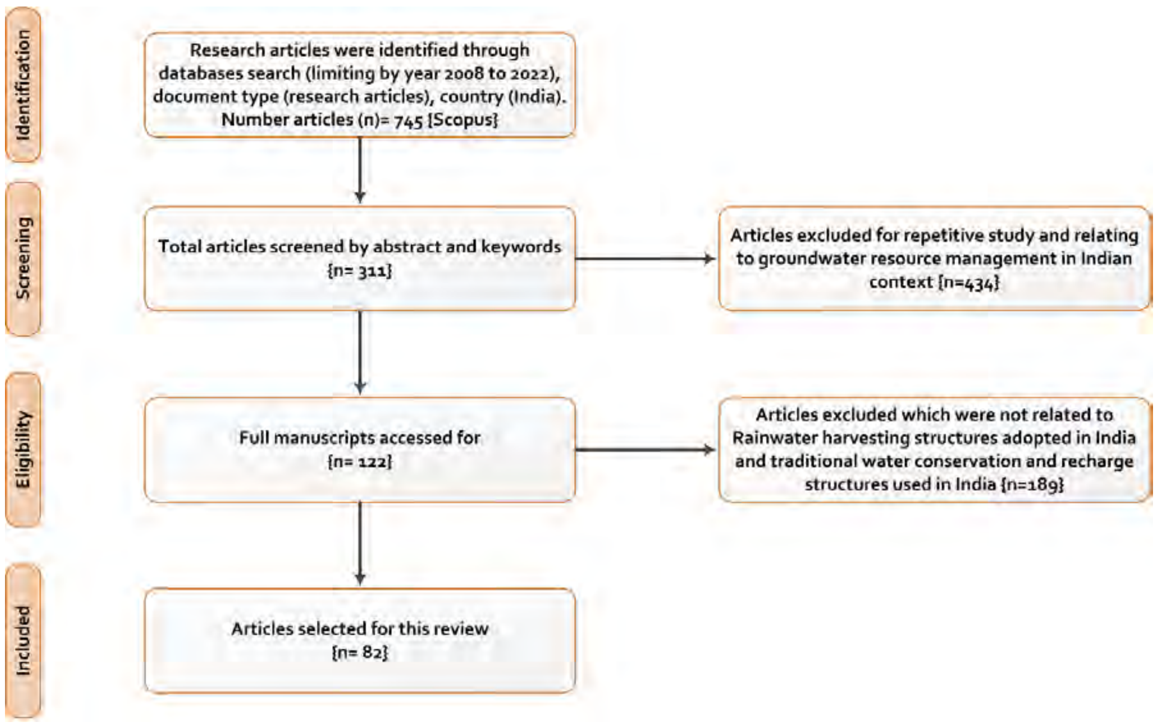

FIGURE 3. Flowchart reflecting the methodology of screening the papers used for the review.

groundwater zones in the Damoh region in Central India. They employed geology, geomorphology, slope, aspect, drainage density, lineament density, topographic wetness index, topographic roughness index and land use land cover to identify possible groundwater zones. These zones are critical in developing the groundwater table by building artificial recharge structures. Rawat et al. (2023) used a GIS and Multi-Criteria Decision Analysis (GIS-MCDA) approach to create rainwater harvesting (RWH) suitability maps in Rajasthan. According to their findings, 3.6%, 8.2% and 27.3% of their study area were highly, partly and inappropriate for rainwater harvesting structure implementation, respectively. A Google Earth Engine and Multi-Criteria Decision Analysis (GEE-MCDA) tool for site suitability mapping of managed aquifer recharge (MAR) structures was tested for the Ganga-Yamuna doab region, India. The tools found 82% of the area under suitable, 12% very suitable and 5% moderately suitable

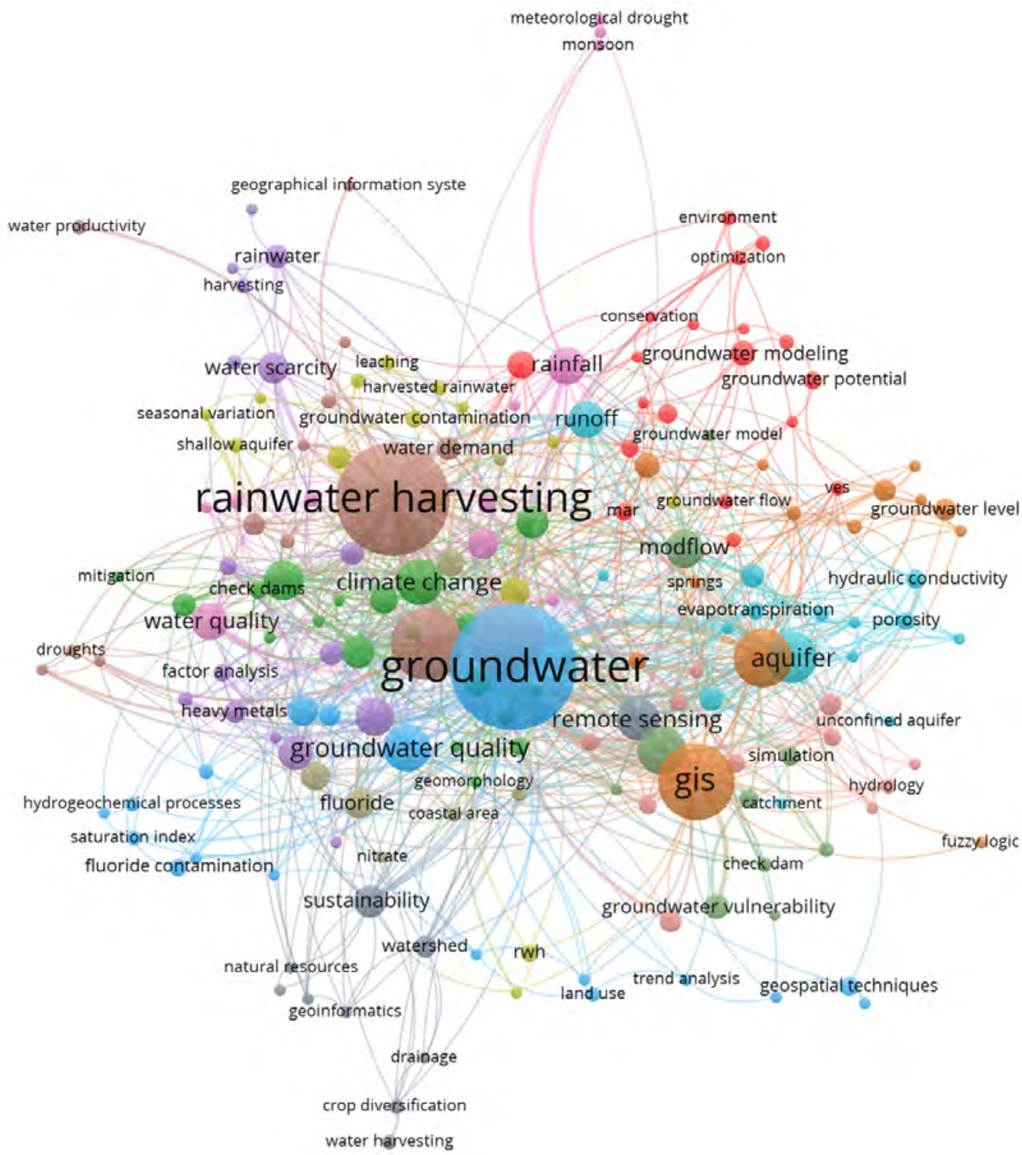

FIGURE 4. Representation of the keywords used across the paper considered for this review for the period 2017–2022.

(Patidar et al., 2023). This tool is an important contribution for site suitability mapping for artificial recharge structures.

Mondal and Singh (2004) introduced a technique that employs cross-correlation between the increase in water levels following the monsoon and precipitation to identify suitable locations for aquifer recharge in hard rock terrain with unconfined aquifers. Dinesh Kumar et al. (2008) adopted environmental isotopes (^{3}H and ^{18}O) in combination with water level and hydrogeological methods to demarcate the appropriate regions for aquifer recharge in the urban area of Delhi. A small watershed in a granitic terrain in Peninsular India was examined and the area was found to have experienced significant exploitation. The study concluded that defunct dug wells are the most suitable structures for recharge purposes in the area, despite their deep-water level, due to their technical feasibility and cost-effectiveness (Sreedevi et al., 2013). The study conducted by Narjary et al. (2014) examined the phenomenon of decreasing water levels and emphasised the significance of groundwater recharge in Haryana. A rise in water level ranging from 2.3 to 3.16 m was reported in the Karnal district during 2009–2010 due to anthropogenic activities. Further, Islam and Talukdar (2016) suggested integrating groundwater recharge and rainwater harvesting could be implemented in urban water supply systems.

Several other approaches have also been used to assess the site suitability such as Samadder et al.

(2011) identified the paleochannels in the West Ganga and used the Tritium Tagging technique to ascertain the natural recharge of groundwater in paleochannel regions, which was found to be between 19–29% of annual precipitation. In contrast, the floodplain area exhibited a recharge rate of only 6–9%. Comparable isotopic and hydrochemical methods were employed to identify appropriate locations for artificial recharge interventions in hard rock regions that are characterised by diminishing groundwater resources. In a study conducted by Saha et al. (2014), various methods, such as electrical conductivity, chloride, heavy oxygen isotopes and deuterium, were employed to determine the paths of aquifer recharge. These methods were combined with hydrogeological sections to identify lineaments where sufficient groundwater can be collected by artificial recharge in granitic aquifers in urban areas of Ranchi, Jharkhand. A three-dimensional mathematical model was formulated to simulate transitory groundwater flow in a multi-aquifer system. The system included a lower constricted aquifer that was replenished through the implementation of rooftop runoff management systems. Subsequently, the model was used to evaluate the operational effectiveness of the artificial recharge systems across varying recharge and extraction capacities (Islam & Talukdar, 2016).

2.2. Water quality issues for artificial recharge

The general opinion among scholars is that the implementation of artificial recharge positively impacts groundwater quality. However, there are also documented instances in which the interaction between percolating water and rock formations compromises the chemical quality of aquifers. Attention has been drawn towards the qualitative aspect of water being recharged and the degree of enhancement of its quality as it traverses the unsaturated layer before its integration with the water table.

In India, various guidelines on water quality for irrigation and drinking purposes are available. These include the Bureau of Indian Standards (BIS) guidelines for drinking water (IS 10500, 1993) and guidelines on quality for irrigation water (IS 11624, 2019). In addition to its other functions, the Central Pollution Control Board (CPCB) has established standards for monitoring protocol for water quality (CPCB, 2007) and the safeguarding of wellheads during the construction of wells for drinking water. To date, there has been a lack of established guidelines on the qualitative aspect of the water being recharged or the susceptibility of the aquifer concerning recharge. However, the CGWB has formulated and disseminated specific standards for source water quality and issued relevant advisories (CGWB, 2007; Singh et al., 2019). Dillon et al. (2014) have introduced a methodology known as the "viability assessment" to address water quality concerns in MAR. This approach comprises four distinct stages: (a) planned utilisation of water resources, (b) the origin of water supply and entitlement to its use, (c) hydrogeological attributes of the area, and (d) capacity for water retention and purification. According to their results, doing a sanitary study before beginning any construction activities is critical to detect possible risks and hazardous occurrences within the catchment's boundaries. Therefore, an aquifer assessment that encompasses developing and implementing a secure recharge facility is imperative. Additionally, they suggested implementing preventative measures, adopting corrective actions and formulating a proposed plan for water safety.

Several regions in India have been reported to enhance water quality by implementing artificial recharge methods. According to Stiefel et al. (2009), significant enhancements in sulphate concentration and electrical conductivity were observed during the post-artificial recharge construction period in arid regions of Rajasthan. Kumar et al. (2009) investigated a basaltic aquifer in Maharashtra using isotopes such as $\delta^{18}O$, ^{3}H and δD. According to the researchers, the chemical nature of the groundwater inside the watershed changed favourably. Saharawat et al. (2011) investigated the recharging mechanism and ensuing revival of an alluvial aquifer holding salty groundwater in northwestern India's semi-arid area. According to their report, the salinity of pumped-out water was found to be lower after recharge. The increase in potassium and borate concentrations can be attributed to their liberation from clay minerals, which persist in the adsorbed state. The occurrence described by Brindha et al. (2016) has been documented in Nalgonda, Telangana, the Pombar River, and the Vaniyar River basin of Tamil Nadu. As per their assertions, the hydrogeological aspects must be considered before implementing AR in a region affected by fluoride. Additionally, continuous surveillance of fluoride levels in groundwater is recommended.

According to Gowrisankar et al. (2017), constructing a check dam in the Krishnagiri area of

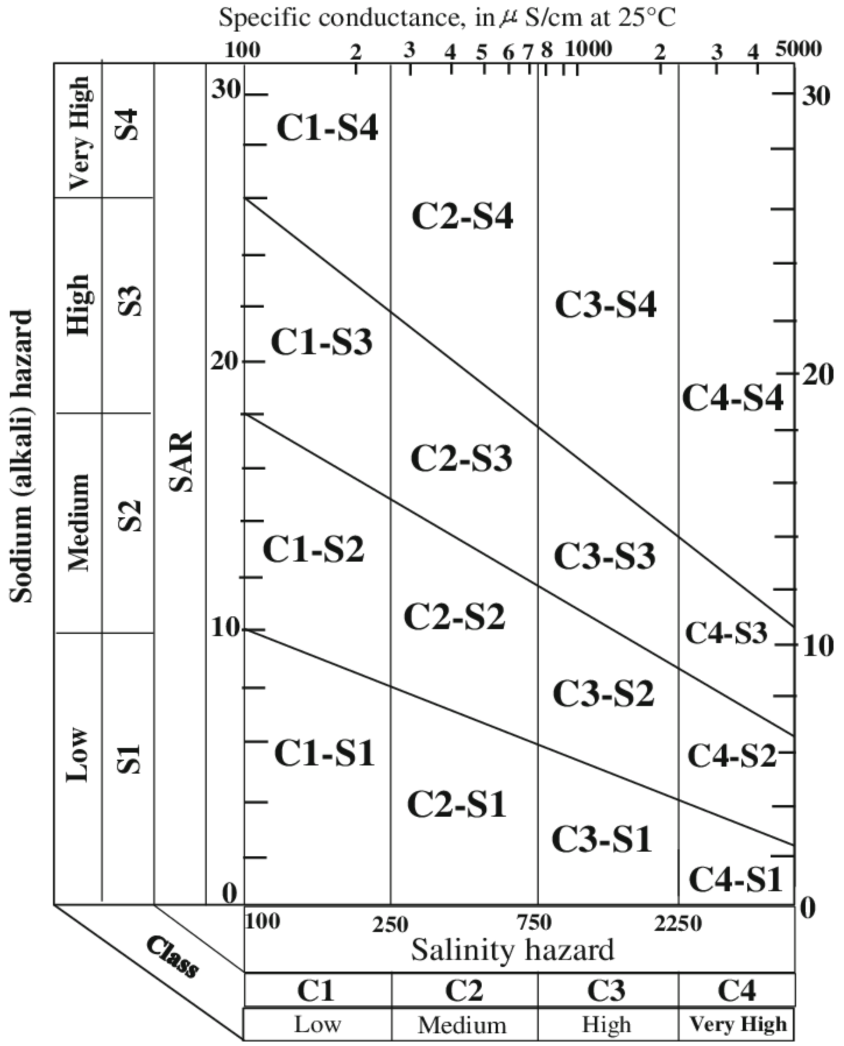

FIGURE 5. United States Salinity Laboratory classification of irrigation waters (USSL, 1954).

Tamil Nadu led to a significant reduction in groundwater fluoride concentration in downstream regions due to the dilution of freshwater recharge. Similarly, Satheeshkumar et al. (2017) observed a comparable improvement in the Vaniyar sub-basin in Tamil Nadu. Thangamani et al. (2017) conducted a study to assess the effects of a check dam on the Amaravathi basin. The study found that the water quality had improved with reference to the U.S. Salinity Laboratory (USSL) classes (Figure 5), which are based on salinity and sodium hazards. Specifically, this study observed an improvement from C2S2 to C2S1 classes. The sodium hazards classification (C) and SAR classification (S) are shown in Table 2. Kalpana et al. (2019) studied the Pamber River basin and identified two distinct impacts. The first impact was observed at a shallow depth less than 20 m below the ground, where fluoride concentration was diluted and reduced. The second impact was observed at a greater depth, up to 90 m (bgl), where the fluoride concentration increased. This increase was attributed to the flushing of fluoride-rich salt, which accumulated in the vadose zone during the recharge process.

Artificial recharge has also been identified as a viable solution for addressing seawater intrusion in coastal aquifers that results from freshwater pumping. In a study by Hollingham (2002), Hubli and Dharwad city in Karnataka was examined, revealing an estimated leakage of 20.5 gigaliters per year (Gl/year) and a 15–24 Gl/year recharge. The seepage has contributed to an elevation in the water table and enhanced the aqueous composition. Nair et al. (2013) examined the chlorine and bromine ratio in the subsurface water of the coastline aquifer in Chennai's northern area. This investigation discovered salty water incursion up to 10 km inland. Installing a check dam resulted in an additional 37% recharge, proving its effectiveness in preventing salty water permeation. As

TABLE 2. Classification system for Salinity Hazards and Sodium Hazards (Rashidi, 2012; USDA).

Salinity hazard class	Range (μS/ cm)	Quality remark	Sodium hazard class	Range (meq/L)	Quality remark
C1	<250	Low	S1	0–10	Excellent (little or no hazard)
C2	250–750	Medium	S2	10–18	Good (appreciable hazard but can be used with appropriate management)
C3	750–2250	High	S3	18–26	Doubtful (unsatisfactory for most crops)
C4	>2250	Very high	S4	>26	Unsuitable (unsatisfactory for all crops)

previously stated, using treated wastewater for agricultural reuse is currently not feasible. The study conducted by Nijhawan et al. (2013) pertained to the opinions of professionals in some areas of Central India regarding the utilisation of treated municipal wastewater for agricultural purposes. This study focused on the efficacy of soil water treatment (SWT) in enhancing water quality. Approximately 64% of those surveyed agreed favourably using processed wastewater for agricultural irrigation, whereas 28% held an opposing viewpoint. Despite undergoing secondary treatment, half of the respondents expressed reservations regarding the quality of the source water (wastewater) before its introduction into the aquifer. In numerous urban areas, unintended recharge is prevalent owing to water supply pipeline leakage. According to the research conducted by Saha et al. (2018), leakage from domestic pipes has neutralised groundwater abstraction and maintained the groundwater level within the shallow, unconfined aquifer of Patna, Bihar.

2.3. Operational problems and challenges

Recharge structures have a connection with a variety of operational issues and challenges that frequently impede their long-term operation. These issues frequently result in the conceptual failure of artificial recharge systems' applicability in certain scenarios. Clogging is one of the most serious issues with artificial recharge structures. There are four forms of clogging: physical clogging, chemical clogging, biological clogging and mechanical clogging.

Physical clogging is the most common kind of congestion and it is produced by the deposition of aquifer sediments as well as organic and inorganic suspended particles in source water (Du Xinqiang et al., 2009; Youngs et al., 2009). In general, it is believed that the smaller the pore size of the permeating soil, the higher the quantity of suspended solids, and the larger the size of suspended solids, the easier the clogging occurs. Whereas the higher the infiltration rate, the smaller the size of suspended solids and the thicker the clogging layer (Skolasińska, 2006; Shan et al., 2013). An aquifer is a symbiotic habitat made up of physical, chemical and biological factors that serve as an antagonist to the chemical composition of groundwater. The recharged water surges dramatically into the aquifer, altering the initial balance of water-rock interaction. As a result, dissolution, precipitation and other reaction mechanisms may cause alterations to water quality as well as aquifer permeability, complicating chemical clogging as it depends on various factors (Zhang et al., 2020). Biological clogging appears to be the second most important mechanism that clogs wells (Oberdorfer & Peterson, 1985). Microbial communities, including bacteria and algae, typically make up the majority of the biological species found in source water and under ambient conditions and these microorganisms can proliferate quickly throughout the recharge process (Zhang et al., 2020). Mechanical clogging, also known as gas bubbles, is created by the flow of water inside the recharge well casing or by air entering the recharge pipe network under negative pressure. This entrapped air raises the oxidation-reduction potential (ORP) and encourages microbial activity and geochemical processes, which leads to additional blockage (Beckwith & Baird, 2001; Heilweil et al., 2004).

2.4. Governance of artificial recharge

Water resources management and environment protection authorities need to be aware of the advantages and disadvantages of MAR in order to guarantee that it continues to produce the intended benefits and prevent excessive piezometric pressures or waterlogging, failure during drought, and contamination of aquifers (Dillon et al., 2019). The best method to control this is to establish well-founded regulations and procedures that guarantee MAR is carried out in a manner that safeguards groundwater conditions and the needs of its receptors, including the surrounding ecosystem. The Indian government has produced a handbook on artificial recharge (CGWB, 2007), which outlines the procedures for designing, planning, monitoring water quality and levels, and assessing the financial viability of augmenting recharge through streambed recharge structures and urban rainwater collection. Based on the UN Water Safety Planning approach, a water quality guide for natural water sources in India was created, and it can be used based on trained villagers' visual observations (Dillon et al., 2014). In order to guarantee efficient operations and to produce the data necessary to support future adoption of MAR, including research and governance, it is essential to monitor current operations and keep up a public repository of site information, reports and statistics.

2.5. Impact assessment of recharge structures

A pertinent demand in examining the influence of artificial recharge pertains to the appropriate level to evaluate its impact on groundwater resources. The use of remote sensing data is a prevalent technique employed for impact assessment. This tool has the potential to facilitate the examination of the expansion of crop acreage and irrigation coverage as well as enhancements in soil moisture. Using the tritium tagging method, Israil et al. (2006) established a correlation between recharge and the resistivity of the upper unsaturated layer of the Himalayan foothills. The researchers concluded that this particular correlation could serve as a means to evaluate the pace of replenishment in comparable regions. For sustainable development of groundwater resources, Becker (2006) explored the use of diverse remote sensing methodologies to evaluate the influence of different recharge structures such as check dams, recharge shafts and recharge borewells on groundwater recharge and suggested that artificial recharge is a viable solution. Chinnasamy et al. (2015) utilised GRACE Tellus satellite datasets to evaluate the recharge potential of Rajasthan and determined that the state exhibits significant potential for recharge. Further comprehensive investigations are required to determine the appropriate recharge methods and their optimal design and to identify precise locations. According to Thiyagarajan et al. (2020), the water storage and recharge potential of RWH structures can be evaluated using satellite data. The utilisation of this method is not limited to small-scale applications because it possesses the benefit of high temporal resolution, rendering it suitable for large-scale areas.

Water level increase is recognised as an essential indicator for measuring the effects of recharge. Rainwater harvesting with runoff preserving barriers (gully plugs, rockfill dams, check dams and bench trenching) is primarily intended to slow or hold back flowing water (subsurface dams and contour trenching) and penetrate (percolation tank) into the subterranean (Raju et al., 2006). The performance of ten recharge wells, each 24 to 30 m deep, built in a previously operating village pond in the Ramganga basin was investigated. During their three-year study, they discovered that volumes ranging from 26,000 to 62,000 m^3 were restored annually over a period of 62 to 85 days. Average recharge rates ranged from 164 to 295 mm/day, with a total recharge rate of 221 mm/day (Alam et al., 2020).

Raju et al. (2006) investigated sub-surface dams built over the Swarnamukhi River. The investigation concluded that the average post-monsoon rise was 1.44 m, and the pre-monsoon rise was 1.80 m. The construction of these underground dams in the Swarnamukhi River watershed enhanced groundwater storage, increasing land productivity. In their study, Parimalarenganayaki and Elango (2015) highlighted that a check dam is an effective MAR method for improving groundwater recharge. They found that the water stored in the check dams increased groundwater level from 1 to 3.5 m until about 2 km. Abraham and Mohan (2019) reported a 4.7 m increase in the water table during the operational period of check dams in Tamil Nadu, compared to an average 1.5 m rise in the water table over the rainy season. The results show that the investigated check dams effectively and efficiently recharge the local aquifer. Dashora et al. (2018) recently investigated the recharge performance of four check dams in the Dharta watershed of the Aravali Hills in the Udaipur region of Rajasthan from 2014 to 2015. The average annual recharge volume was calculated to be 0.7 million m^3, which supported 16% of agricultural production from the neighbouring communities during the rabi season. In 2014 and 2015, total recharge was 37% and 70%

of combined runoff, respectively. Further, Dashora et al. (2019) monitored the recharge estimation of four check dams by daily water balance method for three years (2014–2016) and found the mean annual recharge to be 779,000 m³.

Massuel et al. (2014) used a comprehensive method integrating water accounting, geochemistry and hydrodynamic modelling to investigate the ability of a conventional percolation tank to replenish the aquifer. Over the course of two years, the tank's percolation efficiency varied from 57% to 63%. Abraham and Mohan (2015) investigated the efficiency of recharge structures such as check dams and percolation ponds with percolation wells in improving the recharge process in a Tamil Nadu watershed. They discovered an average increase in water level of 2 to 3 m in locations around individual recharge infrastructure. In contrast, after two years of artificial recharge, the groundwater level increased by roughly 5 m in the region encompassing the combined recharge structures. Yadav et al. (2022) observed that shallow infiltration ponds known as Chaukas may recharge groundwater while boosting soil moisture in Rajasthan. They developed a model using HYDRUS-1D to assess prospective groundwater recharge, and it was discovered that 5% of the precipitation depth had recharged directly into the groundwater. Besides the recharge, the study revealed that the greater soil moisture allowed naturally occurring grass cover to grow, which the locals could utilise as pastureland.

Artificial recharge structures should be planned and conducted on a watershed or sub-basin scale, and their effects should be evaluated. Most artificial recharge structures built in a small region are standalone or, at best, few in number, and local-scale hydrological effects are the main focus of impact analyses. Such impact evaluations do not account for trade-offs between upstream and downstream stakeholders in the watershed or sub-basin (Sharda et al., 2006). Duraiswami et al. (2016) stressed the importance of impact analyses considering hydrogeology, hydrology and ecology. Such studies are challenging because of the regional variability of many characteristics and the need for long-term data generation.

Sakthivadivel and Scott (2005) studied the conflict between upstream and downstream water users. The study found that the construction of numerous recharge structures in the upstream portion of the catchment significantly impacted the reservoir that supplies water to Rajkot Town in Gujarat. Pathak et al. (2013) found a similar impact in an eastern Rajasthan watershed, where increasing water availability boosted the average irrigation area per dug well from 0.5 to 1.4 hectares during the Rabi season. Kumari et al. (2014) evaluated the effects of ten structures on the Parasai-Sind catchment in Uttar Pradesh's Buldelkhand region, which covers 1246 hectares. Following implementation, it was observed that the net recharge experienced a notable increase of 71.8%, and there was also a significant improvement in the well yield. The provision of recharged water ensured irrigation for the Rabi season across the entirety of the treated area within the watershed. Chatterjee et al. (2018) drew attention to the significant depletion of groundwater resources in the Baswa-Bandikui watershed in Rajasthan. The authors emphasised the need for immediate action to prevent further degradation of this vital resource.

The evaluation of the effects of artificial recharge necessitates meticulous consideration of climate change variables. Implementing artificial recharge in the Arvari River basin of Rajasthan has increased the flow. Glendenning and Vervoort (2011) discussed the potential influence of increased rainfall during this period on the observed increase in flow. Using digital remote sensing data on a GIS platform for modelling a watershed presents a more cost-effective and expeditious alternative to estimating the hydrological impact at a watershed scale through field monitoring. The utilisation of this approach is of significant value in the evaluation of the influence of artificial recharge on streamflow and the amount of runoff that can be accumulated by rainwater harvesting. This approach is more appropriate for assessing the impact of surface water than groundwater, especially in the case of anisotropic hard rock aquifers. The Gaiwel watershed of Andhra Pradesh was studied by Perrin et al. (2012) using the Soil Water Assessment Tool (SWAT) model. This study aims to calibrate runoff volumes and storage in 29 percolation tanks. Their observations show tanks contributed 23% of the total annual recharge during a typical monsoon year. Additionally, it was observed that implementing additional construction of structures was deemed impractical because of the potential impact of diminished runoff on the surrounding downstream regions.

3. FUTURE SCOPE IN THE DIRECTION OF AQUIFER RECHARGE

Much progress has been observed in the design, operation, and maintenance of artificial recharge strategies. However, further scope for improvement should be explored for large-scale adaptation and improving resiliency considering climate change. In the context of groundwater recharge, it is significant to understand the sensitivity of hydrological processes to climate variability in the region (Kumar et al., 2020). Future studies can build upon using more advanced modelling techniques and machine learning to improve the understanding of complex hydrological processes governing groundwater recharge. Sahu et al. (2022) suggested that identifying potential groundwater recharge sites can be combined with socio-economic data to assess the feasibility and sustainability of the recommended recharge structures. Yadav et al. (2022) recommended combining the Chauka system with other RWH techniques to maximise groundwater recharge and increase the availability of water resources in water-scarce regions. They also suggested investigating the economic and social benefits of the artificial recharge structure on the local communities. Laskar (2022) recommended integrating traditional RWH with modern RWH, such as injection wells, storage reservoirs and subsurface barriers, to increase artificial recharge's contribution to a sustainable environment for agricultural production. The International Groundwater Resources Assessment Center's (IGRAC) current efforts to create a global inventory of MAR assist in locating MAR locations that are both typologically and geographically close together (Stefan & Ansems, 2018). These initiatives should be supported as they are leaders in the field of big data analytics applied to artificial recharge. It is also anticipated that management based on artificial intelligence would be included in the artificial recharge process as a whole. According to Zhang et al. (2020), there is a need to encourage the use of artificial intelligence and big data analytics techniques in order to produce outcomes that are supported by evidence and can be used with confidence in artificial recharge planning and execution.

Most publications have evaluated the effects on a local scale, specifically the influence of an independent structure. Most of the research works considered in this study employed specific parameters to evaluate the situation, including the increase in water level, the extent of the area that received benefits, quantification of recharge volume, and determination of the proportion of this volume accessible for subsequent irrigation purposes. Nonetheless, there is a paucity of research data on the effects of multiple and dispersed structures at a watershed or sub-basin scale. To conduct a comprehensive evaluation of a watershed or sub-basin, researchers must conduct long-term observations of various factors such as land use and land cover, climatic conditions, depth to water level, variations in groundwater quality, groundwater flow patterns and hydraulic properties of the aquifer, among other variables.

4. CONCLUSION

The increasing reliance on groundwater has resulted in an increase in aquifer strain. The present worldwide groundwater footprint is projected to be 3.5 times greater than the aquifers' physical area. Furthermore, around 1.7 billion people live in areas where groundwater resources are depleted and/or groundwater-dependent ecosystems are threatened. A similar impact on groundwater supplies has been reported in northwest India. Numerous research has indicated that aquifers within the nation are rapidly diminishing, particularly in regions characterised by dry climates. Artificial recharge is widely recognised as the primary measure for augmenting groundwater resources. However, it is worth considering whether such interventions to increase the groundwater supply are sufficient to promote sustainable resource utilisation. The arid and semi-arid areas face limitations in terms of artificial recharge and rainwater harvesting because of the scarcity of water for recharge. This review highlights the various trends, challenges and the future scope of artificial recharge in the Indian context. A brief survey of the literature reveals that the deployment of artificial recharge schemes has several significant challenges, including site suitability, land availability, and water quality concerns. In addition to these two, it is noted that operational and governance concerns impede the appropriate operation of artificial recharge structures. Maintaining an open repository for current operational structures, site data and the establishment of efficient, evidence-based governance are essential to overcoming these obstacles. New insights on artificial recharge must also be disseminated, and further study on the topic, its application, and overcoming operational obstacles are all encouraged.

DATA AVAILABILITY STATEMENT

Data will be provided by the corresponding author upon request.

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Capacity development training workshop on crop simulation modelling and effects of climate risks on agricultural production systems in Southeast Asia

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ABSTRACT

Southeast Asia (SEA) has experienced frequent floods and droughts, posing severe challenges for farmers, agricultural scientists and extension officers. Consequently, crop modelling has become imperative in developing agricultural production systems and making informed decisions at the field level. The Decision Support System for Agrotechnology Transfer (DSSAT) can be effectively utilised at both farm and regional levels to assess the influence of climate change on production across different spatial scales. Moreover, it supports planning adaptation strategies tailored to the needs of farmers. The one-week hands-on training workshop aims to enhance technical and scientific proficiency in crop simulation modelling and evaluate the effects of climate risks on agricultural production systems in Southeast Asian countries such as Cambodia, Lao PDR, Thailand and Vietnam. A total of 62 participants from the selected countries, including Singapore and Ethiopia, were joined in the training. Among them were 48 male and 24 female individuals, comprising researchers, students, scientists, academicians and extension officers. The participants predominantly acquired knowledge of crop simulation modelling techniques by utilising existing case examples and lecture materials from the DSSAT foundation. Furthermore, the training workshops establish research networks and collaborations among the participant countries, facilitating the exchange of scientific knowledge related to innovative farm management practices and fostering interactions between local agricultural communities and scientists.

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KEYWORDS CROP MODELLING, DSSAT TRAINING, AGRICULTURAL PRACTICES, COLLABORATION, NETWORKS, SOUTHEAST ASIA

HIGHLIGHTS

- Crop modelling assists in identifying management options for maximising sustainable agricultural systems.
- Knowledge exchange between scientists, strengthening research networks and promoting regional agricultural development.
- Develop farmers' interactions with scientists to enable improved agricultural practices and mitigate climate variability and risks.

1. INTRODUCTION

Climate change poses a significant challenge to the agricultural sector, particularly in tropical areas that heavily rely on agriculture as a primary source of livelihood for countries in the Southeast Asia region, including Cambodia, Lao PDR, Vietnam, Indonesia and Thailand, where hundreds of millions of rural poor depend on agriculture as their main economic activity. Numerous studies indicate that these regions experience substantial yield losses due to climate change, particularly in rainfed and flood-prone areas, as observed in various climate change scenarios (Le Toan et al., 2021; Vinke et al., 2017; World Bank, 2013). In recent years, increased attention has been given to the risks associated with climate change and climate variability, threatening food production security (Kang et al., 2009; Kumar et al., 2022). It is crucial to prioritise research on sustainable food production systems under climate change, especially for developing countries. Changes in agricultural production as a result of climate change and climate variations can significantly impact both regional and global food production. Therefore, it is urgent to determine the impacts on crop production (Fischer et al., 2002; Gitz et al., 2016; Hoogenboom, 2000; Howden et al., 2007; Kang et al., 2009; Tao et al., 2009; White et al., 2011) to develop effective and innovative strategies.

The agricultural system models are crucial in developing sustainable land management practices in diverse agroecological and socio-economic conditions. Several crop models are integrated into decision support systems to assess alternative management practices (Tsuji et al., 1998). Field and farmer experiments require substantial resources and often need to provide sufficient information in terms of spatial and temporal coverage to identify suitable and practical management approaches (Jones et al., 2017). However, dynamic crop models are primarily available for major crops such as food, feed and fibre. The models simulate biotic stresses like pests, diseases and weeds, making them valuable for various applications ranging from on-farm management to regional assessments of climate variability and climate change impacts. Nevertheless, only a few models support precision agriculture research and practice by incorporating the heterogeneity of farmers' field conditions (Basso et al., 2013; Jones et al., 2017). The development of compatible models for multiple crops, considering historical and future weather data to predict crop yields (Bannayan et al., 2003; Chang et al., 2023; Ziliani et al., 2022), has led to the design of the Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al., 2003, 2017; Hoogenboom et al., 1994).

The DSSAT cropping model system stands out for its exceptional ability to accurately predict crop yields, assist farmers in developing long-term strategies (Tsuji et al., 1994) and support governments in agricultural planning (Hoogenboom, 2000). Moreover, it enables informed decision-making at the farm scale and helps assess the effects of strategies on the economic benefits of rural development (Heady et al., 1958; Heady & Dillon, 1964; Jones et al., 2017). The model outputs are typically compared with local experimental data to evaluate model performance and determine the genetic characteristics of local crop varieties. DSSAT can be utilised at the farm level to determine the impacts of climate change on production and identify potential adaptation practices for farmers.

It can also be employed at the regional level to assess the effects of climate change at different spatial scales, provided accurate input data are available for the specific region.

The DSSAT crop simulation modelling provides valuable strategies and technologies for building cropping systems that are more resilient to the impacts of climate change. The one-week hands-on training promotes capacity building and increased collaboration between scientists, communities and stakeholders. Consequently, the DSSAT crop modelling training workshop can help identify management options that maximise sustainable agricultural systems. However, these models are primarily used by agricultural scientists and extension officers who work with farmers and policymakers. Farmers, particularly those who are more risk-averse, may be less inclined to experiment and adopt new strategies. Therefore, crop models and their recommendations can generate further agricultural information that improves farming practices and provides efficient guidance to farmers in mitigating the risks of climate variability and other challenges.

In order to build capacity and develop risk management strategies in the Southeast Asia (SEA) region, the project aimed to strengthen agricultural adaptation and develop agronomic models that significantly benefit food systems. In contrast, strengthening adaptation capacity requires acknowledging farmers' needs and introducing targeted innovations to create resilient and sustainable agricultural production systems. The objectives to achieve this main goal are:

1. Provide a one-week hands-on practical exercise to properly use and apply DSSAT and its associated crop simulation models to solve agricultural management problems.
2. Identify appropriate and promising technologies and develop suitable strategies to make agricultural production systems profitable, sustainable and resilient using crop simulation methods.
3. Analyse farm production using DSSAT tools to verify inputs and simulate productivity.
4. Strengthen technical and scientific capabilities by enhancing collaboration between the National Agricultural Research System (NARS), policymakers, local communities and international organisations.

2. METHODOLOGY

Enhancing stakeholder capacity involves active participation, monitoring progress, analysing outcomes and implementing adaptive measures. Technical stakeholders will contribute by collecting local agricultural data for calibrating and evaluating crop models, while regional stakeholders will assess the representativeness of model results for spatial upscaling. This coordination among scientists, policymakers, NARS staff, students and local communities will enhance cropping systems. The training programme will lead to behavioural changes and improved communication of information to agricultural producers promptly. Therefore, a one-week hands-on will support significant policy reforms to address the challenges faced in the agricultural sector.

The proposed capacity development training follows a specific methodology, outlined as follows.

2.1. Target participants and selection procedure

The capacity development project involved a series of one-week training workshops held in various locations. In 2019, the first workshop took place in Vietnam, with 21 participants from 13 provinces. The second workshop was organised in Chiang Mai, Thailand, with 20 participants, including one each from Ethiopia and Singapore. The final training workshop was conducted in Bangkok, Thailand and had 21 participants from three countries: Cambodia, Indonesia and Lao PDR in 2023 (Table 1). The selection criteria for participants included their educational background, work experience in agricultural crop systems and a minimum of two to three years of professional experience in a related field. It was also essential for participants to be currently employed in universities or institutions within their respective countries, possess basic computer skills and have a good command of the English language. During the training workshops, participants had the opportunity to interact with farmers in Vietnam and engage in discussions about the challenges and issues they faced in their farm fields and crop yields. This practical interaction provided participants with real-world insights and fostered a deeper understanding of the problems encountered by farmers.

2.2. Training material and software

The participants selected for the programme receive the DSSAT software and a one-week training module that includes hands-on exercises and lectures on a range of topics such as weather, potential crop production, crop genetic coefficients, nitrogen-limited and water-limited crop production, risk evaluation, sustainability applications

TABLE 1. Year-wise DSSAT training programme in Southeast Asia.

Country	Male	Female	Total
2019			
Vietnam	17	4	21
Thailand*	4	14	18
Ethiopia**	1		1
Singapore**	1		1
Total	23	18	41
2023			
Cambodia	6	1	7
Indonesia	4	3	7
Lao PDR	4	2	6
Thailand		1	1
Total	14	7	21

Note: *, ** The workshop was a collaborative effort with Chiang Mai University. Funding from the APN-GCR project supported 15 out of the 20 Thai participants. The participants from Ethiopia and Singapore self-funded their participation in the workshop.

and sequential and spatial applications. DSSAT v4.8.2 is a software that features 42 crop simulation models and efficient data management tools. It helps simulate crop growth, development and yield by considering soil-plant-atmosphere dynamics. The updated version introduces new tools that enable users to create and manage experimental, soil and weather data files. It also includes enhanced application programmes that allow seasonal, spatial, sequence and crop rotation analyses. These analyses help assess economic risks and environmental impacts related to irrigation, fertiliser management, climate variability, soil carbon sequestration and precision management.

2.3. Experimental data

A minimum dataset of experimental data is required for the hands-on exercises using the crop modelling model. Existing datasets, such as soil data, daily weather data and farm management data from institutions like the University of Florida, Gainesville and Chiang Mai, Thailand, are utilised. Participants are encouraged to bring their datasets, including field and crop management data (cultivar, planting date, spacing, irrigation, fertilisation, etc.), climate data (daily temperature, precipitation, solar radiation) and soil data (surface and profile characteristics, water holding capacity, nitrogen content, organic matter, etc.), to simulate crop yield conditions under different weather and management practices.

3. RESULTS AND DISCUSSION

Table 1 presents the results of the DSSAT training programmes conducted in Southeast Asia in 2019 and 2023. The table provides information on the number of male and female participants from each country and the total number of participants in each programme.

In 2019, the training programmes took place in Vietnam and Thailand. Vietnam had a total of 21 participants, with 17 males and four females. There were 18 participants in Thailand, comprising four males and 14 females. Additionally, there was one participant from each country, Ethiopia and Singapore, bringing the total number of participants to 41. The workshop held in Vietnam attracted 21 participants from thirteen provinces in Vietnam, including Ca Mau, Hau Giang, Soc Trang, Long An, Kein Giang, An Giang, Ben Tre, Tay Ninh, Tien Giang, Vinh Long, Can Tho, Bac Lieuand Dong Thap. These participants were young and dynamic researchers, academicians, scientists, engineers and extension officers affiliated with government institutes, universities and organisations.

In 2023, the training programme was held in Chiang Mai, Thailand and included participants from Cambodia, Indonesia, Lao PDR and Thailand. Cambodia had seven participants, consisting of six males and one female. Indonesia had seven participants, with four males and three females. Lao PDR had six participants, comprising four males and two females. Lastly, Thailand had one female participant. The total number of participants in the 2023 programme was 21. The group consisted of academicians, young researchers, students and extension officers from Southeast Asian countries actively involved in agriculture, plant breeding, agroforestry and hydrological issues. The participants' diverse backgrounds contributed to a rich and engaging learning experience. The training programme effectively equipped them with the tools to enhance cropping system management and develop more sustainable and resilient agricultural production systems in Southeast Asia. The participants from Vietnam had the opportunity to engage with farmers and learn about their concerns, such as improving yield gaps during droughts and floods

FIGURE 1. Interactive session between farmers and scientists.

(Figure 1). The importance of using tolerant varieties and technology packages and conducting rice value chain analysis was highlighted.

A comprehensive six-day training workshop focused on various aspects of DSSAT modelling is shown in Table 2. The workshop was to provide participants with practical skills and knowledge in utilising DSSAT for agricultural analysis and decision-making (Figure 2). The training commenced with an introduction to DSSAT and its applications, followed by installing the latest version of DSSAT 4.8 software and an overview of the file system. Participants delved into different facets of crop production, including the simulation of water-limited and nitrogen-limited production processes in soil and plants. They also gained insights into weather data inputs and utilities, soil data management and the creation of files for water and nutrient balance. The sessions further covered topics such as uncertainty, risk assessment, best management practices and sustainability in agricultural systems. The participants underwent an intensive training programme with in-depth learning and practical exercises. The training programme's significant focus was on crop modelling, encompassing the simulation of crop rotations and long-term experiments. Participants acquired skills in using the DSSAT software to model phenological development, conduct sensitivity analyses and simulate basic growth processes (Figure 3). They also delved into the concepts of genetic coefficients and cultivar sensitivity, learning how to estimate these coefficients and employing calibration techniques using tools like the Generalised Likelihood Uncertainty Estimation (GLUE) tool.

Spatial modelling applications were also explored, with participants learning to perform seasonal and spatial analyses using DSSAT. Participants are encouraged to apply their knowledge to their own experimental data and gain practical insights into modelling climate change and predicting in-season crop yield. Throughout the training, participants engaged in exercises and received feedback on their software usage. The sessions provided a platform for knowledge exchange, with country-specific presentations and discussions on applications and requirements related to climate change and climate variability.

On the other hand, we gathered feedback from participants about their satisfaction with the session content, benefits gained from the training workshop and suggestions for improvement using Google Forms. According to the results, 81.0% rated the DSSAT training workshop as "Extremely Good," while 19.0% rated it as "Very Good." These ratings indicate widespread appreciation for the workshop's success in exceeding participant expectations (Figure 4). The training proved insightful for participants, as they gained valuable knowledge of DSSAT software, modelling interpretation skills, a fundamental understanding of theory and expanded modelling concepts. Participants found the training useful in various applications, including PhD studies, introducing their course

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TABLE 2. Day-wise DSSAT programme agenda on crop simulation modelling and effects of climate risks on agricultural production systems.

Session	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
Morning (8:00–12:00)	Registration Introduction of resource persons and participants Workshop goals, course outline, schedule History and overview of DSSAT & examples of applications Installation of DSSAT version 4.8 software Overview of DSSAT	Potential crop production Feedback on exercises and software Weather data inputs and utilities WEATHERMAN Using WEATHERMAN Minimum data set concept Learning the DSSAT File System Concept of crop genetic coefficients species vs. ecotype vs. cultivar coefficients	Feedback on exercises and software Simulating water-limited production soil and flood water balance in rice Soil data inputs and utilities Creating soil data files Soil data files and utilities	Feedback on exercises and software Simulating nitrogen-limited production processes in the soil Simulating nitrogen-limited production processes in the plant Creating FileX: Water and N balance ON Nitrogen-limited crop production	Feedback on exercises and software Uncertainty, Risk, BMPs, and Sustainability Creating FileX for Seasonal Analysis Seasonal Analysis	Feedback on exercises and software Cropping Systems – Simulating Crop Rotations Creating FileX for a Crop Rotation Simulation Creating a Crop Rotation or Sequence FileX Using XBuild Simulating Crop Rotations in Long-term Experiments Case Study – Chiang Mai, Thailand

Continued on next page

TABLE 2. *Continued.*

Session	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
Afternoon (13:00–18:00)	Running crop models in DSSAT Simulating phenological development Introduction to Sensitivity Analysis Tool Sensitivity Analysis Tool Simulating basic growth processes Creating FileX: Potential crop production Simulating potential crop production	Genetic Coefficients – CROPGRO & CERES Cultivar sensitivity analyses Estimating genetic coefficients, concepts Tools for estimating cultivar coefficients GLUE Tool Cultivar coefficient calibration using the GLUE Tool	Creating FileX: Water balance ON Water limited production Experimental data collection - Model Evaluation Experimental data files and utilities Creating crop measurement files for model evaluation Calibration and evaluation of the DSSAT models using in-season growth analysis data	Continue with nitrogen-limited Crop production Modelling soil organic matter Creating FileX: Water and N balance ON Continue with nitrogen exercise	Spatial modelling applications Creating FileX for spatial analysis 1. Seasonal analysis 2. Spatial analysis 3. Work with your personal experimental data	Climate change and climate variability Creating FileX for modelling climate change Creating FileX for in-season yield prediction Country's presentation and discussion on applications and needs

FIGURE 2. Practical exercise sessions and results verification among participants.

FIGURE 3. Comparing results: Risk analysis and adoption exercise by participants.

curriculum, testing crop production scenarios and addressing challenges like climate change. They also recognised its significance in improving crop production predictions and guiding farmers' and decision-makers' decisions. One key suggestion for improvement is to extend the training's duration. Participants expressed a desire for a more immersive learning experience, allowing them ample

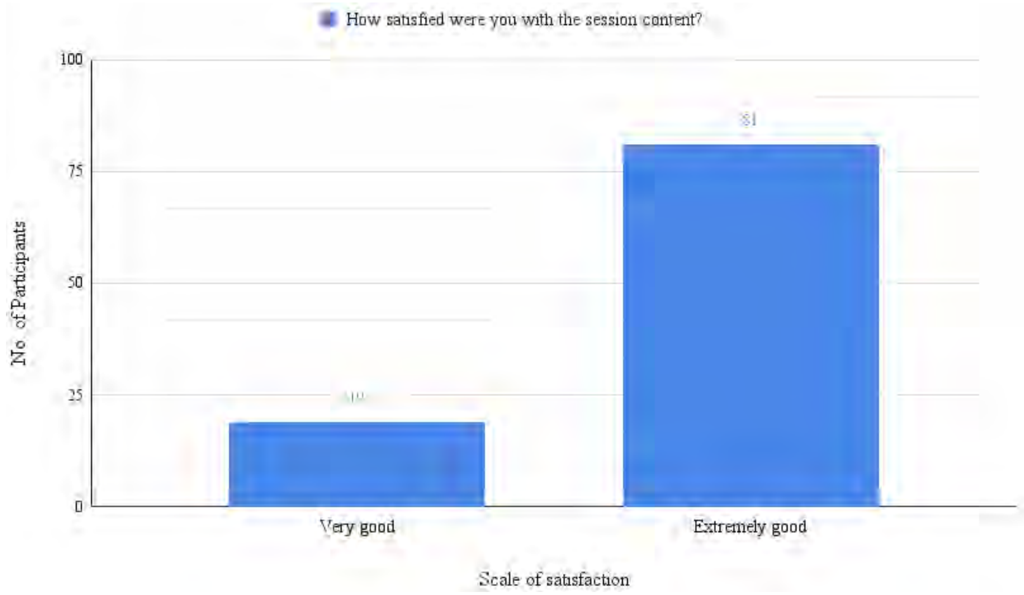

FIGURE 4. Participant satisfaction scale - Training workshop content.

time to grasp complex concepts, refine their skills and interact more with trainers. According to the feedback received, additional days for in-depth exploration and hands-on practice would provide a more comprehensive understanding of the material and align with the participants' expectations.

4. CONCLUSION

The six-day training workshop focused on DSSAT modelling, aiming to equip participants with practical skills and knowledge for agricultural analysis and decision-making. Participants learned about DSSAT and its applications, software installation and file system overview. They explored crop production, including simulating water-limited and nitrogen-limited processes in soil and plants. Weather data inputs, soil data management and water and nutrient balance were covered. The sessions also addressed uncertainty, risk assessment, best management practices and sustainability in agriculture.

The training emphasised crop modelling, including crop rotations and long-term experiments. Participants learned phenological development modelling, sensitivity analysis and basic growth processes simulation. Genetic coefficients, cultivar sensitivity and GLUE tool calibration techniques were explored. Participants worked with their own data, empowering them to make informed decisions and predictions in their agricultural practices. They gained insights into modelling climate change and in-season crop yield prediction.

Exercises and feedback were provided to enhance participants' software usage. Knowledge exchange occurred through country-specific presentations and discussions on climate change and variability. The training improved stakeholder capacity and facilitated collaboration among scientists, policymakers, NARS staff, students and local communities. It also led to behavioural changes and effective information dissemination to agricultural producers. Ultimately, the one-week hands-on training programme supports significant policy reforms and addresses the challenges faced in the agricultural sector, fostering sustainable and resilient agricultural practices.

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Pioneering plant metabolomic library of Indonesian plants for research, conservation, capacity building and economic development

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ABSTRACT

Indonesia, one of the world's most biodiverse countries, is undergoing mass deforestation, exacerbating climate change and leading to accelerated loss of species. This project addressed the urgent need to conserve endangered Indonesian biodiversity, specifically the potentially life-saving bioactive compounds harboured within its plants. A group of Indonesian researchers from Universitas Nasional (UNAS) in Jakarta received training in RApid Metabolome Extraction and Storage (RAMES) technology, an ethical, low-impact, field-deployable and cost-effective methodology developed by Rutgers University. The team of Indonesian scientists used this technology to create the first metabolomic library of Indonesian plant species and an easily transportable collection containing 501 metabolome samples from 296 species. This pioneering and readily shareable resource aims to foster collaborative research into plant metabolomics and natural products, reaching across Indonesia and the broader Southeast Asia region. The project also facilitated four formal discussion forums, two of which were international conferences, promoting exchange among Indonesian, Southeast Asian and USA scientists, with notable participation from the Indonesian National Research and Innovation Agency (BRIN). These efforts culminated in the formation of a strategic partnership among UNAS, BRIN and Rutgers.

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HIGHLIGHTS

- Trained 34 young Southeast Asian scientists in using RAMES-STN technologies.
- Created the first metabolomic library of Indonesian plants containing 296 species.
- Held two practical training workshops and two international conferences.
- Signed MOU for collaboration between UNAS, BRIN and Rutgers University.

1. INTRODUCTION

Plants are critical for human survival. Their contributions to humanity stretch from producing oxygen to forming the foundation of all food chains – including those required for human nutrition. Plants also provide an indispensable foundation for all ecosystems on Earth. Many plant-derived natural products have been converted into human medicines – with up to 70% of all drugs currently in the market being inspired by nature (Newman & Cragg, 2016) – as well as crop protection agents, dietary supplements, cosmetic ingredients, preservatives, disinfectants, flavours, fragrances, colourants and sources of fibre (Schmidt et al., 2007). This breadth of contributions arises from plants being exceptional sources of functional molecular diversity and novel molecular chemotypes, fine-tuned over millions of years of evolution to offer protection against stresses, diseases, and predators (Dixon, 2001). It has been demonstrated that existing plant species harbour a much greater diversity of bioactive metabolites than any synthetic chemical library ever created (Schmidt et al., 2007). Conservation of plant biodiversity is, therefore, crucial for the wellbeing of humankind and fundamental to the health of all ecosystems on Earth.

However, this critical link between biodiversity and human health is under grave threat due to the ongoing sixth mass extinction event driven by anthropogenic global climate change (Ceballos et al., 2015). Current estimates indicate that around one million plant and animal species are at risk of extinction within decades, marking a crisis unparalleled in human history with potentially catastrophic global ramifications (IPBES, 2019). Concerning flora alone, it is estimated that out of the approximately 450,000 species of flowering plants in existence, a third is at risk of extinction (Pimm & Joppa, 2015). Habitat destruction and deforestation are the major causes of plant extinction, particularly pronounced in the world's most biodiversity-rich, tropical regions (Estoque et al., 2019). In addition, projections suggest that without radical reductions in carbon emissions, "there will be further acceleration in the global rate of species extinction, which is already at least tens to hundreds of times higher than it has averaged over the past 10 million years" (IPBES, 2019). The urgency of the situation cannot be overstated and there is an immediate need for interdisciplinary adaptation measures, along with stringent policy changes promoting mitigation efforts worldwide.

Indonesia, one of the world's most biodiverse countries (CBD, n.d.), is a prime example of a country rapidly losing its biodiversity. This archipelago includes two global biodiversity hotspots, Sundaland and Wallacea (CBD, n.d.). It houses the largest coral reef area in Southeast Asia (ADB, 2014), most of the world's tropical peat forests (Posa et al., 2011), the world's largest mangrove forest area (Basyuni et al., 2022), and about 15.5% of the entire world's flora, including approximately 80,000 species of spore plants and 30–40,000 seed plants (Maskun et al., 2021). The country also exhibits remarkable endemism, with roughly 40–50% of flora species specific to each island, except for Sumatra (Maskun et al., 2021). However, Indonesia's rapid population and economic growth, coupled with deforestation caused by fires, rampant logging, and the expanding palm oil industry, are causing swift habitat degradation, which, alongside climate change, pollution and alien species, severely threaten this crucial biodiversity (CBD, n.d.; Cleary & DeVantier, 2011).

Therefore, there is an urgent need to protect and catalogue Indonesia's biodiversity and the biochemical compounds contained by its endangered flora since the irreversible loss of potentially life-saving drugs and other bioactive compounds derived from these species would represent an immense tragedy for human health and wellbeing. To address this challenge, particularly given that many of these ecosystems are in countries in need of scientific capacity development, Rutgers scientists developed RApid Metabolome Extraction and Storage (RAMES) technology (Skubel et al., 2018). This is an ethical, innovative, simple, rapid, highly cost- and space-efficient method to efficiently catalogue and preserve the metabolome and genome of living organisms using compact glass fibre discs as a physical platform. It is also fully field-deployable and highly sustainable, as it requires sampling just two grams of fresh tissue, minimising plant damage. This technology is complemented by a liquid chromatography mass spectrometry (LC-MS)-based method to generate a complete metabolomic signature for each plant sample, supporting chemodiversity studies and taxonomic identification. Functional analysis of RAMES samples can be performed using a fully compatible set of Screens-To-Nature (STN) bioassays designed for simple, compact, low-cost and portable assessment of bioactivity of RAMES samples. These pioneering technologies have been validated and described in full detail by Skubel et al. (2018).

In Stage 1 of this project, selected Indonesian researchers received theoretical and practical training in natural product research methodologies, including RAMES and STN technologies. In Stage 2, the researchers applied this knowledge to create the Indonesia Metabolome And Genome Innovation and Conservation (MAGIC) Library, the first metabolomic collection of Indonesian plant species. The project's commitment to promoting health, education, innovation, and biodiversity conservation is aligned with Sustainable Development Goals 3, 4, 9 and 15.

2. METHODOLOGY

2.1. Hybrid training of Indonesian researchers

2.1.1. Online training

The training of Indonesian participants was initiated in the context of the Center for Botanicals and Chronic Diseases, or CBCD (https://cbcd.rutgers.edu/), funded by the USA National Institutes of Health – Fogarty International Center (NIH–FIC). This centre provides training across a spectrum of research disciplines, spanning basic biomedical and botanical to clinical and applied sciences, including translational and implementation science. Using a culturally sensitive approach, it connects traditional use of botanical therapeutics in participating countries – Indonesia and Tajikistan – with the state-of-the-art research capabilities of participating USA institutions. By combining intensive training in Western science with robust knowledge of traditional botanical medicines, the CBCD program aims to cultivate scientists who can integrate these two systems for the benefit of participating countries. Instruction is organised around four sections: Ethics Core, Botanical Core, Analytical Core and Drug Development Core.

The 2021–22 cohort of the program included twenty-five trainees, sixteen of whom were Indonesian from three Indonesian institutions. Trainee selection considered academic performance, English proficiency, and personal research interests. Training was conducted online using the Rutgers University Canvas learning management system and Zoom video conferencing, avoiding disruption by the global COVID-19 pandemic lockdowns. A mix of synchronous and asynchronous lectures was used for instruction delivery, and regular assignments and examinations were used to monitor progress and assess understanding. In addition, trainees undertook research on a self-selected topic under the guidance of mentors from Indonesia and the USA.

2.1.2. Practical RAMES-STN workshop

After the easing of COVID-19 lockdown measures, an immersive in-person full-day training workshop on RAMES and STN technologies, funded by the Asia-Pacific Network for Global Change Research (APN), took place in July 2022 in the Mt. Halimun-Salak National Park in West Java. This protected, highly biodiverse location was selected to underscore the portable character of these technologies while reinforcing the notion that our natural environment contains a vast array of phytochemicals with invaluable bioactivities. The seventeen Indonesian trainees included six PhD students, eight MS students, and three BSc students. Thirteen of these trainees were selected from the group who had already completed CBCD training, while the remaining four were candidates for the subsequent CBCD cohort.

The large number of workshop participants, as well as their heterogeneous levels of technical

FIGURE 1. **Collection sites for Indonesia MAGIC Library**. Due to budget limitations, most samples were collected from forest parks, botanical gardens, and other green spaces within the Jakarta Metropolitan Area, as well as some collection sites around the city of Bandung, and one site in Bali (not shown in map).

expertise, potential language barriers and time limitations, all posed significant potential challenges. These were addressed prior to the event through careful organisation, and all trainees were also sent a detailed manual in English and asked to read it before the workshop. On workshop day, two Rutgers scientists provided instruction in plant collection methods, including documentation and species identification. They subsequently learned the rapid preparation of ethanolic extracts and their immobilisation onto glass microfiber discs using RAMES technology and then learned to apply STN field-adapted bioassays to assess the antibacterial, antifungal, and antioxidant bioactivities of the freshly prepared extracts. All technical details about these methodologies are published in Skubel et al. (2018). After the workshop, participating researchers from Universitas Nasional (UNAS) received a kit containing all materials for performing RAMES extraction and STN functional assays on 1,000 samples.

2.2. Creation of the Indonesia MAGIC Library

2.2.1. Collection and extraction of samples using RAMES technology

The development of the pilot Indonesia MAGIC Library was spearheaded by a team of Indonesian scientists from UNAS. This team comprised three senior researchers specialising in medicinal plants, environmental sciences, and ethnobotany, along with three young scientists who had completed the training described in Section 2.1. Rutgers scientists also assisted via regular progress meetings and participation in some collection activities. The UNAS team conducted field collection trips to 25 areas of Indonesia (Figure 1, Table 1), and local guides assisted with preliminary taxonomic identification. Species selected for the library at this pilot stage were Indonesian species with previously known medicinal properties. Whenever a species of interest was preliminary identified in the field, the team took pictures of the whole plant, as well as flowers or fruits if present, and recorded its GPS coordinates prior to collecting it using scissors and placing it inside a labelled plastic bag. The collected samples were then individually photographed using a

TABLE 1. Collection sites for Indonesia MAGIC Library.

Province	Collection site	No. samples
Special capital region of Jakarta	Jati Padang, South Jakarta	73
	Srengseng City Forest, West Jakarta	44
	South Jakarta	16
	Pasar Minggu, South Jakarta	12
	Rawa Barat, South Jakarta	6
	Pejaten, South Jakarta	5
	Pondok Pinang, South Jakarta	3
	Ragunan, South Jakarta	2
	Kemang, South Jakarta	2
	Pancoran, South Jakarta	2
	Pramuka Island, Seribu Islands	1
	Jakarta total	**166**
West Java	Cilembu, Sumedang	79
	Djuanda Forest Park, Bandung	70
	Bandung	64
	Sringanis Park, Bogor	33
	Bogor Botanical Garden	32
	Bojonggede	13
	Depok	8
	Bogor	7
	Bekasi	4
	Kranji	2
	Citayam	2
	West Java Total	**314**
Banten	Tangerang	15
	Serpong	5
	Banten Total	**20**
Bali	Tabanan	1
	Bali Total	**1**
Grand Total		**501**

portable lightbox just before their extraction. These images would later be used to confirm preliminary identification using taxonomic keys.

For each species, samples were collected from various tissues – leaves, stems, rhizomes, tubers, flowers, fruits and/or seeds – depending on availability and with minimal disruption to the plants. Samples were processed using RAMES technology while still in the field to minimise phytochemical degradation during transport. For each species, two grams of plant material were extracted in 5 ml of 95% ethanol using a specially modified Dremel® cordless rotary tool. The extract was filtered and loaded onto 10 mm borosilicate glass microfibre discs, which were dried using a portable fan (Skubel et al., 2018). The process was repeated until reaching a minimum of 40 discs per sample, each holding 90 µl of extract. Dry discs were stored in resealable

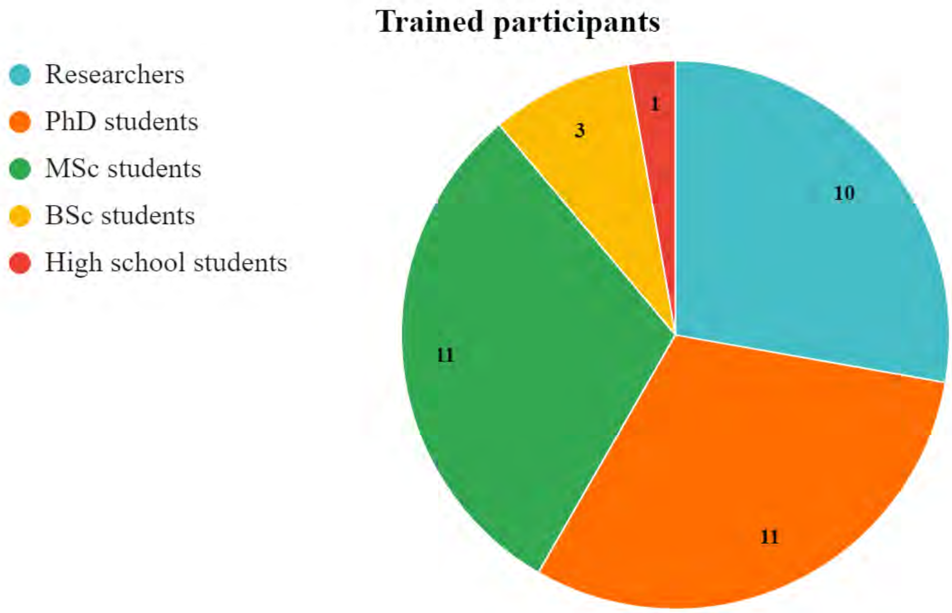

FIGURE 2. Participants trained during RAMES-STN workshops. 32 trainees were from Indonesia, 2 were from Japan, and 2 were from the USA conducting PhD studies in Indonesia. The July 2022 group was comprised by 6 PhD students, 8 MSc students, and 3 BSc students. The May 2023 group was comprised by 10 researchers, 5 PhD students, 3 MSc students, and 1 senior high-school student.

plastic bags and transported back to UNAS for storage at −20 °C.

2.2.2. *Long-term sample storage and data management*

Once dry, discs from each sample were stored in resealable plastic bags, each labelled with the corresponding unique sample ID and species name. These bags were then stored in a −20 °C lockable freezer within the UNAS laboratories.

While the library was being created, comprehensive data about each sample was kept in an Excel spreadsheet. This information included unique identification numbers, scientific and common names, family, plant organ collected, name of collector, GPS coordinates, plant habitat, whether the sample was from a cultivated species, and a summary of its traditional medicinal uses. Upon formally establishing the Indonesia MAGIC Library as a distinct unit within the Center for Medicinal Plants Research (CMPR) at UNAS, a section was created within the CMPR website to centralise all available information.

3. RESULTS AND DISCUSSION

3.1. Outcome of the hybrid training

The online training through the 2021–22 CBCD program resulted in sixteen Indonesian participants from three Indonesian institutions gaining comprehensive knowledge in phytochemistry, biostatistics, drug development, botanical supplements for human health, scientific article writing, and research ethics. After passing the theoretical component of this program, trainees acquired the required knowledge to prioritise, identify and collect plants for the Indonesia MAGIC Library. They also learnt the laboratory and data analysis skills necessary to study samples from the growing library and gained expertise for developing useful and sustainable natural-product-based medicines and consumer products. Several peer-reviewed articles have been published by CBCD trainees on their topic of research within the program (Adilah et al., 2023; Kuswandari et al., 2022; Rahayu et al., 2022; Swandiny et al., 2023).

Following the RAMES-STN practical workshop, seventeen Indonesian trainees from three Indonesian institutions, including thirteen who had already completed the CBCD training, acquired hands-on skills in plant extraction and bioactivity screening using RAMES and STN technologies (Figure 2, Table 2). The extracted flowers, leaves, and fruits revealed predominantly high antioxidant activity, with some also exhibiting low-to-moderate antimicrobial properties (results not collected as they were for demonstrative purposes).

TABLE 2. Participants trained during RAMES-STN workshops.

Workshop	Institution	Region	No. trainees
Mt. Halimun Salak National Park, July 2022	Universitas Nasional	Jakarta, Indonesia	11
	Universitas Pancasila	Jakarta, Indonesia	5
	Universitas Sriwijaya	South Sumatra, Indonesia	1
	July 2022 workshop total:		**17**
Bali Botanical Garden, May 2023	BRIN - Research Center for Plant Conservation, Botanical Gardens and Forestry	Jakarta, Indonesia	2
	BRIN - Research Center for Veterinary Science	Jakarta, Indonesia	1
	Indonesia International Institute for Life Sciences	Jakarta, Indonesia	1
	Institut Teknologi Bandung	West Java, Indonesia	1
	Jagatnatha Jembrana Botanical Garden	Bali, Indonesia	1
	Pangkep State Polytechnic of Agriculture	South Sulawesi, Indonesia	1
	Prefectural Kaiho Senior High School	Okinawa, Japan	1
	Rutgers University	New Jersey, USA	2
	Universitas 17 Agustus 1945 Jakarta	Jakarta, Indonesia	1
	Universitas Airlangga	East Java, Indonesia	1
	Universitas Nasional	Jakarta, Indonesia	2
	Universitas Sriwijaya	South Sumatra, Indonesia	3
	Universitas Udayana	Bali, Indonesia	1
	University of the Ryukyus	Okinawa, Japan	1
	May 2023 Workshop total		**19**
Total number of participants trained			**36**

While the success of the practical training was not formally assessed, the training ran smoothly thanks to detailed logistics planning and anticipation of potential problems prior to the event. Participants showed remarkable engagement and enthusiasm, even after extended periods of outdoor work (Figure 3). This was reflected in a high level of commitment, engagement, enjoyment, and productivity. These observations align with previous RAMES-STN workshops (Kellogg et al., 2010, 2016), which aim to create an engaging, exciting environment that captures the thrill of scientific discovery. Factors contributing to this include unconventional research settings, the rapid and visual nature of STN assays – such as the antioxidant test, which offers striking colourimetric outcomes within seconds – a high percentage of positive test results, and dynamic, highly experienced trainers. During the Q&A session and informal discussions which took place the day after the event, all participants voiced their positive outlook on the workshop and their intention to incorporate the learned techniques into their future research.

3.2. Significance of the Indonesia MAGIC Library

By June 2023, the UNAS team had gathered a total of 501 plant samples, comprising 296 species across 90 families (Table 3; Figure 4). The detailed list of collected samples containing all publicly available information is available on the UNAS CMPR website. Botanists at the Herbarium Bogoriense, the

FIGURE 3. RAMES-STN training workshop in Mt. Halimun Salak in July 2022.

largest herbarium in Southeast Asia, verified the identity of all species.

To our knowledge, this is the first metabolome collection of Indonesian plant species, as well as the first metabolomic library worldwide, which uses a miniaturised, physical platform. One significant advantage of RAMES technology over traditional extract libraries is storage efficiency, minimal curation time required, and potential higher compound stability during storage. Instead of being kept in liquid form, extracts are stored on lightweight, 10 mm diameter glass microfiber discs, each containing 90 µl of volume. This compact format allows the approximately 20,000 discs comprising the Indonesia MAGIC Library to fit easily in a box within a standard freezer drawer, facilitating future expansion with regard to storage and organisation. This novel format remains compatible with the application of high-throughput screening approaches for the identification of chemical leads, as the extracts can be readily eluted from the discs, enabling a range of studies from metabolite quantification to traditional bioassays.

Another key advantage of this miniaturised library is its potential for scientific collaboration and sample sharing. Unlike the glass vials traditionally used to hold extracts (Beutler, 2019), or more modern approaches using microplates (Potterat & Hamburger, 2014), these small and lightweight discs can be easily transported and shipped across large distances to researchers interested in a particular species, reducing the need for constant field collection, and saving time and natural resources. To facilitate such collaborations,

TABLE 3. List of collected plant species. As of June 2023, the Indonesia MAGIC Library contained RAMES discs loaded with ethanolic extracts from 296 different plant species.

Abelmoschus manihot	*Bougainvillea glabra*	*Curcuma amada*
Abrus precatorius	*Bougainvillea spectabilis*	*Curcuma longa*
Acalypha hispida	*Brucea javanica*	*Curcuma xanthorrhiza*
Acalypha siamensis	*Brunfelsia americana*	*Cyanthillium cinereum*
Adenanthera pavonina	*Caesalpinia pulcherrima*	*Cyclea barbarata*
Adiantum capillus-veneris	*Caesalpinia sappan*	*Cymbopogon citratus*
Aegle marmelos	*Caladium bicolor*	*Datura metel*
Aerva sanguinolenta	*Calamus rotang*	*Delonix regia*
Agathis alba	*Calliandra calothyrsus*	*Diospyros blancoi*
Ageratum conyzoides	*Calliandra tetragona*	*Dombeya × cayeuxii*
Aleurites moluccana	*Calophyllum soulattri*	*Dracaena angustifolia*
Allamanda cathartica	*Cananga odorata*	*Dyera costulata*
Allium cepa	*Canna × generalis*	*Elaeocarpus angustifolius*
Allium sativum	*Canna indica*	*Elaeocarpus ganitrus*
Allophylus cobbe	*Capsicum annuum*	*Elaeocarpus grandiflorus*
Alocasia macrorrhizos	*Capsicum frutescens*	*Elatostema calcareum*
Alpinia galanga	*Carica papaya*	*Emilia sonchifolia*
Alstonia scholaris	*Catharanthus roseus*	*Epiphyllum anguliger*
Alternanthera dentata	*Ceiba pentandra*	*Epipremnum aureum*
Alternanthera philoxeroides	*Celosia argentea*	*Eriobotrya japonica*
Alternanthera sessilis	*Centratherum punctatum*	*Eryngium foetidum*
Altingia excelsa	*Chromolaena odorata*	*Etlingera elatior*
Alyxia reinwardtii	*Chrysothemis pulchella*	*Eucalyptus deglupta*
Amaranthus spinosus	*Cinnamomum porrectum*	*Eugenia uniflora*
Anacardium occidentale	*Cissus quadrangularis*	*Euphorbia milii*
Ananas comosus	*Citrus hystrix*	*Euphorbia pulcherrima*
Angelonia sp.	*Citrus limon*	*Euphorbia tirucalli*
Annona muricata	*Clerodendrum intermedium*	*Euphorbia tithymaloides*
Annona reticulata	*Clerodendrum serratum*	*Evodia suaveolens*
Annona squamosa	*Clerodendrum splendens*	*Excoecaria cochinchinensis*
Anredera cordifolia	*Clerodendrum thomsoniae*	*Ficus ampelas*
Anthurium crystallinum	*Clitoria ternatea*	*Ficus binnendijkii*
Anthurium palmatum	*Cnidoscolus aconitifolius*	*Ficus carica*
Antidesma bunius	*Codiaeum variegatum*	*Ficus coreana*
Apium graveolens	*Coleus atropurpureus*	*Ficus elastica*
Arachis pintoi	*Coleus* sp.	*Ficus pumila*
Arenga pinnata	*Colocasia esculenta*	*Ficus septica*
Averrhoa bilimbi	*Combretum indicum*	*Finschia chloroxantha*
Averrhoa carambola	*Cordyline fruticosa*	*Fragaria × ananassa*
Bauhinia purpurea	*Cosmos caudatus*	*Gardenia augusta*
Begonia cucullata	*Costus speciosus.*	*Glochidion arborescens*
Belamcanda punctata	*Costus spicatus*	*Gmelina arborea*
Bellucia axinanthera	*Crassocephalum crepidioides*	*Gnetum gnemon*
Boesenbergia rotunda	*Crossandra pungens*	*Graptophyllum pictum*
Bouea macrophylla	*Cuminum cyminum*	*Gynura segetum*

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TABLE 3. *Continued.*

Heliconia rostrata	*Moringa oleifera*	*Pometia pinnata*
Hemigraphis alternata	*Morus alba*	*Premna oblongiifolia*
Hevea brasiliensis	*Mucuna bennettii*	*Pseuderanthemum maculatum*
Hibiscus acetosella	*Musa paradisiaca*	*Psidium guajava*
Hibiscus rosa-sinensis	*Mussaenda pubescens*	*Pterocarpus indicu*
Hibiscus sabdariffa	*Myristica fragrans*	*Pterygota horsfieldii*
Hibiscus tiliaceus	*Nephelium lappaceum*	*Pyrrosia piloselloides*
Hippobroma longiflora	*Ochna serrulata*	*Quassia amara*
Hopea celebica	*Ocimum basilicum*	*Ricinus communis*
Hylocereus costaricensis	*Ocimum tenuiflorum*	*Rivina humilis*
Hymenocallis littoralis	*Oncus esculentus*	*Rosa hybrida*
Impatiens balsamina	*Ophiorrhiza mungos*	*Rosmarinus officinalis*
Ipomoea batatas	*Orthosiphon aristatus*	*Ruellia napifera*
Ixora chinensis	*Pachystachys lutea*	*Ruellia simplex*
Juglans major	*Palaquium rostratum*	*Ruellia tuberosa*
Justicia gendarussa	*Pandanus amaryllifolius*	*Salacca zalacca*
Kaempferia galanga	*Parkia speciosa*	*Santalum album*
Kalanchoe pinnata	*Passiflora quadrangularis*	*Sauropus androgynus*
Khaya anthotheca	*Pelargonium graveolens*	*Schima wallichii*
Kigelia aethiopica	*Pemphis acidula*	*Senna siamea*
Lactuca sativa	*Peperomia pellucida*	*Sesbania grandiflora*
Lagerstroemia loudonii	*Persea americana*	*Sida rhombifolia*
Lantana camara	*Phaleria macrocarpa*	*Sinningia spesiosa*
Laportea interrupta	*Philodendron rugosum*	*Solanum betaceum*
Laportea stimulans	*Phoenix dactylifera*	*Solanum diphyllum*
Leea aequata	*Phyllanthus urinaria*	*Sonchus oleraceus*
Leucaena leucocephala	*Phymatosorus scolopendria*	*Spathodea campanulata*
Lithocarpus platycarpus	*Physalis angulata*	*Spathoglottis affinis*
Lunasia amara	*Pilea cadierei*	*Spondias dulcis*
Macaranga tanarius	*Pilea trinervia*	*Spondias pinnata*
Maesopsis eminii	*Piper betle*	*Stachytarpheta jamaicensis*
Malvaviscus penduliflorus	*Piper caninum*	*Sterculia foetida*
Mangifera indica	*Piper ornatum*	*Sterculia javanica*
Manihot esculenta	*Piper pellucida*	*Stevia rebaudiana*
Manilkara kauki	*Piper sarmentosum*	*Streblus asper*
Manilkara zapota	*Pistia stratiotes*	*Strobilanthes dyeriana*
Maniltoa grandiflora	*Pithecellobium dulce*	*Swietenia macrophylla*
Mansoa alliacea	*Plantago major*	*Synedrella nodiflora*
Melaleuca cajuputi	*Plectranthus amboinicus*	*Syngonium podophyllum*
Melia azedarach	*Pluchea indica*	*Syzygium antisepticum*
Mimosa diplotricha	*Plumeria alba*	*Syzygium aqueum*
Mimosa pudica	*Plumeria* sp.	*Syzygium cumini*
Momordica charantia	*Podocarpus* sp.	*Syzygium malaccense*
Montanoa hibiscifolia	*Pogostemon cablin*	*Syzygium oleana*
Morinda citrifolia	*Polyscias scutellaria*	*Syzygium polyanthum*

Continued on next page

TABLE 3. *Continued.*

Tabernaemontana divaricata	*Tilia tomentosa*	*Vigna unguiculata*
Talinum paniculatum	*Tinospora cordifolia*	*Voeniculum vulgare*
Tamarindus indica	*Tithonia diversifolia*	*Wedelia chinensis*
Taraxacum sp.	*Toona sureni*	*Wrightia antidysenterica*
Terminalia catappa	*Tradescantia pallida*	*Zephyranthes candida*
Terminalia mantaly	*Tradescantia spathacea*	*Zingiber cassumunar*
Tevesia burckii	*Tridax procumbens*	*Zingiber officinale*
Theobroma cacao	*Triphasia trifolia*	*Ziziphus spina*
Thunbergia affinis	*Vanilla planifolia*	

FIGURE 4. Collections and extractions during creation of the Indonesia MAGIC Library.

the CMPR website contains a comprehensive list of the collected species, along with all non-sensitive sample information and photographs. The site includes basic search features for easier user navigation. Although specific GPS coordinates are not publicly disclosed to protect plant populations, they can be provided upon request.

A primary goal of this novel resource is to stimulate sustainable and collaborative plant metabolomic and natural products research among scientists in Southeast Asia and globally while decreasing the necessity to export plant materials from the country and allowing Indonesian researchers to remain in full control of their natural resources. Traditional approaches used to build extract libraries often involve destructive and laborious harvesting of large amounts of plant materials, which are then dried in the sun or under hot air before being transported to developed countries for lengthy, multi-step processing and, finally, long-term storage (Eisenberg et al., 2011; Risener et al., 2023). The substantial time necessary to collect, grind, extract and dry plant materials using this traditional approach facilitates the degradation

FIGURE 5. "1st International Conference on Natural Products and Chronic Diseases 2022". The conference included speakers from Indonesia, Tajikistan, Malaysia, and the USA. The event also featured presentations from graduating CBCD students on their selected topics of research, and a ceremony for the signature of a Memorandum of Understanding between UNAS and Universitas Pakuan.

of unstable phytochemicals, which in turn requires harvesting of additional plant materials and can also lead to the formation of unnatural compounds (Tiwari et al., 2013). The creation of metabolomic libraries using traditional approaches is, therefore, highly laborious, expensive, logistically complicated, and potentially harmful for the affected plant populations. In contrast, the simple method used to establish the Indonesia MAGIC Library is not only highly cost- and time-effective but also sustainable, and it sidesteps the complexities of plant material import/export regulations while mitigating the risk of exploitative bioprospecting.

3.3. Larger context of the project

This project unfolded within the broader objectives of strengthening the partnership between Rutgers and UNAS, expanding the network of scientific collaborations within Indonesia and Southeast Asia, and fostering natural-product-based research, sustainable development and biodiversity conservation. Thanks to generous funding from the USA NIH–FIC and APN, these efforts have achieved significant success.

3.3.1. First international conference and signature of strategic partnership

In June and July 2022, three forums for scientific discussion and networking were held alongside the RAMES-STN workshop described in Section 2.1.1. These included a small conference between UNAS and Rutgers scientists, a formal meeting and discussion between scientists from Rutgers and the Indonesian National Research and Innovation Agency (BRIN) – Indonesia's government agency in charge of all government affairs in the field of research and technology–, and most notably, a novel International Conference organised by UNAS, the "1st International Conference on Natural Products and Chronic Diseases 2022", held in Jakarta, Indonesia (iconference-ncd.unas.ac.id). This hybrid conference, focusing on the impact of plant natural products on human health, featured speakers from five universities across four countries and garnered wide coverage from local newspapers. The list of attendees, which included a total of 206 participants, featured representatives from fifteen Indonesian and foreign institutions (Figure 5, Table 4).

TABLE 4. Number of attendees and institutions present at the "1 st International Conference on Natural Products and Chronic Diseases 2022".

Number of attendees	
Speakers	6
Presenters	16
On-site audience	111
Online audience	58
Other	15
Total	**206**
Number of institutions	
Indonesian	12
Foreign	3
Total	**15**

FIGURE 6. "The International Conference and Workshop in conjunction with the 8th Indonesia Biotechnology Conference 2023". The conference included speakers from BRIN, the Indonesian Ministry of Environment and Forestry, the Indonesian Biotechnology Consortium, Avicenna Tajik State Medical University (Tajikistan), Kyoto University (Japan), Rutgers University (USA), and the private biotechnological sector, among others.

TABLE 5. Number of attendees and institutions present at "The International Conference and Workshop in conjunction with the 8th Indonesia Biotechnology Conference 2023".

Number of attendees	
Speakers	19
Presenters	48
On-site audience	65
Online audience	161
Total	**293**
Number of institutions	
Indonesian	57
Foreign	4
Total	**61**

These discussion forums solidified a strategic partnership among UNAS, BRIN, and Rutgers, leading to the signature of a Memorandum of Understanding (MOU) for long-term collaboration. At the end of 2022, a BRIN researcher and former scientific advisor to the Indonesian president conducted research at the Raskin laboratory at Rutgers as a Fulbright scholar, facilitating further discussion and networking opportunities.

3.3.2. Second international conference and second training workshop

These developments culminated in the rapid organisation of a second, larger international conference as well as a second RAMES-STN training workshop, "The International Conference and Workshop in conjunction with the 8th Indonesia Biotechnology Conference 2023" (https://www.icw-ibc2023.com/). The combined event was jointly organised by BRIN, UNAS, the Indonesian Biotechnology Consortium (KBI), Universitas Mahasaraswati Denpasar (UNMAS) and Rutgers. The two-day hybrid conference took place in Denpasar, Indonesia, in May 2023 and explored the intersection of biodiversity, biotechnology, and health for enhancing sustainable development. It featured nineteen keynote speakers from four countries and attracted 293 participants from 61 institutions (Table 5, Figure 6).

The second RAMES-STN training workshop took place at the Bali Botanical Gardens the day after the conference (Figure 7), following the same full-day format and covering the same topics as the workshop already described in Section 2.1.1. The nineteen participants were conference attendees who had registered for the workshop due to their personal interest, and they included ten researchers, five PhD students, three MSc students and one senior high school student, coming from fourteen institutions across Indonesia (from Java, Sumatra, and Sulawesi), as well as from Okinawa in Japan and from the USA (Figure 2, Table 2). Careful workshop planning prior to the event helped the training run smoothly despite the potential challenges posed once again by the diverse backgrounds of participants, the time limitations and potential language and technical barriers. Once again, the workshop was not formally assessed but rather followed by a post-workshop Q&A session and discussion, during which trainees offered

FIGURE 7. RAMES-STN training workshop at Bali Botanical Gardens in May 2023.

highly positive feedback, expressing eagerness to incorporate the learned techniques into their research. Post-workshop, BRIN representatives received a kit containing all necessary materials for performing RAMES extraction and STN bioassays on 1,000 samples. Both events received thorough coverage from local newspapers as well as the BRIN and KBI websites. Furthermore, two additional Indonesian universities have recently joined the Indonesia MAGIC Library and will participate in future sample collections: Universitas Surabaya (UBAYA) from East Java and Universitas Pancasila from Jakarta.

3.4. Ways forward and areas for future improvement

3.4.1. Suggested next steps

As a completely new resource, the Indonesia MAGIC Library provides numerous avenues for contributing to research, conservation, and economic development in Indonesia. A suggested starting point would be conducting quality control and stability studies of the RAMES disc contents. This can be achieved by eluting the extracts, identifying and quantifying metabolites through UPLC/MS analysis, and comparing them with freshly prepared extracts. A subsequent step could involve rapid functional screening by assessing the antioxidant, antifungal, and antibacterial bioactivities of the extracts with the corresponding STN bioassays.

As Rutgers scientists have developed a broad range of simple, rapid, and portable bioassays beyond the antioxidant, antibacterial, and antifungal – including, for example, assays to detect anti-roundworm, anti-flatworm, anti-Leishmania, or wound healing properties – this rapid functional screening can be broadened to include many bioactivities of interest. Upon identifying extracts with promising bioactivities, it is recommended that detailed metabolic profiling and extensive quantitative analysis of their constituents be performed.

The present pilot version of the library focused on Indonesian plant species with known medicinal properties. Future expansion efforts of the library are also planned to include Indonesian endemic and endangered plant species. In parallel, it would be of great interest to expand the collection by including marine organisms, fungi and insects. Another course of action could be resampling already catalogued species in different seasons or under varied stress conditions to conduct comparative studies, which would provide valuable insights into the impact of environmental and biological stresses on metabolomic profiles. In any case, each new RAMES sample collected in the future should also include a supplemental small, dehydrated piece of tissue (under one gram would suffice) within the same envelope for DNA barcoding and other sequencing strategies, which would serve as a means to validate species identification, thus providing a practical substitute for traditional herbarium vouchers. The incorporation of genomic samples into the Indonesia MAGIC Library was an integral part of the initial vision, as indicated by the acronym MAGIC, which stands for Metabolome And Genome Innovation and Conservation. Consequently, Rutgers scientists have developed and validated a rapid method for field collecting plant samples for DNA studies and barcoding, using silica gel as a drying method (Skubel et al., 2018). In the future, it might also be interesting to develop a near-infrared (NIR) spectroscopy method for the metabolite profiling of RAMES samples, which could serve as a simple, portable, and cost-effective alternative to the current LC-MS method.

Lastly, raising awareness of this unique biological resource at academic gatherings like conferences and scholarly forums is crucial. By doing so, we hope to initiate sample sharing among researchers, leading to the establishment of collaborative research projects within Indonesia and worldwide. Moreover, we expect that awareness of the Indonesia MAGIC Library will encourage more institutions to participate in the collection of samples, thus ensuring its growth over time.

3.4.2. Challenges faced and recommendations for the future

It must also be noted that the project encountered several challenges described below. While these were tackled as effectively as possible, they require attention and strategic planning, providing valuable lessons for any future initiatives. These issues also emphasise the need for subsequent studies to validate the quality of the library.

3.4.2.1. Difficulties in accessing resources

As the UNAS team prepared to conduct functional screening of the samples using STN bioassays, they faced difficulties in procuring the necessary reagents within Indonesia. They encountered significantly higher prices than in the USA and lengthy delivery times of approximately three months. To circumvent this, reagents were purchased by Rutgers and shipped to Indonesia from the USA. However, this process encountered its own setbacks, including significant customs delays and problems with shipping regulations. Therefore, acquiring these reagents from Indonesia requires a substantial budget and meticulous planning to account for extended waiting periods.

Another concern pertains to the long-term preservation of the metabolites in the discs. While stability studies so far have shown that storage at −20 °C causes only relatively minor quantitative and qualitative changes compared to fresh extracts (Skubel et al., 2018), Rutgers scientists suggest −80 °C for optimal longevity of large valuable collections such as the Indonesia MAGIC Library. However, UNAS currently lacks a −80 °C freezer, and thus the library samples are stored at −20 °C. Potential solutions may include securing funds for a −80 °C freezer or transferring the collection to an institution equipped with such facilities. The new strategic partnership between UNAS, BRIN and Rutgers opens doors for finding alternative facilities for the library. The future quality control and stability studies mentioned above will also help determine the long-term effect of storage of the discs at −20 °C versus −80 °C.

3.4.2.2. Technical problems caused by local conditions

The high humidity levels in Indonesia extended the typical sample drying time from 3–8 min to approximately 2 h. This prolonged drying period, coupled with moist conditions, could potentially lead to metabolite degradation. To try to minimise metabolite degradation, the drying step was subsequently always conducted in conditions as dry and as protected from direct sun and heat as field conditions allowed. Additionally, equipment such as the Dremel® cordless rotary tool exhibited faster humidity-related corrosion than usual, even when stored in relatively dry environments such as the laboratory. The importance of carefully drying all Dremel components before storage in their original hermetic box was emphasised, measures which helped slow down the rusting process but did not fully stop it. In the future, common desiccants like silica gel can be used both to expedite drying and to try to maximise the useful life of the equipment.

Power outages also pose potential risks. Presently, the laboratory housing the Indonesia MAGIC Library lacks a backup generator to maintain freezer functionality during power disruptions. Even though this type of incident has not occurred, it is recommended that a contingency plan be established.

Solutions might involve installing a backup generator on the premises or relocating the collection to a facility with backup power. Furthermore, when future funding allows the expansion of the library, producing a larger quantity of discs per sample would enable the creation of two mirror libraries, housed on different premises and potentially in different cities.

3.4.2.3. Challenges in maintaining scientific rigour

While the trainees were selected partly for their English proficiency, some language barriers hindered comprehension of certain details from the RAMES manual or during online progress meetings. This was most noticeable when the Indonesian team enlisted temporary assistance for collection and extraction from UNAS graduate students, who had more limited English skills and had not undergone RAMES training. The English instruction manual proved less effective in these instances, so the trainees orally translated procedures into Indonesian, resulting in some loss of detail. To overcome this challenge in the future, Rutgers scientists are committed to creating bilingual training materials, a task that recent advancements in AI-based translation have greatly simplified.

4. CONCLUSION

The creation of this MAGIC Library positions Indonesia as the world's leader in collecting and cataloguing metabolomic samples of its rare, endangered plants. This project underscores the potential of RAMES technology as a tool for promoting conservation and scientific/economic capacity in biodiversity-rich regions like Indonesia. A single RAMES-STN workshop empowered seventeen young Indonesian scientists with these ethical, low-impact, cost-effective, and portable technologies, and they, in turn, became trainers within their institution, sharing the methodology with peers whenever they required support for project-related collections and extractions. The ripple effect of the project also inspired a second training workshop within less than a year, fostering skills in an additional nineteen early-career scientists spanning diverse institutions within Indonesia and Japan. Given the enthusiasm expressed by attendees, the simplicity of the techniques, the materials left behind and the continuing support from Rutgers researchers, we anticipate these methodologies will continue to expand across the scientific community in Southeast Asia.

In parallel, the creation of the Indonesia MAGIC Library, the first of its kind worldwide, marks a significant stride towards preserving the unique and potential life-saving metabolites contained in Indonesian flora. Despite the challenges faced and the need for subsequent studies to verify the quality of the collection, this project demonstrates the feasibility of developing a substantial collection of extracts with very limited resources and within a very short time frame. Thanks to the ease of sharing RAMES discs, this growing library, now available to the global scientific community, paves the way for extensive collaborative natural products research and sustainable product development. We are optimistic that the success of the project will prompt future funding for expanding the library to incorporate other Indonesian regions and taxonomic groups.

Encouraging international collaboration and knowledge exchange is best exemplified by the long-term strategic partnership formed among UNAS, BRIN, and Rutgers. The network of connections has continued to expand through the multiple formal and informal discussion forums, including two international conferences, which have been inspired by the potential of the Indonesia MAGIC Library. We hope that this fostering of knowledge and resource sharing among scientists and conservation specialists from diverse countries leads to other future partnerships that can impact the region's biodiversity conservation.

Overall, the project's success and enduring legacy lie in empowering young Indonesian scientists with useful scientific tools and skills that boost their sense of ownership and stewardship over Indonesia's biodiversity. As the Indonesia MAGIC Library continues to expand, facilitating collaborative research and illustrating the pharmacological and economic value of the species it contains, we anticipate it can be leveraged by Indonesian science policy advisors to push for stricter protection laws in the country, contributing to global efforts towards sustainable development and biodiversity conservation.

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LIST OF ACRONYMS

APN: Asia-Pacific Network for Global Change Research

BRIN: National Research and Innovation Agency (Badan Riset dan Inovasi Nasional)

CBCD: Center for Botanicals and Chronic Diseases

CMPR: Center for Medicinal Plants Research

KBI: Indonesian Biotechnology Consortium (Konsorsium Bioteknologi Indonesia)

MAGIC: Metabolome And Genome Innovation and Conservation

NIH–FIC: National Institutes of Health – Fogarty International Center

RAMES: RApid Metabolome Extraction and Storage

STN: Screens-To-Nature

UBAYA: Universitas Surabaya

UNAS: Universitas Nasional

UNMAS: Universitas Mahasaraswati Denpasar

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Fostering the Regional Circulating and Ecological Sphere approach to translate global goals into local actions: Lessons from national scoping workshops in ASEAN countries

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ABSTRACT

The Regional Circulating and Ecological Sphere (Regional-CES) is a guiding concept for environmental policies to support the achievement of the Sustainable Development Goals (SDGs) in urban and rural communities with maximum utilisation of local strengths and resources. To promote the Regional-CES concept as a useful guiding principle, a scoping project was designed to engage key stakeholders in selected Southeast Asian countries, namely, the Philippines, Thailand and Indonesia, by organising workshops in these countries. These workshops consisted of sessions to explain the Regional-CES concept, discuss and identify opportunities for applying Regional-CES based on each country's context, and share practices that may have been conducted under similar frameworks or concepts. Common obstacles include limited scientific understanding, ignorance of local needs and reality in the top-down decision-making process, and limited capacity of local agencies and society. Participants acknowledged the potential of the Regional-CES approach to advance transformative actions towards low-carbon society, resource circulation, and living in harmony with nature at regional, national and local levels, and the importance of aligning the Regional-CES concept to specific local contexts, such as local needs, policy relevance and priorities that could address social, economic and environmental challenges.

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KEYWORDS REGIONAL CIRCULAR AND ECOLOGICAL SPHERE (REGIONAL-CES), REGIONAL DEVELOPMENT, URBAN-RURAL/RURAL-URBAN LINKAGE, SUSTAINABLE DEVELOPMENT, RESILIENCY, RESOURCE MANAGEMENT

HIGHLIGHTS

- Regional-CES links global sustainable development with local actions based on existing approaches.
- Entry points of Regional-CES exist in the context of Southeast Asian countries.
- Existing policy frameworks aligned with Regional-CES are available in these countries.
- However, there has been little or no implementation of these policy frameworks.
- Several enabling solutions for advancing Regional-CES are suggested.

1. INTRODUCTION

The Regional Circulating and Ecological Sphere (Regional-CES) was first proposed in the Fifth Basic Environment Plan of the Government of Japan in 2018 as a guiding concept for environmental policies to support the achievement of the Sustainable Development Goals (SDGs) in Japan as well as in other countries (Ministry of the Environment, Government of Japan [MOEJ], 2018). The Regional-CES aims to create "a self-reliant and decentralised society where different resources are circulated within each region, leading to symbiosis and exchange with neighbouring regions according to the unique characteristics of each region" (Ortiz-Moya et al., 2021). It requires active collaboration with neighbouring regions to benefit all parties by applying their strengths. This concept also brings together existing approaches, such as rural-urban linkages, ecosystem-based solutions for decarbonisation, and resource circulation for economic revitalisation and resilient society, which links global sustainable development agendas with local actions. Regional-CES, therefore, can be understood as a comprehensive concept that aims to apply principles of circularity on a regional scale with close collaboration between rural and urban areas for maximum utilisation of local strengths and resources. Figure 1 illustrates the Regional-CES concept.

A number of local governments in Japan have applied the CES approach for the localisation of SDGs together with economic revitalisation and creation of a resilient society. These include the Hokusetsu CES Model in Hyogo Prefecture (Takeuchi, 2019), Kanagawa Prefecture Water Environment Conservation Programme (Sukhwani et al., 2019), and Yokohama City Net Zero Vision, which promotes urban-rural partnerships (Takahashi, 2023). The Institute for Global Environmental Strategies (IGES) has promoted the Regional-CES concept in Asia, working with its partners, including local governments, the private sector, and civil society organisations in Japan, Southeast Asia (Marome et al., 2022), and South Asia (Thapa et al., 2020). A Regional platform, namely the CES-Asia consortium, was established on 14 October 2021 to further advance the Regional-CES concept, with the aim of building resilience in city regions across South and Southeast Asia (Mitra et al., 2024). To advance the Regional-CES concept, IGES and the Asia-Pacific Network for Global Change Research (APN) set up the Regional-CES Scoping Project to identify opportunities and potential in applying Regional-CES in Southeast Asia. This article highlights the key findings from this scoping project to promote the application of Regional-CES, thereby coordinating local actions to achieve global goals such as the SDGs.

2. METHODOLOGY

The scoping project on Regional-CES was designed to engage key stakeholders of selected Southeast Asian countries, namely, the Philippines (IGES, 2022), Thailand (IGES, 2023a), and Indonesia (IGES, 2023b), by organising stakeholder workshops in each country. The process of stakeholder engagement is discussed below.

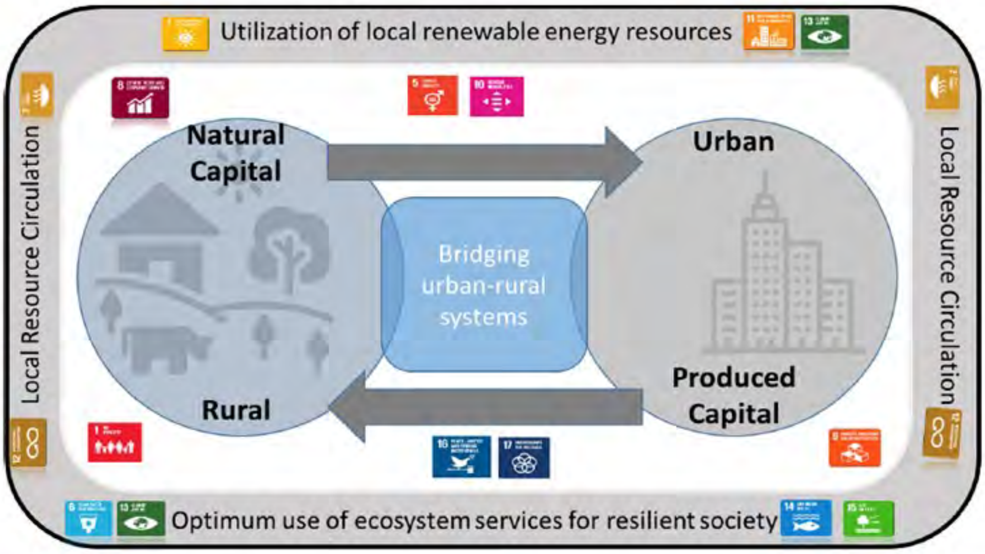

FIGURE 1. Regional-CES concept.

2.1. Selection for national workshops

Three ASEAN countries — the Philippines, Thailand, and Indonesia — were selected based on the following selection criteria: (1) having existing national/local policy frameworks/programmes which have relevance to Regional-CES, (2) having policies focused on strengthening local resiliency or sustainability; (3) having projects/programs which might be applicable for/relevant to Regional-CES.

2.2. Outline of national workshops

Three national-level workshops were organised on 17–18 February 2022 in the Philippines, 20–21 October 2022 in Thailand, and 10–11 May 2023 in Indonesia. The first national workshop was organised in the Philippines and held online due to the COVID-19 pandemic, and national workshops in the other two countries (Thailand and Indonesia) were organised in person. All three workshops were designed with several sessions, including a session to explain the concept of a circulating and ecological sphere, followed by sessions to discuss the applicability of the Regional-CES in each country's context, including its relevance to policies and actions at the local, sub-national and national levels (Figure 2). Breakout group exercises were conducted in each workshop to explore entry points related to challenges and enable environments to mainstream the Regional-CES concept in development policies and plans at national, subnational, and local levels.

2.2.1. Overview of the Technical Sessions

In order to provide orientation on the Regional-CES concept to the participants, a keynote presentation was made by the president of IGES, Professor Kazuhiko Takeuchi. His presentation highlighted the importance of localising the global goals and introduced the principle of the Regional-CES approach by showcasing several examples from different local contexts. The workshops were structured to ensure participants better understood existing policies, priorities and actions and to explore where the Regional-CES concept could be applied to provide comprehensive solutions. Experts from national and local agencies were invited to provide an overview of existing policies, actions, and projects at the national and local levels.

2.2.2. Overview of Group Discussions

Participants were divided into several groups (Figure 3). First, all participants were classified according to stakeholder types (national government agencies, local governments, community organisations, academia or researchers). Each group consists of representatives of each type of stakeholder. A facilitator was selected for each group, and the groups were given a number of prepared discussion points to facilitate interactive discussions that would lead to identifying potential entry points for Regional-CES application and discovering any challenges in applying the Regional-CES. Discussions were also instrumental in bringing up possible solutions for mainstreaming Regional-CES into policy processes that would enhance the localisation of the global agenda and national development goals through integrated and collective actions.

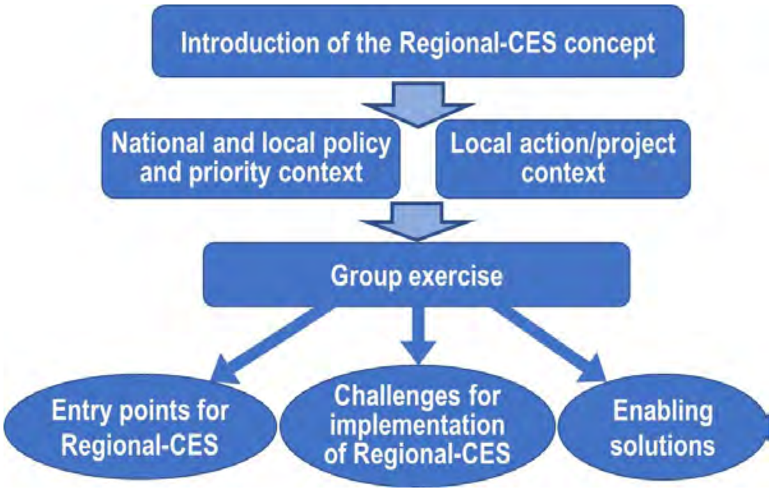

FIGURE 2. Framework of country workshops on Regional-CES.

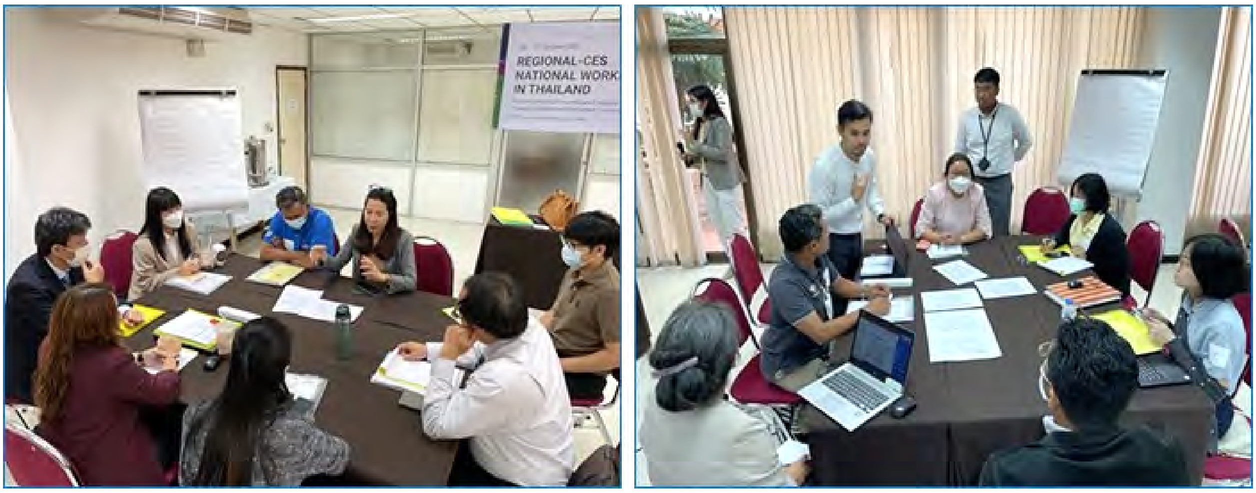

FIGURE 3. Group Discussions during breakout sessions.

2.2.3. Stakeholders of the Regional-CES Workshops

The Regional-CES workshops brought together academic personnel, local community practitioners, researchers, policymakers of national/sub-national government agencies, as well as private sector representatives to share practical experiences and discuss issues, barriers, and applicability of the Regional-CES concept in the context of each country. At the workshops, hands-on interactions and discussions among group members were particularly encouraged, and participants shared discussion results including entry points and proposals to apply the concept with other groups. The first workshop was organised in the Philippines using an online platform, bringing together 259 participants from various stakeholder groups. The second workshop was organised at the Asian Institute of Technology in Thailand, where 46 participants attended and collectively worked to achieve the workshop's objective. The third workshop was held in Depok City Hall in Indonesia and Universitas Indonesia, with an average of 168 participants. These three workshops also actively engaged young researchers, enabling them to develop their capacity.

A summary of the workshop locations and participants is shown in Table 1.

3. RESULTS AND DISCUSSION

The Regional-CES workshops familiarised stakeholders with how the Regional-CES concept can be used to integrate climate change issues and the circular and ecological economy. They also looked at scoping activities and interventions that address these issues simultaneously. Participants recognised that the Regional-CES approach could advance transformative actions towards low-carbon society, resource circulation and enable residents to live in harmony with nature at local, national and regional

TABLE 1. Overview of workshop locations and participants.

Country	Date	Workshop Venue	Target Participants	No. of Participants
Philippines	17–18 February 2022	Online	Local, sub-national and national-level policymakers, Decision makers, Practitioners and Private sector representatives	259
Thailand	20–21 October 2022	[Onsite] Asian Institute of Technology (AIT), [Online] for overseas speakers	Policymakers, Academic personnel, Local community practitioners, Researchers, and Private sector representatives	46
Indonesia	10–11 May 2023	[Onsite] Day 1: Depok City Hall Day 2: Universitas Indonesia [Online]: For participants living far and overseas	Policymakers from government agencies and research centres, Academicians, Practitioners, and NGOs' and private sector representatives	168

levels through cross-sectoral arrangements and strategies incorporating various concepts. It was also acknowledged that the Regional-CES approach could stimulate integrated and collective actions at the local, sub-national and national levels, thereby working towards localising climate and sustainable development goals. The workshop emphasised that the Regional-CES should be applied only after fully understanding the context of specific local needs, policy relevance and priorities and in this way, it could simultaneously address social, economic and environmental challenges.

3.1. Supporting policies for integrated approaches

Integrated approaches have been introduced in a number of important policies in the selected three countries (Table 2).

In the Philippines, the localisation of climate goals has been integrated by formulating the Local Climate Change Action Plan (LCCAP).[1] LCCAP is the action plan formulated by local governments to address climate change concerns by implementing nature-based solutions, decarbonisation, and other issues. The Philippine Action Plan for Sustainable Consumption and Production (PAP4SCP) calls for sustainable behaviour and practices across sectors and levels of government, including resource circulation and rural-urban linkage (National Economic and Development Authority, 2020).

TABLE 2. Supportive existing policies to promote the Regional-CES approach in the Philippines, Thailand, and Indonesia.

Country	Supportive existing policies
Philippines	• Local Climate Change Action Plan (LCCAP) • Philippine Action Plan for Sustainable Consumption and Production (PAP4SCP)
Thailand	• Bio-Circular-Green (BCG) Economy in Thailand
Indonesia	• Presidential regulation 60/2020 of Indonesia on urban rural development in Jabodetabekpunjur • Smart Literacy Box • Mobil Aspirasi Kampung Juara (Maskara) Program for distribution of multi-use vehicles

[1]National Integrated Climate Change Database and Information Exchange System. Local climate change action plan. https://niccdies.climate.gov.ph/action-plans/local-climate-change-action-plan. Date accessed 14 September 2023.

Thailand is promoting a people-centric approach, and the Regional-CES concept could complement the existing national-level strategy on the Bio-Circular-Green Economy (BCG) model. The Thai Government introduced BCG as a strategy for national development and post-pandemic recovery. Citizens are the main actors in actual sustainable transformation, which will eventually have an impact. The BCG model integrated three well-known economic policy concepts: Bio-Economy, Circular Economy, and Green Economy. These concepts aim to stimulate global sustainable development goals and targets through the efficient use of resources, sustainable management of ecosystems, and implementation of a circular economy to address all environmental challenges (APEC, 2022). Like the Regional-CES, the BCG model also calls attention to the effective use of available resources locally and considers effective collaboration among key stakeholders, including public entities, private companies, community, academia, research institutes and global networks to localise SDGs through collective actions.

In Indonesia, Presidential Regulation 60/2020 stipulates spatial planning to bridge urban and rural dichotomies (Cabinet Secretary of The Republic of Indonesia, 2020). In order to accelerate progress on the village level, West Java Province has implemented various programmes, including Smart Literacy Box (Kolecer) Program, Mobil Aspirasi Kampung Juara (Maskara) Program for the distribution of multi-use vehicles, Prosperous Economic Community Credit (Kredit Masyarakat Ekonomi Sejahtera/Mesra), One Village One Company (OVOC), One Pesantren One Product (OPOP), and Bright Villages (Kampung Caang) for village electricity (Gustiana Sabarina and Siti Maryam, 2022; Pemerintah Daerah Provinsi Jawa Barat, 2023).

3.2. Entry points for application of the Regional-CES

The entry points for applying the Regional-CES and similar integrated approaches vary depending on the context of each country (Table 3).

In the Philippines workshop, the entry points in applying the Regional-CES approaches were identified through voting by participants based on the SWOT (strengths, weaknesses, opportunities and threats) analysis results (Figure 4). Resource circulation, ecosystem-based adaptation, and rural-urban linkages were found to be potential entry points for Regional-CES.

TABLE 3. Potential entry points for application of Regional-CES in the Philippines, Thailand and Indonesia.

Country	Potential entry points
Philippines	• Resource circulation • Ecosystem-based adaptation • Rural-urban linkages • Decarbonisation aspect of Regional-CES • R&D on circular economy (CE), green technology/product development • Establishment of innovative solutions, technologies, business models • Existing programmes, frameworks, and initiatives related to CES
Thailand	• Sustainable and Climate Resilient Development • Water Food Nexus in Rural-Urban Linkage • Revitalisation by utilising local resources and enhancing rural-urban linkages
Indonesia	• Balanced urban expansion by preserving green areas and protecting rural spaces • Sustainable resource management • Spatial planning for disaster and environmental risk management

Furthermore, the following potential entry points were suggested at the summary session of the workshop:

- Research and development on circular economy (CE)
- Green technology/product development
- Continuous capacity building and information, education and communication-related activities, for planners, especially at the subnational levels, to mainstream CE/waste reduction into their plans, programmes and practices.
- Establishment of innovative solutions, technologies, and business models

The group discussion at Thailand's workshop identified three major entry points: (1) sustainable and climate-resilient development, (2) the water-food nexus in rural-urban linkage, and (3) revital-

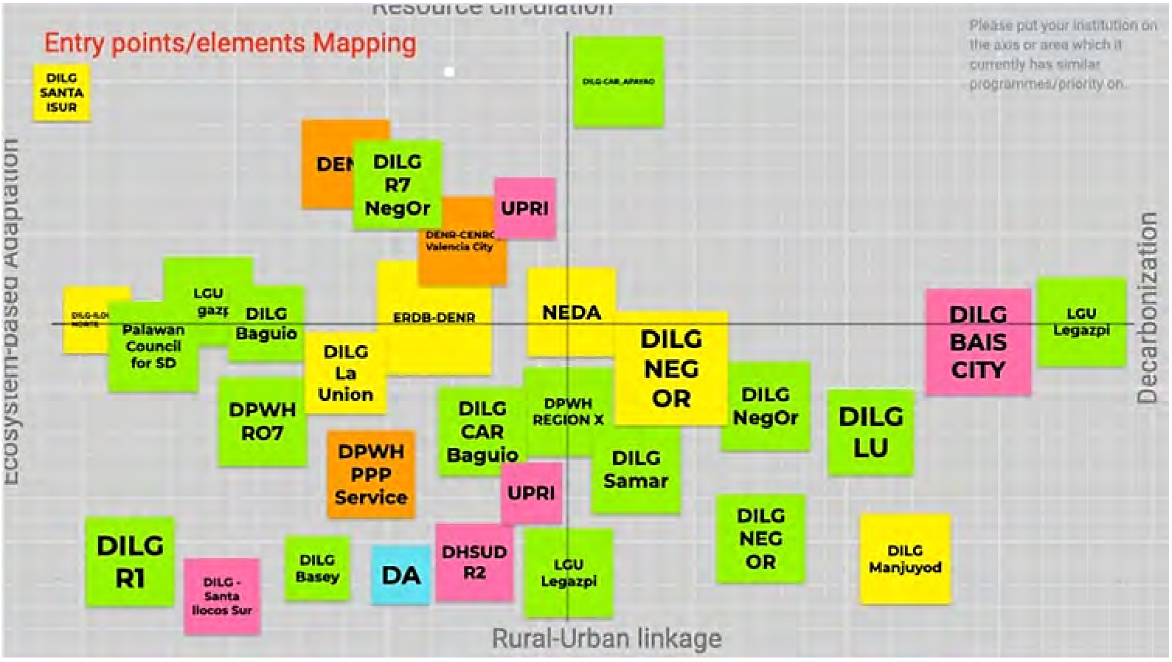

FIGURE 4. Participant voting results based on SWOT analysis at the workshop in the Philippines.

isation by utilising local resources and enhancing rural-urban linkages. These were entry points for applying the Regional-CES approach, the BCG model and other similar concepts in Thailand. As one of the most vulnerable countries, Thailand has prioritised its efforts to ensure climate-resilient development in energy, water, transportation, agriculture, human settlements and public health (Government of Thailand, 2018; The World Bank Group and the Asian Development Bank, 2021). In order to achieve climate-resilient development in water, energy and agriculture, it is vital to consider how these sectors are interdependent beyond administrative boundaries. Likewise, it is critical to strengthen urban-rural linkages for optimal management of the water-energy-food nexus. Urban-rural partnerships can contribute to economic revitalisation by creating new economic opportunities to use local resources.

The Regional-CES workshop in Indonesia identified three entry points for applying the Regional-CES concept, which differed from those identified in Thailand's workshop. These were: (1) balanced urban expansion with preserving green areas and protecting rural spaces, (2) sustainable resource management considering spatial integration, and (3) spatial planning for disaster and environmental risk management enhancing rural-urban linkages.

3.3. Challenges to applying Regional-CES

The challenges to applying Regional-CES in a country context are summarised in Table 4.

In the context of the Philippines, the Regional-CES application challenges include lack of infrastructure to link the circular economy, limited budget/financial support, duplication of plans from various agencies, low acceptance/support from LGUs when applying Regional-CES, and insufficient means for implementation, which make it very difficult for key players to implement the concept. As for scaling up climate change resiliency through a Regional-CES approach, this is challenged by mismatched priorities in the localisation of development, lack of sufficient shared knowledge and information about climate change, and insufficient financial resources for climate mitigation.

The interactive discussions at the workshop in Thailand made participants realise that there were no straightforward ways to apply Regional-CES, BCG, or similar integrated approaches in the context of Thailand because many challenges hindered their application (Figure 5). The workshop identified a number of barriers to applying the Regional-CES and similar integrated sustainable development approaches, including lack of knowledge on the concept, absence of guidelines for Regional-CES or even BCG Economy, lack of location-based supportive laws and regulations, incompatibility between top-down implementation and local demands, lack of science-based assessment on locally available resource, obstacles to financial support, limited funds, a lack of effective partnership or networking,

TABLE 4. Challenges to applying Regional-CES in the Philippines, Thailand, and Indonesia.

Country	Challenges for Regional-CES
Philippines	• Limited budget/funds for integration and climate mitigation • Mismatched priorities for localisation of development • Lack of shared knowledge and information • Lack of infrastructure that could close the link to circular economy • Conflicting policies at the local and national levels • Wasteful duplication of plans from various agencies at various levels • Insufficient means to implement plans/weak implementation • Low acceptance/support of Local Government Units (LGUs) when applying Regional-CES concept due to conflicting/other priorities
Thailand	• Lack of institutional structures and information on the concept • No guidelines for Regional-CES or even BCG Economy • Lack of location-based law and regulation • Incompatibility between top-down implementation efforts and local demands • Lack of understanding of locally available resources • Obstacles of financial support, research funds, lack of awareness of Regional-CES and lack of networking • Different approaches between urban and rural settings
Indonesia	• Urban bias whereby urban areas have a strong position compared to rural areas • High urban land price • Lack of infrastructure • Lack of human resources with the necessary skills • Lack of inter-municipality coordination • Lack of community involvement/consultation in formulating and implementing spatial planning • Different cultures/traditions between urban and rural areas • Urban migration, particularly of young people

and an uncoordinated approach in terms of urban and rural development.

The Regional-CES workshop in Indonesia identified several challenges for advancing the Regional-CES and urban-rural linkages. These challenges include a lack of human resources with necessary skills, weak inter-municipality coordination, limited community involvement/consultation in formulating and implementing spatial planning, inequity between urban centres and rural communities, as well as various social and cultural differences between urban and rural areas.

3.4. Enabling measures for promoting Regional-CES application

The enabling measures to promote Regional-CES approaches in line with the country context are summarised in Table 5.

In the Philippines workshop, breakout discussions came up with enabling solutions such as better technical expertise, more cross-sectoral coordination and linkages, sustainable funding sources, and shared knowledge, as well as raising awareness and empowering stakeholders. In addition, harnessing key resources, providing favourable conditions for securing human capital and well-being, and forward-looking actions/policies were identified as some of the enabling conditions for the efficient implementation of the Regional-CES approach. As the next step, it was proposed to establish a platform to co-learn and co-develop collective action based on the lessons learned from the national workshop, with the aim to sustain momentum through doable activities.

The Thailand workshop explored various solutions to the abovementioned challenges in applying the Regional-CES, BCG and similar integrated approaches. The group discussions came up with a list of enabling solutions, including that laws and regulations should be reviewed based on locations,

TABLE 5. Enabling measures for application of Regional-CES in the Philippines, Thailand, and Indonesia.

Country	Enabling measures
Philippines	• Harnessing of human, natural, and financial resources • Forward-looking actions/policies • Enabling Regional-CES experts who could extend technical expertise • Strengthening cross-sectoral coordination and linkages • Sustainable funding sources • Sharing sufficient knowledge of Regional-CES-related best practices/successful models • Increasing awareness and empowering stakeholders
Thailand	• Laws and regulations should be reviewed based on locations • Enhancing rural and urban linkages for a sustainable society • Establishment of local stakeholder platforms (e.g., Regional-CES platform) • Enhancing spatial planning with accurate mapping • Community participation/consultation to formulate and implement spatial planning • Effective law enforcement • Addressing conflicts between land ownership rights and spatial regulations • Promotion of sustainable agriculture • Enhancing vocational training • Provision of infrastructure • Vertical residential development in urban areas for better land use
Indonesia	• Enhancing spatial planning with accurate mapping • Community engagement to formulate and implement spatial planning • Effective law enforcement • Addressing conflicts between land ownership rights and spatial regulations • Promotion of sustainable agriculture • Enhancing vocational training

rural and urban linkages for sustainable society should be enhanced, local stakeholder platforms (e.g. Regional-CES platform) should be established, and the concept of integrated approaches (e.g. Regional-CES, BCG, ecosystem-based approaches) for sustainable development in the education curriculum should be promoted. Subsequently, it was proposed that the regional-CES concept be made practicable and feasible by considering the needs and realities of local implementors and encouraging co-development to ensure integration of the existing policies for broader acceptability.

The Indonesia workshop selected spatial planning with accurate mapping as one of the policy tools to advance the Regional-CES approach. In addition, the workshop also highlighted several other enabling solutions, including rural community participation/consultation to formulate and implement spatial planning, law enforcement, and vocational training on the integrated approach. The next step was for participants to suggest various potential actions, including creating a network of researchers, policymakers, and practitioners to foster collaboration and knowledge sharing, organising future workshops to discuss urban-rural linkages, and developing a database of best practices on urban-rural linkages.

4. CONCLUSION

The Regional-CES is an integrated approach to synergistically localise global and national agendas on sustainable development through integrated actions for economic development, social inclusion and sound ecosystem management. Regional-CES provides a framework for bringing together various approaches: rural-urban linkages, ecosystem-based solutions for decarbonisation, and resource circulation for economic revitalisation and resilient society.

The scoping workshops on Regional-CES aimed to disseminate the concept and explore its relevance to existing policies and sustainable de-

FIGURE 5. Group discussion report of the identified challenges to Regional-CES application.

velopment strategies in three selected countries (Philippines, Thailand, and Indonesia). Through these three scoping workshops, it was revealed that the Regional-CES concept is particularly relevant to national sustainable development pathways as well as line policies such as the Bio-Circular-Green (BCG) Economy in Thailand, Presidential regulation 60/2020 of Indonesia, and the Local Climate Change Action Plan (LCCAP) developed by the Philippines. Several potential entry points for applying the Regional-CES to stimulate sustainable development in each country's context were identified. Likewise, the workshops also pointed out several challenges in the context of each country. Common challenges include limited scientific understanding, top-down policymaking processes, ignorance of local needs and reality, lack of capacity in local agencies and societies, and insufficient financial schemes and research funds. There was also a lack of awareness about Regional-CES among local people and limited networking. In order to overcome the identified challenges, the workshops discussed sets of enabling solutions that included enhancing linkages for sustainable society between urban and rural areas through the generation of location-specific scientific knowledge, developing a science-policy-society interface, establishing a local stakeholder platform to enhance the co-development of local actions, and implementing a capacity development programme on integrated approaches. The lessons learned from these three national workshops could facilitate a regional-level, cross-learning mechanism for applying the Regional-CES to tackle sustainability challenges in various national, sub-national and local contexts.

The Regional-CES concept introduced by the workshops has already generated some impacts. Following workshop discussions, a project for development of several villages in Indonesia is now planned which will incorporate agrivoltaics for enhancing resilience and sustainability. This exemplifies how the Regional-CES concept can contribute to local development by focusing on effective rural-urban linkages, as well as sufficiently utilising potential local resources in line with respective national contexts.

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Technical Report

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Engaging young people in community-based flood risk management in Pekalongan, Indonesia

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ABSTRACT
This technical report describes a capacity development project for flood risk management in Indonesia. The project aimed to equip tertiary students, referred to as 'learners,' with the basic knowledge and skills for flood risk management. We adopted a holistic approach that integrated online lectures, remote coaching and locally-based activities. We implemented a wide range of field activities to foster collaborative experiential learning. Our project took place in Pekalongan, a coastal city in Central Java Province. The significance of our efforts was underscored by the formal endorsement and support provided by the City Government of Pekalongan, which actively engaged 18 government officials in our programme. The capacity development project was structured into two parts. The first part encompassed six online lectures, delving into various aspects of flood risk management. In the second part, 18 enthusiastic Indonesian students took part in our field activities, which included water quality testing, flood exposure assessment, community vulnerability evaluation and community disaster planning. The majority of participants conveyed that the project either met or surpassed their expectations, significantly altering their understanding of climate change and climate vulnerability in Indonesia, while also redefining their roles in local climate change adaptation efforts.

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KEYWORDS FLOODING, WATER QUALITY, VULNERABILITY ASSESSMENT, TRAINING, STUDENT, INDONESIA

HIGHLIGHTS

- This project helped young people build their capacity in flood risk management.
- Online lecturing, remote coaching and field activities were provided.
- The project was supported by the governments of Central Java Province and Pekalongan City.
- Learners developed hands-on skills and a better understanding of flooding impacts.

1. INTRODUCTION

Indonesia is a sprawling archipelago comprising over 17,000 islands and uniquely vulnerable to the impacts of sea level rise. Located in Southeast Asia, this tropical country is renowned for its rich biodiversity, stunning landscapes and vibrant cultures. However, it is also profoundly affected by the rising sea levels resulting from global climate change. With approximately 54,720 kilometres of coastline, Indonesia's extensive network of islands, low-lying coastal areas and densely populated regions face an imminent threat as sea levels continue to surge (Setiadi et al., 2023; Setiadi & Frederika, 2022; Setiadi & Lo, 2019).

The primary driver of sea level rise is the melting of polar ice caps and the expansion of seawater due to increasing temperatures. These factors, exacerbated by human-induced climate change, pose a significant challenge to Indonesia's future stability and resilience. The nation's geographical diversity, comprising mountainous terrains and coastal plains, further complicates the impact of rising seas. While mountainous regions may experience increased flooding downstream, coastal regions are particularly susceptible to inundation, saltwater intrusion, and erosion, which threaten the livelihoods and homes of millions of people.

Pekalongan is one of the most climate-sensitive cities in Indonesia. It is a secondary city in the Central Java Province with a total land area of approximately 45 km^2 and about 308,000 people. Pekalongan is significantly affected by tidal flooding and rising sea levels. This region is particularly vulnerable to these threats due to its low-lying topography and proximity to the Java Sea.

Tidal flooding is a recurrent problem in Pekalongan. The city experiences more frequent and severe inundation events as sea levels rise. During high tides or storm surges, coastal areas, particularly those along the northern coast of Java, including Pekalongan, are at risk of being submerged. Flooding can cause significant damage to infrastructure, disrupt daily life, and harm the local economy. Furthermore, rising sea levels exacerbate the problem of saltwater intrusion into freshwater sources, including underground aquifers and rivers. This intrusion can contaminate drinking water supplies and damage agricultural lands, affecting the livelihoods of local communities that rely on farming and fishing for their sustenance.

The district of North Pekalongan faces the Java Sea and is exposed to higher risks of tidal flooding than other districts in the city. There have been various efforts, mainly through the development and management of flood infrastructure. The main initiatives include (i) preventing tidal floods from entering the mainland, (ii) developing polders or pool retention to regulate the water before flowing downstream, (iii) pumping water from the polders to the sea regularly and (iv) increasing the capacity of rivers. Infrastructure projects in the city include the development of dykes, long storages and pumping stations, increased rivers' embankment, river normalisation, dredging and development of collector drainage.

Although Indonesia is sensitive to climate change impacts, most young Indonesians lack the basic skills and knowledge in flood risk management. The lack of hands-on experience was exacerbated by the pandemic-related restrictions in the past three years, which reduced opportunities for field learning. Our project was designed to address these gaps in capacity development among young people in Central Java Province and the areas around Pekalongan. It is known as 'Developing the Capacity of Student Scientists for Supporting Disadvantaged Communities to Cope with Flooding (DECAF)'.

The project aimed at enabling tertiary students ('learners') to develop knowledge and skills in flood risk management and build connections with members of the local community, government officials, and stakeholders on flood-related issues. We supported learners who aspire to pursue a career in applied science, research and practice. The remainder of this technical report describes our project design and key outcomes.

2. PROJECT DESCRIPTION

2.1. Pedagogical approach and objectives

The design of this capacity development programme is informed by the notion of 'citizen science'. Citizen science projects call on individuals to gather data for scientists to investigate research questions (Bonney et al., 2009; Chow et al., 2014). These projects can produce research databases and increase science literacy. By engaging in authentic field-based science, environmental citizen scientists gain a better understanding of scientific requirements and data collection processes and gain technical capabilities and confidence. This will benefit those in a disadvantaged situation who would otherwise lose an opportunity to develop a science or research career. This is particularly important for developing countries, where formal opportunities for science training are more limited.

Citizen science is less commonly practised in developing countries (Pocock et al., 2019). While most citizen science projects involve a 'contributory' approach, in which people engage with activities designed by professionals, increasingly more projects are taking a 'collaborative' approach, in which potential participants are involved in defining the scope, purpose and methodology (Pocock et al., 2019). Enabling and empowering citizen scientists is valuable for interdisciplinary projects with social science elements. This is because the pandemic and major social events limit the mobility of international researchers to conduct human-centred research activities, such as interviewing remote villagers. Building students' capacity for performing such tasks will strengthen their ability to contribute to international projects. Disaster risk reduction research often involves community-based activities in collaboration with local people. A collaborative approach with senior students co-designing the project is crucial because international researchers might not know as much about the community as the students and their ability to learn about it is affected by mobility barriers. A collaborative citizen science approach is essential for our capacity development project, which includes tasks about community response.

Our project explores a collaborative citizen science approach. It enabled learners to conduct a scientific inquiry - at a level appropriate to undergraduate students - into the impact of flooding, evaluate people's responses and coping strategies, and work with the community to develop a risk reduction plan. The project had two practical objectives:

1. Strengthen the capabilities of senior tertiary students in assessing flood exposure and helping local communities to address flood risks.
2. Explore an approach for capacity development that involves remote coaching and collaborative field-learning components.

Our multidisciplinary team implemented a capacity development programme that included a combination of online lectures (Part I) and guided field-learning activities (Part II), as described below.

2.2. Part I. Introduction to scientific concepts and practice

A total of six two-hour lectures were provided to learners. These lectures enabled learners to not only understand the science, but also find solutions for the community. The lectures were delivered by a team of international experts and practitioners. Topics included:

1. Causes of flooding from a geographical perspective (A/Professor Lincoln Fok at Education University of Hong Kong, Hong Kong).
2. Impacts of storms and flooding on water quality (Professor Alex Chow at Clemson University, USA).
3. Flood risk management and infrastructure (A/Professor Faith Chan at University of Nottingham Ningbo, China).
4. Understanding and assessing people's vulnerability to flooding (Dr Alex Lo at Victoria University of Wellington, New Zealand, and A/Professor Rukuh Setiadi at Diponegoro University, Indonesia).
5. Adaptation to flooding and local community planning (A/Professor Rukuh Setiadi at Dipone-

TABLE 1. Criteria for selection.

Criteria	Sub-Criteria	Note
Primary	• Completion of the post-test	Compulsory
	• Expression of interest in proceeding to Phase 2	DECAF only considers those who confirmed to dedicate to Phase 2 in full-time
	• Attendance of at least 3 to 7 online lectures	More attendance is beneficial and valued in the selection
Secondary	• Diversity in the origin of universities attended by the applicants.	DECAF consider inclusive principle
	• Diversity in the fields of study or majors.	DECAF consider inclusive principle
Tertiary	• Balance in terms of gender representation.	DECAF consider gender equality

goro University, Indonesia, and Dr Alex Lo at Victoria University of Wellington, New Zealand).

6. What can young people do to help local communities manage flood risk and adapt to climate change? (Ms Shar Thae Hoy from Spring University Myanmar, Myanmar, and Ms Aniessa Delima Sari from the Initiative for Urban Climate Change and Environment, Indonesia).

2.3. Part II. Collaborative experiential learning

Eighteen highly motivated learners were selected to participate in Part II based on the criteria listed below. Learners completed four modules, guided by one or two project team members. Part II aimed to equip learners with scientific knowledge and skills about flood risk management. Our pedagogical approach is to enable them to co-design the learning process by selecting key local spots, attributes, and processes to conduct field activities and by leading the problem-solving module. Moving from Module 1 to Module 4, learners will be given more discretion about what and how to learn and increasingly take on a lead role to identify solutions for the community. These modules comprised interactive sessions and hands-on tasks, as described in Table 1.

Module 0: Co-design and planning

We equipped learners with scientific knowledge and skills in flood risk management. Our pedagogical approach was to enable them to co-design the learning process by selecting key local spots, attributes, and processes to conduct field activities and by leading the problem-solving module. Moving from Module 1 to Module 4, learners were given more discretion about what and how to learn and increasingly took on a lead role to identify solutions for the community.

Module 1: Water quality assessment

This module began with a technical session to introduce the sampling and analytical procedures for surface water quality. Based on Professor Chow's advice and supported by local project leaders, learners identified specific locations (a safe spot with access to a river) in their study areas for field work and collected water samples in the rainy season.

Module 2: Flood exposure assessment

Learners identified an area in North Pekalongan and assessed its flood exposure using basic tools. They formulated a plan for data collection and identified and visited a previously flooded human settlement in the study area. In their field visits, they interviewed locals to obtain an oral history of previous flood events in the past two decades in that area and identified related information from historical floods (e.g., flood depth) and their impacts (e.g., economic losses of households, injuries and casualties, etc.) at specific locations. Upon identifying the 'flood spots', learners used a web-based map platform (e.g., Google Maps) to integrate this information into a digital map to determine the area flooded and, thereby, flood exposure of the site location.

Module 3: Participatory vulnerability assessment

This module helped learners understand and use existing tools for vulnerability assessment and ways to implement participatory elements. Under guidance, learners formulated a plan for assessing the flooding sensitivity and the coping and adaptive capacities of the selected community in the study area. They also identified suitable and relevant indicators for vulnerability assessment and developed a participatory approach for gathering data. Learners, supported by local project leads, visited the community and conducted intensive field surveys, interviews, and focus group discussions to assess community vulnerability to flooding.

Module 4: Community-based risk reduction planning

This collaborative module involved a small research project. Learners gained problem-solving skills by developing a plan for reducing flood risks in their case-study community (e.g., a village). Under our guidance, learners were involved in defining the scope and methodology for this research, which aimed to review the local actions taken and policy and institutional support and identify opportunities and resources required for coping with and adapting to flooding (including pre-, during and post-flooding response). Six learners formed a group and prepared a final report.

Post-learning joint conference

On 31st August 2023, learners presented their findings and final report in an online workshop. Learners shared their learning experiences with fellow learners as well as the PI and collaborators. Each learner who completed the programme and attended the joint conference was named a 'DECAF Fellow' and presented a certificate to recognise their participation in the programme.

3. PROJECT OUTCOMES

3.1. Activity highlights

Part I (online lecture series)

The DECAF received formal written support from the Central Java Province Government and the City Government of Pekalongan. In addition to student participation, the City Government of Pekalongan assigned 18 government officials whose scope of work is related to flood management to participate in phase 1. It shows that DECAF was highly relevant to the capacity development needs of the Indonesian local government.

A total of 228 Indonesian learners registered for the DECAF online lecture series. Most of them (>70%) did not previously receive any training in flood risk management and related field activities. An opening ceremony was held on the 2nd of May 2023, at Diponegoro University, Semarang, Indonesia. It was attended in person by approximately 80 students, the Dean of Engineering Faculty Universitas Diponegoro, the Head of Department of Urban and Regional Planning, the Head of Planning and Development Agency of Pekalongan City Government, and the representation of Agency for Water Resource and Spatial Planning of Central Java Province Government. Six weekly online lectures were conducted between May and June 2023. The online lectures attracted over 120 learners to attend via Zoom, including 18 local government officials from the Pekalongan City Government.

Part II (field activities)

Eighteen university students were trained in field activities in a coastal area of Pekalongan that is exposed to tidal flooding and sea level rise. These learners collected and analysed data about water quality (Figure 1), flood exposure (Figure 2) and community vulnerability (Figure 3). These included 183 onsite observations about flood exposure and 270 completed questionnaires about community vulnerability. They then came together to discuss possible strategies for helping communities to cope with flood risks (Figure 4). Field activities were completed in July 2023.

As part of the field activities, the learners had meetings with representatives of two relevant local government agencies in Pekalongan (Figures 5 and 6) and visited a climate adaptation pilot project site under the guidance of local NGO representatives. Learners also directly engaged in 3 separate focus group discussions that involved about 30 local community members, who represented small businesses, women, and youth, respectively (Figure 7).

3.2. Learners' feedback

This session summarises the project evaluations completed by the eighteen learners, which were based on a list of structured and open-ended questions.

The majority of students expressed that the DECAF programme not only met but also surpassed their expectations. They valued the programme for its capacity to offer fresh perspectives, hands-on experience, and opportunities for teamwork. Notably, the programme's emphasis on flood risk management, especially in relation to flood inundation and adaptation planning, received significant recognition. The fieldwork encompassed diverse modules conducted in groups, which proved highly effective in improving individual skills and teamwork capabilities. The firsthand experience of

FIGURE 1. Collecting and testing water sample from an aquaculture site.

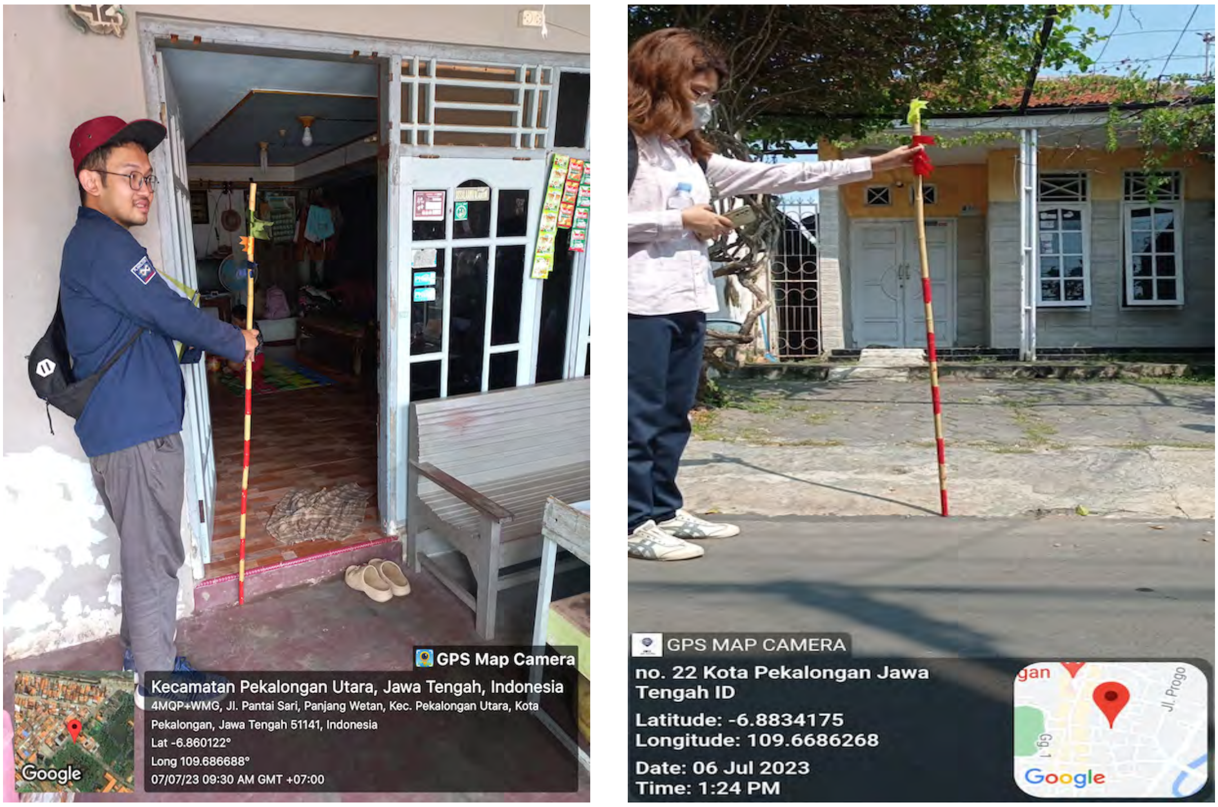

FIGURE 2. Measuring house elevation.

visiting flood-prone areas, engaging with the local community, and gaining knowledge about water testing left a profound impact.

Learners derived substantial value from the initial phases of the programme, encompassing group introductions, active engagement in activities, and the acquisition of knowledge. They also expressed gratitude for the opportunity to interact with local communities and gain firsthand insights. Many emphasised that the DECAF programme not only met their expectations but also broadened their perspectives, particularly concerning flood management systems, flood barriers, and social aspects. The DECAF programme earned praise for its co-design approach, which allowed participants to contribute to the planning and execution process. Furthermore, the support provided by practitioners and faculty members was commended for enhancing the overall programme experience.

FIGURE 3. Interviewing local community.

FIGURE 4. Community Planning Workshop.

In summary, learners felt that DECAF's immersive experiences and practical knowledge equipped them with valuable tools to make effective contributions in their chosen fields, whether through research, policy-making, or community engagement. The programme was lauded for bridging the gap between theoretical knowledge and practical applications, ultimately enhancing their preparedness for future work. There was a sense of confidence that the knowledge acquired from DECAF, encompassing aspects like drainage systems, coastal infrastructure, and social considerations, would prove instrumental

FIGURE 5. Learners' visiting the Planning and Development Agency (BAPPEDA) of Pekalongan City Government.

FIGURE 6. Learners' visiting to the Agency for Water Resource and Spatial Planning (PUSDATARU) of the Central Java Province Government.

in their future endeavours, especially in fields such as urban planning and disaster management. The programme was regarded as a stepping stone toward developing critical thinking skills and adapting to real-world challenges.

Many learners highlighted that they had the opportunity to participate in the design and operation of the programme modules through the co-design approach. They were engaged in various aspects, including suggesting adjustments to the survey system, proposing modifications to the order of transects and clusters, and even combining certain modules for efficiency. Several of them mentioned that they played a role in selecting sampling locations, determining transect points, and adjusting the course of fieldwork to align with real-world conditions.

FIGURE 7. Focus group discussions with representatives of the local business sector.

However, learners expressed that their input was not fully considered and indicated that they could have had a more substantial influence on the design and operation of the modules. Nevertheless, the prevailing sentiment was that the co-design concept was present, affording students the opportunity to shape the execution of the modules and tailor them to real-world scenarios. Learners valued the collaborative process and the chance to adapt the programme based on practical considerations.

Moreover, learners identified ways to further enhance the overall experience and outcomes of the project. They believed the programme was already comprehensive, covering various aspects of flood risk management, and felt it provided a sufficient understanding of the subject matter. Other suggestions included:

- Additional elements, such as conducting community awareness campaigns or providing training related to floods and water composition, should be included. This could involve sharing information about water quality after testing (Module 1).
- Time constraints were raised by multiple learners, particularly concerning Module 3. They expressed the need for more allocated time in certain modules to facilitate more in-depth activities, such as interviews and assessments.
- Communication with the local community could have been more extensive before field activities to assist in identifying suitable locations for surveys and tests.
- Suggestions for improvement encompassed better coordination, more intensive mentorship, clearer questionnaires for interviews, and a more effective strategy for distributing incentives to encourage community participation (Module 3).
- Providing direct feedback to the community regarding the survey results and policy proposals.

In addition, learners reported that their field experience led to a change in their perspective or differed from their initial expectations in the following ways. They were surprised by the extent of flooded houses, shorter building structures compared to road levels, and the transformation of the landscape due to embankments. Conditions in their assigned areas diverged from what they had anticipated, varying in the degree of impact from flooding. Others were taken aback by the prevalence of flooded homes. Some learners observed aspects that didn't align with their expectations, particularly concerning the poor state of drainage systems in specific locations. They were often surprised by the physical and economic conditions in the affected areas, including older, less-maintained buildings. There was an expectation that more focus should be placed on structural solutions like embankments.

4. CONCLUSION

In conclusion, our project represented an innovative and collaborative initiative aimed at addressing the educational needs of senior tertiary students in Indonesia who were impacted by the disruptions caused by the pandemic. By focusing on flood risk management, we set out to equip these aspiring students with the knowledge and skills necessary to pursue careers in applied science and research, making them better prepared for the challenges of our ever-changing world.

Our unique approach, combining online learning, remote coaching, and local field activities, was tailored to create a more robust and adaptable digital training environment. This approach not only enhances the learners' understanding but also fosters collaborative experiential learning, an invaluable asset for their future careers. The project was also successful in fostering North-South collaboration, bringing together expert educators from New Zealand, the United States, Hong Kong, and Indonesia. This collaboration enriched the educational experience, promoted cross-cultural understanding and ensured that the skills and knowledge gained would be readily applicable to the needs of Indonesia. Furthermore, the creation of digitally reusable resources underscores our commitment to the sustainability and long-term impact of this project, paving the way for future capacity development initiatives in the Global South.

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Green technologies to enhance sustainable food production in colder regions via adoption of smart greenhouse

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ABSTRACT

Amidst climate change, dwindling resources and a growing population, the farming industry has faced significant pressure. Nevertheless, rapid advancements in modern agricultural technology offer substantial potential for increasing production efficiency in colder regions. The proposed Smart Greenhouse (SGH) provides a controlled environment for crops. The SGH consists of heat sources from an 8 m^2 solar water heating system, weather stations to monitor the outside SGH temperature and humidity, light sensors, humidity sensors and temperature sensors inside SGH to monitor SGH performance. Several selected crops were experimented with and grown inside the developed SGH during the cold winter when cultivable land is typically left fallow due to extreme cold weather conditions. The prototype SGH results show improved environmental conditions compared to the exterior conditions of the SGH, with a temperature difference of 7 °C and a relative humidity (RH) level of 25%. This paper also discusses the limitations of current SGH system designs and proposes future design improvements.

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KEYWORDS SMART GREENHOUSE, HUMIDITY, TEMPERATURE, TEMPERATE REGION

HIGHLIGHTS

- A solar water heating system (solar thermal system) was employed as the heat source for circulation within the SGH.
- Three primary sensors were utilised to monitor and control temperature, humidity, and light intensity.
- A prototype was developed after validating the simulation results obtained from EnergyPlus software.
- Performance of SGH was analysed and crops could be harvested during off-season.

1. INTRODUCTION

In earlier research by Hossain et al. (2014), the pivotal role of agriculture in the economies of South Asian Association for Regional Cooperation (SAARC) countries was emphasised, contributing about 20% to the gross domestic product (GDP) and serving as the livelihood for 51% of the population. Projections foresee this region accommodating nearly half of the world's population by 2050, heightening vulnerability to hunger and poverty. Disseminating up-to-date scientific research and innovative agricultural technologies through farmer education is crucial for effective agriculture extension services. A shift from conventional to contemporary, integrated farming approaches shows promise in enhancing crop yields and productivity, addressing regional challenges and promoting agricultural development.

Weather and climate significantly influence agriculture, impacting sunlight exposure, temperature, humidity, rainfall, and soil moisture crucial for crop growth (Parolini, 2022). Chhogyel and Kumar (2018) emphasise that weather and climate are environmental determinants profoundly affecting crop production and productivity. Bhutan boasts a range of agricultural ecological zones and climates, offering opportunities for cultivating various crops (Centre, 2021).

Bhutan's temperate region encompasses two zones: warm temperate and cool temperate. The former spans 1800–2600 m above sea level (masl) with an average annual temperature of 12.5 °C, while the latter ranges from 2600–3600 masl with an average annual temperature of 9.9 °C. Both regions receive annual rainfall of 650–850 mm, suitable for agriculture. Above 3600 masl lies the alpine area with yearly precipitation of less than 650 mm and an annual average temperature of 5.5 °C. These regions experience minimum temperatures and yearly rainfall of 0.1 °C and 650 mm, respectively. Additionally, solar irradiance measurements exceed 4.5 $kWh/m^2/day$ (NCHM, 2018). These climatic characteristics offer opportunities for researchers to explore and propose alternative solutions for sustainable food production in the agriculture sector. This research paper aims to study the technical feasibility of implementing SGH on a larger scale in cold temperate regions to enhance future food sustainability. A small-scale prototype of SGH, equipped with controllers and data loggers, was designed and implemented.

According to Lefers et al. (2020), emerging technologies are solutions for sustainable agriculture in extreme coastal environments. This paper explains the potential of combining emerging technologies like transparent infrared solar panels and low-energy saltwater cooling systems to develop sustainable controlled environment agriculture in the extreme coastal regions of the Middle East and North Africa. This indicates technology can assist in converting uncultivable land into cultivable land. The study by Al-Naemi and Al-Otoom (2023), the use of smart sustainable greenhouses in Gulf Cooperation Council (GCC) countries demonstrates significant potential for reduced water usage and high return on investment (RoI). This paper demonstrates the viability of a smart sustainable greenhouse model in GCC countries, powered by solar

FIGURE 1. Smart greenhouse developed in the temperate region with SWHS as the heat source.

energy and advanced control systems, showcasing reduced water usage, significant RoI potential (340%), and a five-year pay-out period when scaled to commercial operations, thereby contributing to food security and profitability in the region.

The implemented prototype SGH yields promising results and is feasible for large-scale operations. Crops such as cauliflower, broccoli, cabbage, spinach, radish, cucumber, beans, and onions all yield well, except for chili. The following sections present detailed construction materials, methodology, system sizing, results and conclusions.

2. SGH CONSTRUCTION MATERIALS

2.1. SGH structure materials

Building a Smart Greenhouse (SGH) for agricultural activities using low-cost materials and solar energy can regulate the required temperature, humidity, and luminosity. Kodali et al. (2016) and Li et al. (2019) designed a smart greenhouse model that helped farmers automate farm monitoring. Malik et al. (2010) also discussed devices and communication protocols in developing smart greenhouses.

This technical report discusses the outcomes of the SGH prototype implemented in Genekha, located in the temperate region of Bhutan. The SGH prototype, measuring 12 × 7.5 m, was developed after simulating its performance in the TRNSYS and OpenStudio simulation software. The central concept in developing the SGH was to assess the viability of implementing SGH in temperate regions to enhance food production during the cold winter season when cultivable lands are left fallow due to harsh weather conditions. The energy source for the SGH was supplied using a solar thermal heating system. Based on the SGH's location and weather conditions, the size of the thermal collector, the primary energy source for SGH, was 8 m^2. In winter, the first four hours of the morning are when SGH requires the most heating. Figure 1 illustrates the complete construction and development of the SGH using solar thermal collectors. The SGH comprises a solar thermal system, including an auxiliary tank, solar collector, hot water tank, sensors for monitoring the SGH, a data logger inside the SGH and a weather station installed outside the SGH.

Inside the SGH, temperature, humidity and light intensity sensors are optimally placed to ensure the correct operation of the system. Polypropylene Random Copolymer (PPR) pipes, each spaced 0.5 m apart, are laid beneath the soil, which has a thickness of 0.3 m. The hot water tank circulates hot water when the temperature switch inside SGH activates. The PPR pipes release heat, thereby increasing the soil temperature. This heating of the soil helps maintain the required temperature inside the SGH.

(a) (b) (c)

FIGURE 2. Sensors (a) temperature sensor, (b) humidity sensor (c) light intensity sensor.

TABLE 1. Crop adaptation parameters in SGH.

Vegetable(s)	Min Temperature	Max Temperature	Average humidity (%RH)	Soil pH	Soil thickness (Inches)
Radish	7.2 °C	21 °C	95–100	6–7	6
Cabbage	4.5 °C	24 °C	90 or higher	6–7	1–2
Broccoli	4.5 °C	21 °C	95	6–6.5	1–3
Spinach	2 °C	30 °C	90–95	6.5–7	1–2
Cucumber	20 °C	38 °C	60–70	6.5–7	0.5–0.75
Cauliflower	17 °C	20 °C	85–90	6–6.8	17

2.2. SGH data loggers and controllers

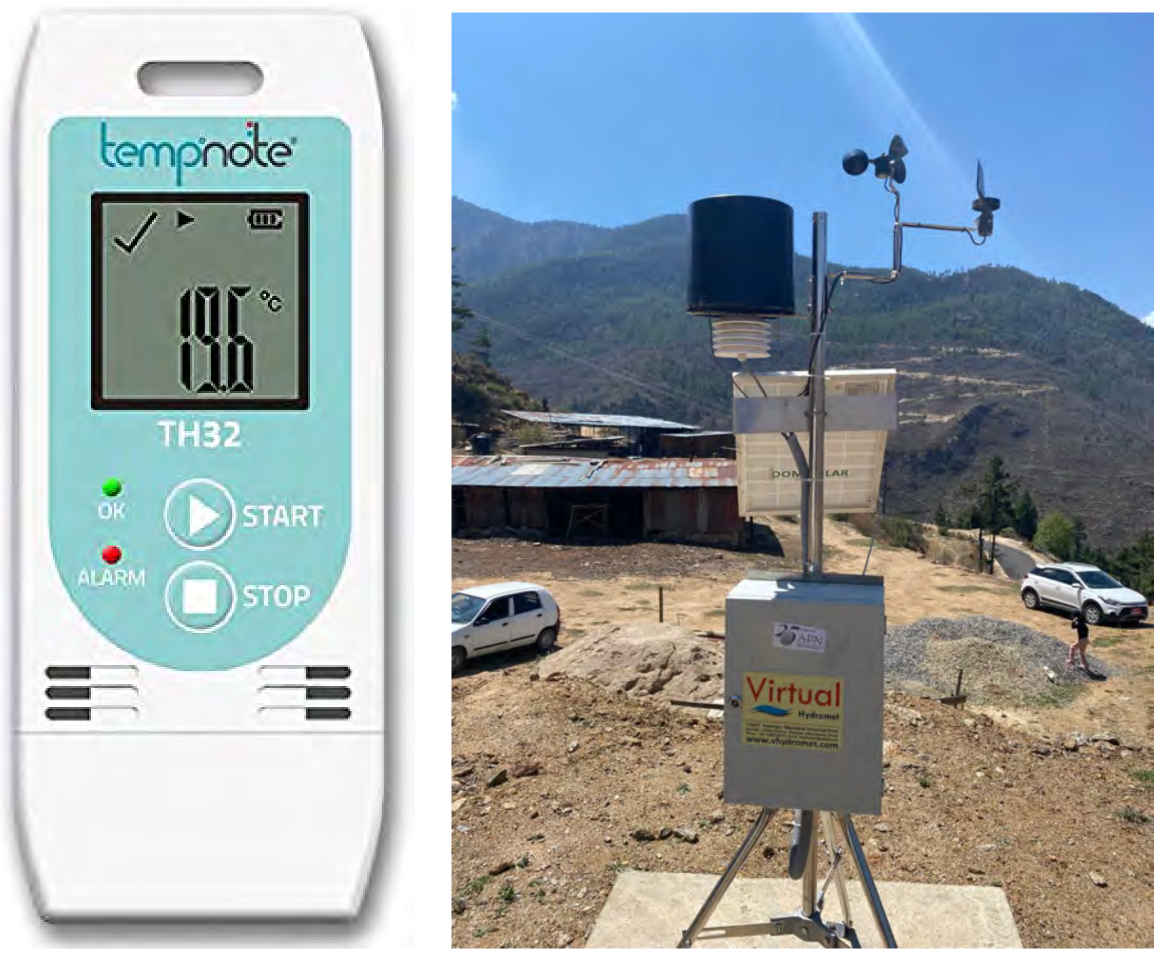
In the SGH, three primary sensors are used: temperature, humidity and light, as shown in Figure 2.

The temperature sensor is a central component of the SGH, functioning when there is an electricity supply. The temperature sensor switch activates when the temperature inside the SGH crosses a specified threshold level.

The selected crops to experiment inside SGH are mentioned in Table 1. The commonly grown vegetables in the colder regions are radish, cabbage, broccoli, spinach, cucumber, cauliflower, beans and chillis. The seasonal vegetables were experimented with in the smart greenhouse by providing required growth conditions like light, humidity and temperature. The vegetables growth periods have been critically considered to conduct experiments within the three-month winter season.

The data logger inside the SGH provides statistics on the comparison between the inside and outside environment. The weather station recorded the exterior environment data. Figure 3 shows the data logger installed inside SGH and the weather station outside SGH.

The humidity sensor was set between 40% RH and 95% RH. The specific maximum and minimum settings of these sensors are determined by the types of crops selected for the experiments. For instance, beans and chillis, which require lower humidity levels, were also included in the experiment. The vegetables selected in experiments are commonly grown vegetables in the region. The light sensor was configured to activate the switch when the luminosity of lights falls below a certain level, automatically turning on the switch until the sun rises. Adequate light intensity is essential for promoting plant growth. Soil testing is conducted to assess the conditions favouring crop growth. Soil parameters such as pH and moisture content (MC) were tested to assess the conditions favouring crop growth. Soil pH is crucial as it influences several soil factors that affect plant development, such as soil bacteria, nutrient leaching, nutrient availability, toxic elements and soil structure. Soil moisture content (SMC) determines the water content in the



(a) (b)

FIGURE 3. Data loggers (a) Inside SGH data logger (b) Weather station with data logger.

soil. The test results show an average pH and SMC of 5.83 and 22.25%, respectively.

3. METHODOLOGY

This section discusses two subsections: the overall layout of the smart greenhouse and the controller flowchart (Section 2.1) and heating system sizing (Section 2.2).

3.1. SGH simulation and controller layouts

The site selection was based on the research objectives, leading to a colder region where all experiments were conducted during the off-season. Typically, the selected site becomes barren during winter, with a short cultivable duration. The proposed SGH aims to extend the usability of cultivable land. Before implementing the SGH at selected sites, a simulation was conducted to confirm construction material selection. Based on simulation results, SGH was constructed, and sensor threshold levels were set. The experiment was conducted during the winter season, from November 25th, 2022, to April 2023. Sensors and controllers were employed to maintain the required environmental conditions for the crops inside the SGH. Figure 4 illustrates the schematic control system of the SGH.

The temperature and humidity sensors are the important controller equipment in the SGH. When the temperature inside the SGH drops below 2 °C, the temperature sensor activates pump A, as shown in Figure 4. These temperature sensors are evenly distributed within the SGH. The optimal placement of the sensors is crucial to prevent false operation of the hot water circulation pump. If the temperature inside the SGH exceeds 35 °C, the switch connected to the exhaust fans, located at two edges of the SGH, is activated. This facilitates the exchange of hot air inside the greenhouse with the outside environment, bringing a cooling effect inside SGH.

Similarly, the humidity inside the SGH is maintained within 40% RH to 95% RH. If the humidity drops below 40% RH, the humidity sensor, optimally positioned inside the SGH, activates water Pump B to enhance humidity by sprinkling water

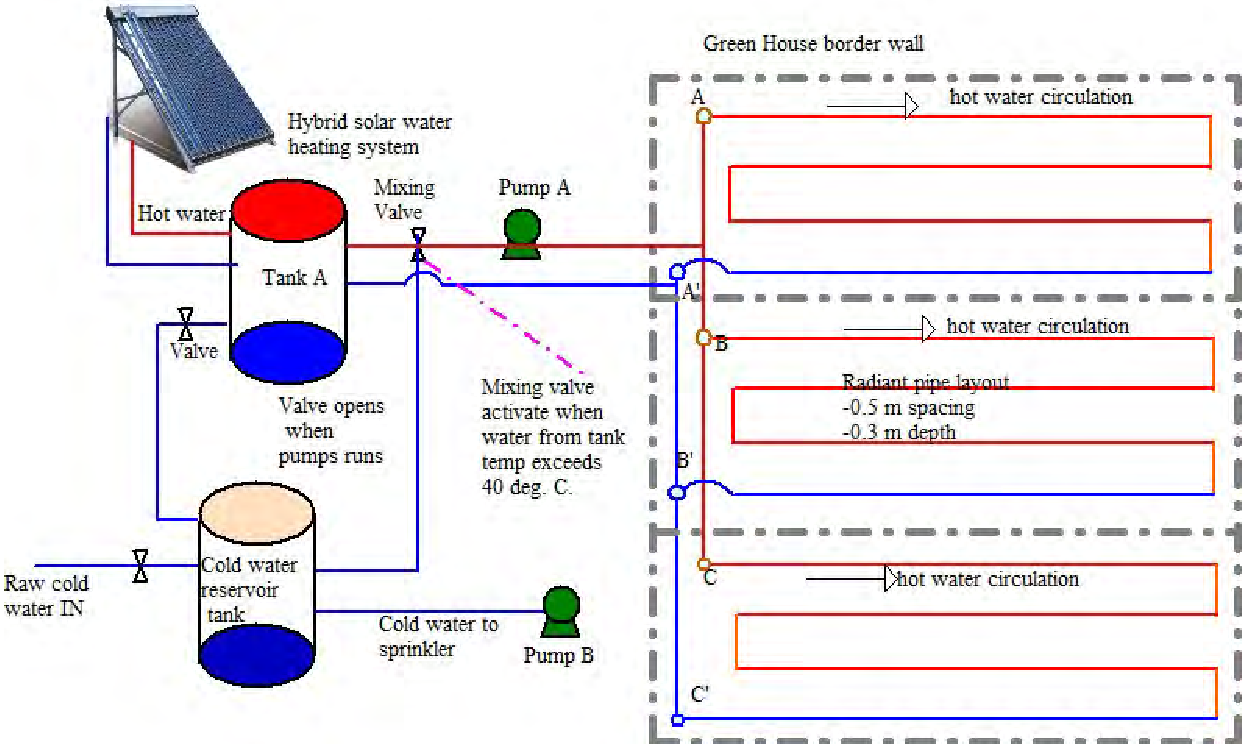


FIGURE 4. Smart Greenhouse controller schematics embedding all sensors.

inside the SGH. Pump B operates until the humidity level reaches 40% RH. If the humidity inside the SGH exceeds 95%, the exhaust fan is triggered to introduce dry air from outside the greenhouse. These settings of the controllers are based on Table 1 by selecting the minimum and maximum %RH required by crops.

In a study by Paradiso and Proietti (2022), it was emphasised that the quantity and quality of light affect plant growth. In the prototype developed, diffused light was provided during night hours. The light-dependent resistor (LDR) sensor was used as a switch to control the light automatically when the dark started. Figure 5 shows the detailed workings of temperature sensors and pump operation.

3.2. Heating system sizing

The sizing of the heating system in the SGH faces a significant challenge due to heat loss through the glazing. The sizing of the heat source takes into account the temperature difference, glazing area (A), and the U-factor of the covering sheet. To perform the sizing of the SGH in a colder region, ambient temperature is necessary as a reference. The minimum temperature requirement for the crops is also mandatory for sizing the SGH. The following steps are followed for the heating system sizing:

- The minimum required temperature inside the SGH is 2 °C.
- Recorded data indicates the minimum outside temperature as −6 °C.
- The temperature difference (ΔT) is 8 °C.
- Heat loss through the glazing is calculated as ΔT × A × U-factor, resulting in 8.04 kW.
- Taking into account 10% system losses, the collector area is calculated as follows:

$$\begin{aligned}\text{Collector Area} &= \text{Load Demand} / \\ &(\text{Collector Efficiency} \times \text{Solar Irradiance}) \\ &= (8.04 + 0.804)\ \text{kW} / (0.69 * 4.5\ \text{kW/m}^2) \\ &= 3.14\ \text{m}^2\end{aligned}$$

The minimum collector area required to heat the same air volume in one hour is 3.14 m². Simulation results show peak heating is necessary from 4:30 AM to 6:30 AM, totalling two hours on average. Therefore, the recommended total collector area is 8 m².

To determine the cooling system, the average maximum temperature at the selected site is 19.8 °C per the data recorded by the weather station installed at the project site. Simulation results indicate that the maximum temperature inside the SGH is 32.22 °C, while the plant's temperature requirement is 35 °C. As a result, no cooling mechanism is needed. Practically, the temperature inside SGH crosses the limits, and no crops will grow during summer. The winter and summer maximum temperatures and humidity are given in Tables 2 and 3. Therefore, the

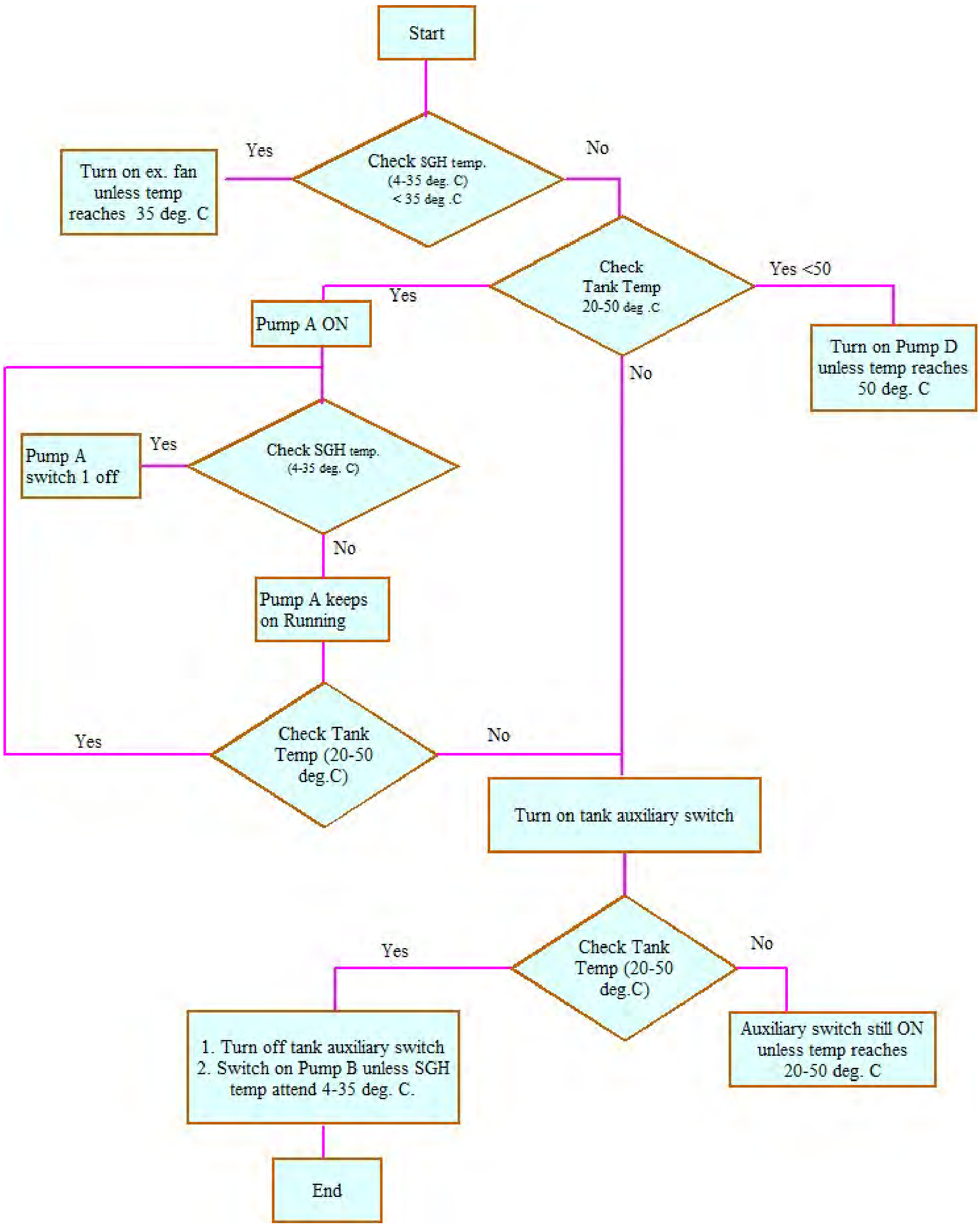


FIGURE 5. Temperature and humidity control flowchart.

TABLE 2. Maximum and minimum temperature and humidity inside SGH.

	Temperature (°C)			Humidity (%RH)		
Seasons	**Maximum**	**Average**	**Minimum**	**Maximum**	**Average**	**Minimum**
Winter	35.4	14	0.9	97.4	86	60
Summer	53.2	23.2	0.8	97.1	70.7	17.7

TABLE 3. Maximum and minimum temperature and humidity outside SGH.

	Temperature (°C)			Humidity (%RH)		
Seasons	**Maximum**	**Average**	**Minimum**	**Maximum**	**Average**	**Minimum**
Winter	8.5	6.2	−3.17	68.02	63.44	53.94
Summer	31.1	19.72	12.49	96.2	74.17	25.43

FIGURE 6. Crops grown inside SGH during winter.

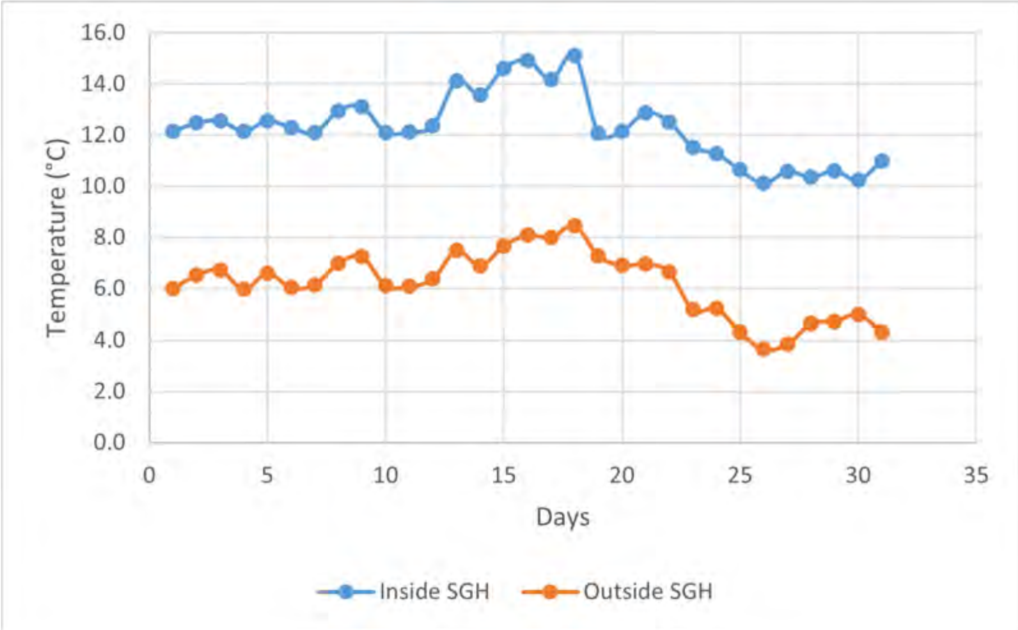
cooling system should also be considered for the large-scale implementation.

4. RESULTS AND DISCUSSION

The performance of the SGH was analysed using sensors and data loggers. The 12 × 7.5 m smart greenhouse underwent experiments with various crop varieties on a small scale during the winter season. The primary aim of the research was to determine the growth of crops inside the smart greenhouse during the winter season. The initial stage of sowing seeds and the harvest period were recorded. The yield for selected vegetables experimented within the SGH could be reaped within 5 to 15 weeks.

The crops experimented inside the SGH during the colder winter season are thriving. Figure 6 depicts broccoli, cabbage, radish, onion and chillies grown inside the SGH during the winter when the fields outside the SGH are barren.

The significant environmental parameters that affect the growth of crops are light, temperature and humidity. The humidity content in the air also affects the soil moisture content. Therefore, all these parameters are recorded and compared with the outside ambient environment. Figure 7 shows an average temperature compared with the interior and



(a)

(b)

FIGURE 7. Average day temperature compared in (a) December and (b) January.

exterior of the SGH in December and January 2023. With the help of an external heat source, the inside temperature of the SGH is improved. The minimum outside day temperature was recorded −3.17°C in January and is presented in Figure 8. The greenhouse inside temperature was compared and shown in Figure 9.

The temperature inside SGH is always high, as expected after applying interventions compared to the outside temperature. Similar comparisons were made for November, January, February, March and April. The data comparison reveals the SGH temperature is always higher by 7°C on average with outside temperature, as depicted in Figure 9.

The humidity inside and outside of SGH is also recorded, as humidity plays a pivotal role in determining the soil moisture content. Figure 10 shows the daily average humidity during the peak cold winter months. The detailed performance data of SGH can be seen in Dorji et al. (2024).

Figure 11 displays the daily average humidity difference for each day in December. On average, a

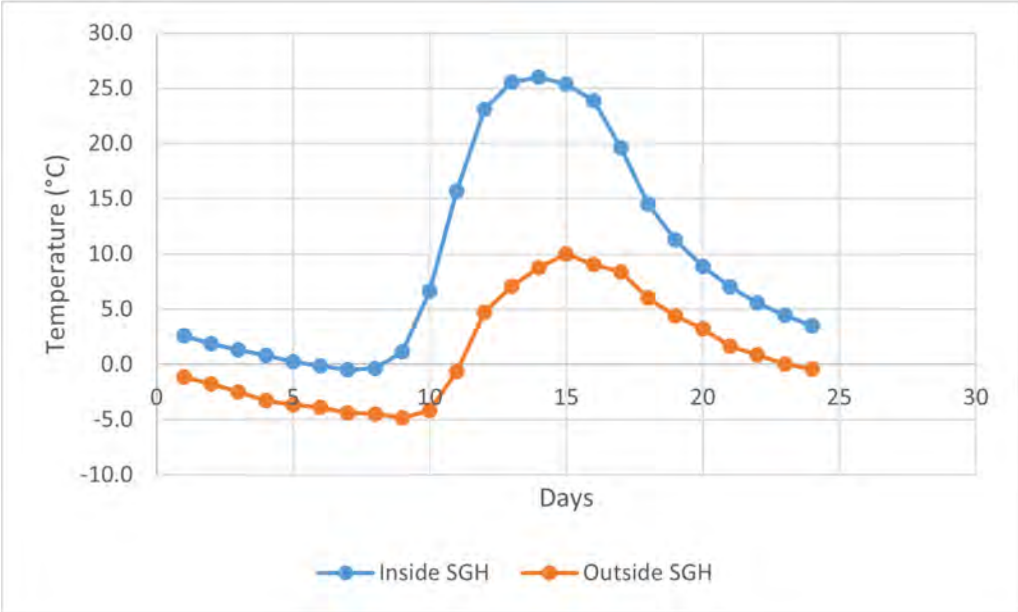


FIGURE 8. Minimum temperature compared on 18th January 2023.

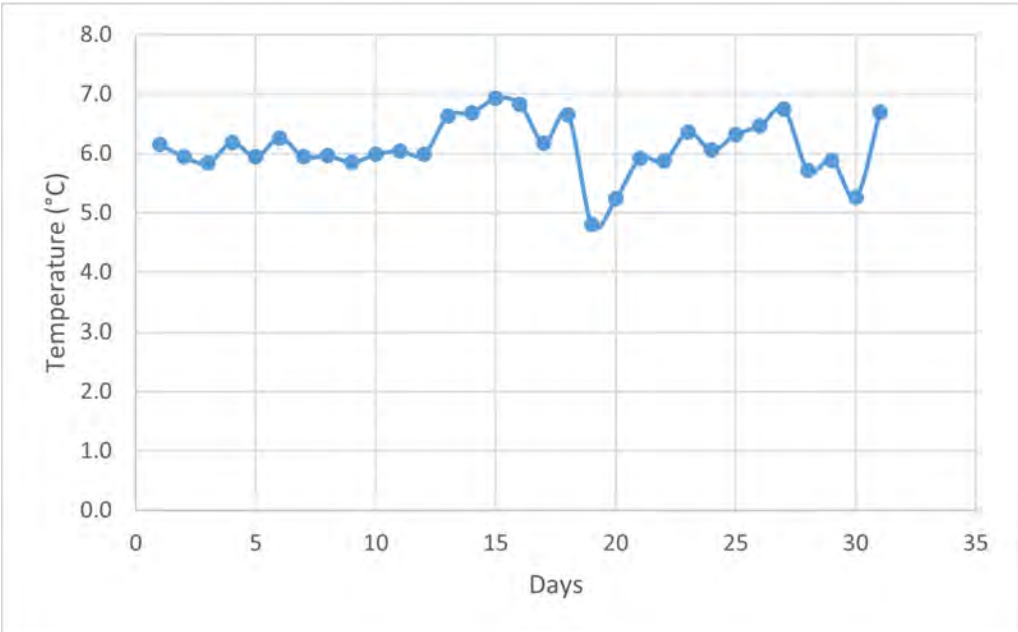


FIGURE 9. Daily temperature difference of December month.

humidity difference of 25% RH supports healthy seed germination and faster crop growth. It was also observed that there is a relationship between temperature and humidity: when the temperature drops, the moisture content in the air increases and vice versa. The increased humidity during low temperatures is attributed to the precipitation rate. Figure 12 illustrates the inverse relationship between temperature and humidity on one of the coldest days. Starting from midnight, the temperature decreases, and humidity increases.

Inside the SGH (assuming this refers to a specific location), the inverse relationship is only observed during the day when the temperature rises, as shown in Figure 13. This indicates that the temperature inside the SGH consistently exceeds the ambient conditions outside.

5. CONCLUSION

The experimental findings from the implementation of the SGH prototype in Genekha, Thimphu, Bhutan, situated in a temperate region, offer in-

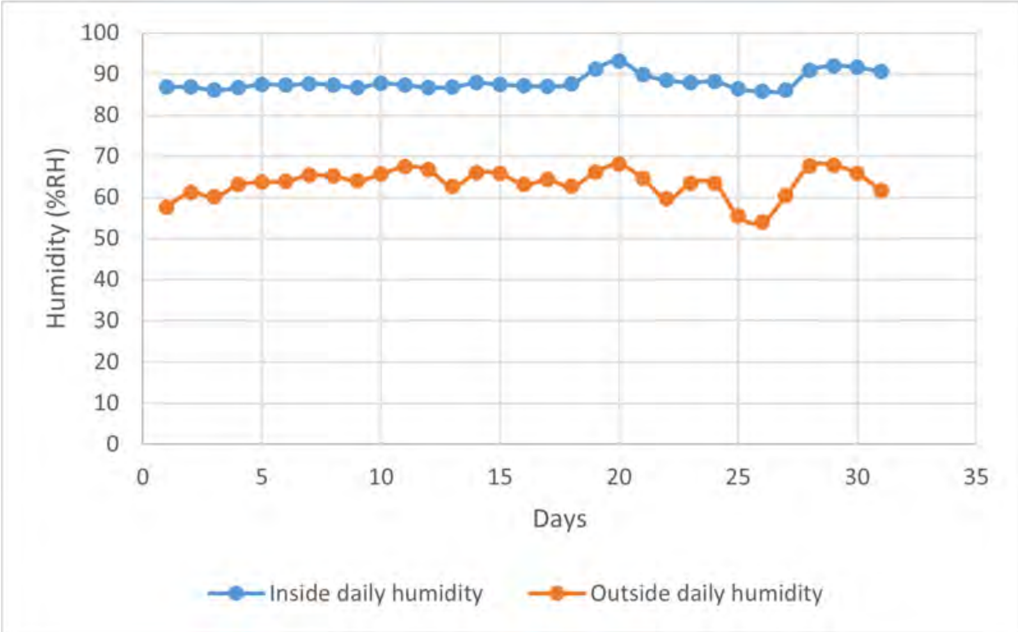


FIGURE 10. Daily average humidity comparison of December month.

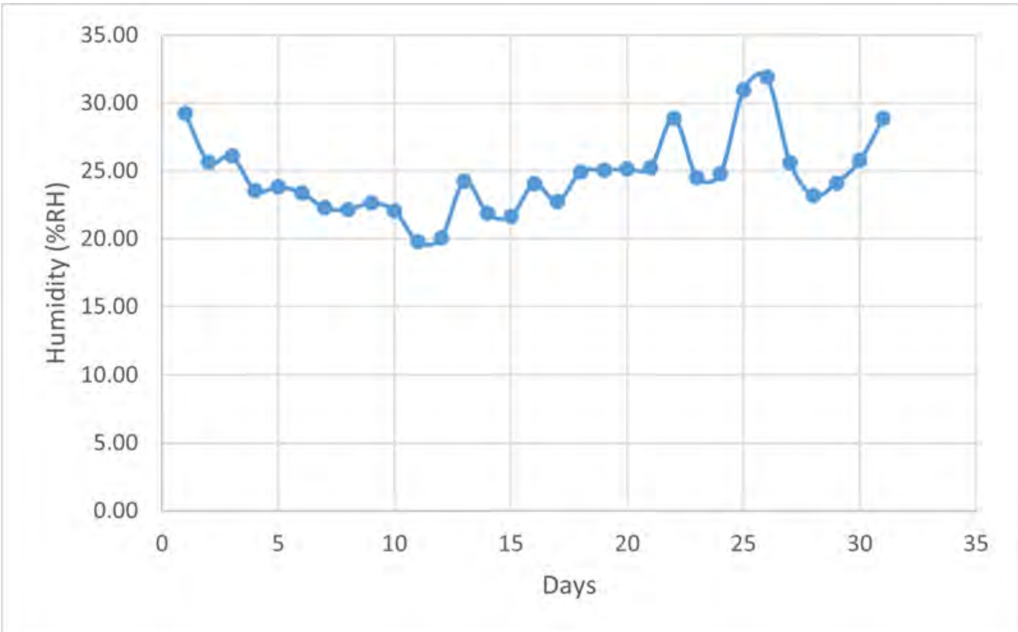


FIGURE 11. Daily average humidity difference of December month.

sights into its performance concerning both environmental conditions for crops and their growth.

The SGH operates without an external heating source during the daytime. However, when temperatures drop below freezing, the hot water circulation pump activates, providing necessary heating, primarily during the early morning hours. The integration of SWHS (Solar Water Heating System) significantly improves the SGH environment, fostering favourable conditions for crop growth. This accomplishment aligns with the research objective of converting underutilised winter lands in temperate regions into year-round cultivable spaces. This expanded cultivation area is poised to enhance land utilisation rates and subsequently improve food production.

Throughout the experimentation, a notable average temperature difference between the interior and exterior of the SGH was observed. On average, the interior temperature of the SGH increased by 7 °C during winter, indicating its suitability for scaling up SGH initiatives across the region.

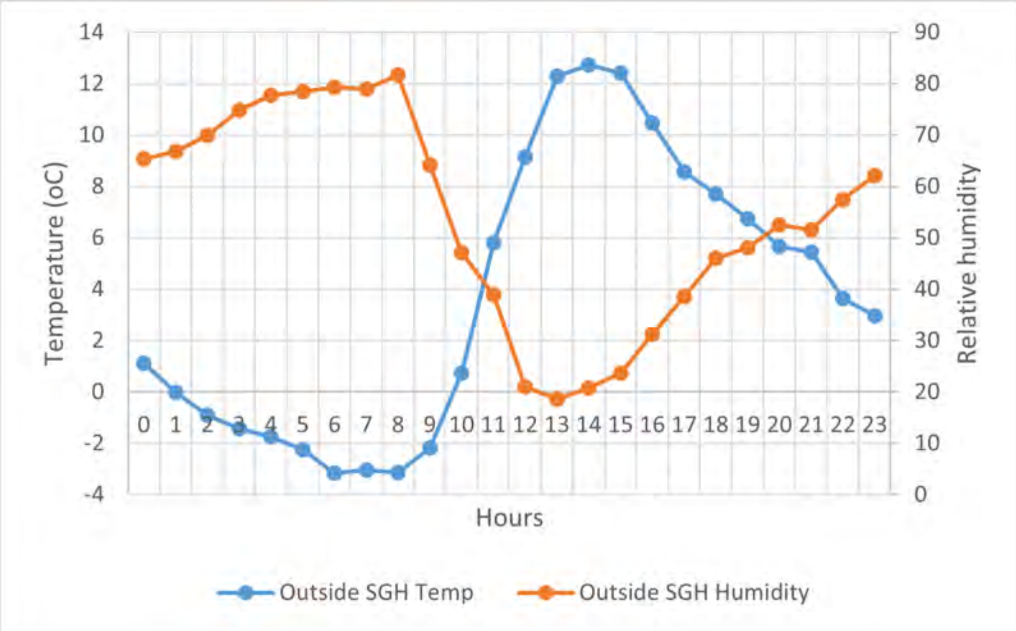


FIGURE 12. Relationship between humidity and temperature outside SGH.

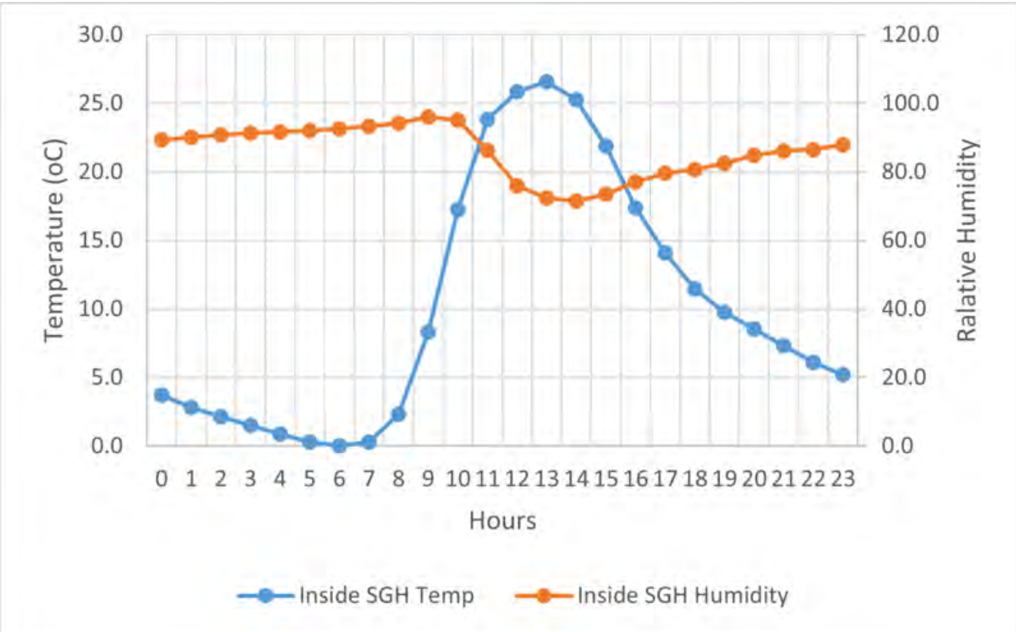


FIGURE 13. Relationship between humidity and temperature inside SGH.

The temperature and relative humidity data analysis shows an inverse correlation between the two. As the temperature increases, the relative humidity decreases since water turns into vapour and evaporates inside the greenhouse, as shown in Figures 12 and 13.

Multiple crop experiments were conducted, and their results are shown in Figure 6. While supplementary light via LDR sensors was provided to accelerate crop growth, certain crops, such as cucumber, exhibited fruiting tendencies when subjected to minimal light exposure. Upon adjusting the lighting based on relevant literature, the cucumber started fruiting after a few weeks without light exposure.

Moreover, the SGH demonstrated the ability to expedite seed germination and growth periods. For instance, broccoli, cabbage, spinach and cauliflower sown on November 12th, 2023, showed rapid germination within a week as shown in Figure 14, while the harvesting periods remained consistent. In the experiment inside greenhouse, it took 115 days to sow and reap the harvest.

FIGURE 14. Timeline of vegetables growth (a) Seed sown on 12-11-23, (b) seed germination on 20-11-23, (c) vegetable growth status on 10-12-23, (d) growth status on 24-12-23, (e) growth status on 09-01-24, (f) growth status on 21-01-24, (g) growth status on 21-02-24, (h) harvested on 06-03-24.

Vegetables such as chillies and beans grew well, but fruiting was not observed due to the high temperature inside the greenhouse as SGH temperature was set between 2 °C and 35 °C, which is generic for all crops. The general parameter setting for SGH is one of the limitations of this research. To get a clear picture of individual crop's growth characteristics, each greenhouse should experiment with only one vegetable species and classify the same family crops.

It is imperative to note that this report did not delve into a cost-benefit analysis of the project. However, this area presents an avenue for future exploration and consideration.

6. ACKNOWLEDGEMENT

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Original Article

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Sustaining livelihoods and building resilience: Policy implications for the Lower Mekong Basin

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ABSTRACT

The diverse agricultural landscape in the Lower Mekong Basin (LMB) encompasses vulnerable smallholder farmers, whose livelihoods are exposed to the impacts of natural hazards, environmental degradation and climate change. This paper aims to understand the vulnerability and risk drivers to agricultural livelihoods in the LMB and the existing capacities, policies and strategies to strengthen livelihoods. The inherent capacities (capitals) of these communities have helped them withstand and cope with the impacts of natural and anthropogenic stressors on their livelihoods. Skills, training and indigenous knowledge complemented by social networks and co-operatives are crucial to human and social capital. Similarly, water management, irrigation infrastructure, and demarcation and protection of natural resources have helped reduce potential impacts on agricultural activities and outputs. These are supported through financial instruments such as grants, subsidies and loans. On the other hand, while extant policies and strategies in LMB countries acknowledge the vital role of agriculture in socioeconomic development, the utilisation of robust assessment frameworks pertaining to livelihood resilience is limited. This paper discusses the potential advantages of incorporating integrated livelihood resilience assessments in current policies, which can help in designing context-specific strategies and optimise resource allocation for sustainable livelihood development in the LMB. However, to ensure robust assessments, stakeholders must harmonise assessment frameworks, promote community engagement, enhance data availability and strengthen institutional collaboration.

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KEYWORDS LOWER MEKONG BASIN, LIVELIHOOD, RESILIENCE, TOOL FRAMEWORK

HIGHLIGHTS

- Natural and anthropogenic stressors impact agricultural activities in the Lower Mekong Basin (LMB) and diminish livelihood security and resilience.
- Communities in LMB have developed several capacities (capitals) to cope with the stressors, which are complemented by several government policies and strategies.
- LMB policies prominently emphasise the promotion and protection of agriculture; however, there is a significant gap in specific and integrated assessment frameworks.
- Integrated resilience assessment frameworks and tools enable policymakers to prioritise resources and design interventions that address risks and strengthen livelihoods.
- A standardised and common assessment approach will be helpful at the regional and national levels operative through institutional collaboration and coordination for effective communication across different agencies and communities.

1. INTRODUCTION

Over the past decade, there has been a significant shift in the disaster risk management paradigm, transforming the response-centric approach to a mitigation-centric approach (Pal et al., 2022). On the other hand, supplemented by scientific research, real-world evidence and the realisation and acceptance among scientists, policymakers and the general public, the climate change debate has evolved from its 'reality' to a focus on mitigation and adaptation strategies (Gramberger et al., 2015; Hoang et al., 2018; Pilli-Sihvola & Väätäinen-Chimpuku, 2016; Tanner et al., 2015). The increasing impacts of climate-induced natural hazards are a testament to the need for global action for disaster resilience and sustainable development.

The Lower Mekong Basin (LMB) is located in Southeast Asia, covering parts of Cambodia, Lao PDR, Thailand and Vietnam. The river basin plays a significant role in the region's social, cultural, bio-physical and environmental nexus (Morton & Olson, 2018). More than sixty-five million people residing within the basin region depend on the river, its ecosystem, and natural resources for livelihood and economic activities, particularly in agriculture, transportation and energy production (Pal et al., 2023). However, the region faces numerous challenges, which create stress and cause changes in the Mekong River basin hydrology. Natural hazards such as floods and drought, and anthropogenic activities such as infrastructure development, urbanisation and environmental degradation exert multiple stresses on the river ecosystem and directly impact livelihood security and disaster resilience among the communities. Because of these challenges, the LMB countries and regional agencies such as the Mekong River Commission have formulated various policies and strategies to mitigate risks, cope with impacts and build resilience.

In this backdrop, the objectives of this study were as follows:

1. Identify the drivers of vulnerability and risk, existing capacities and the challenges faced in strengthening agricultural livelihoods in the LMB.
2. Synthesise existing policies and strategies implemented in the LMB for livelihood protection and resilience and identify gaps.
3. Provide recommendations to strengthen the existing policies for effective actions in enhancing the resilience of local livelihoods.

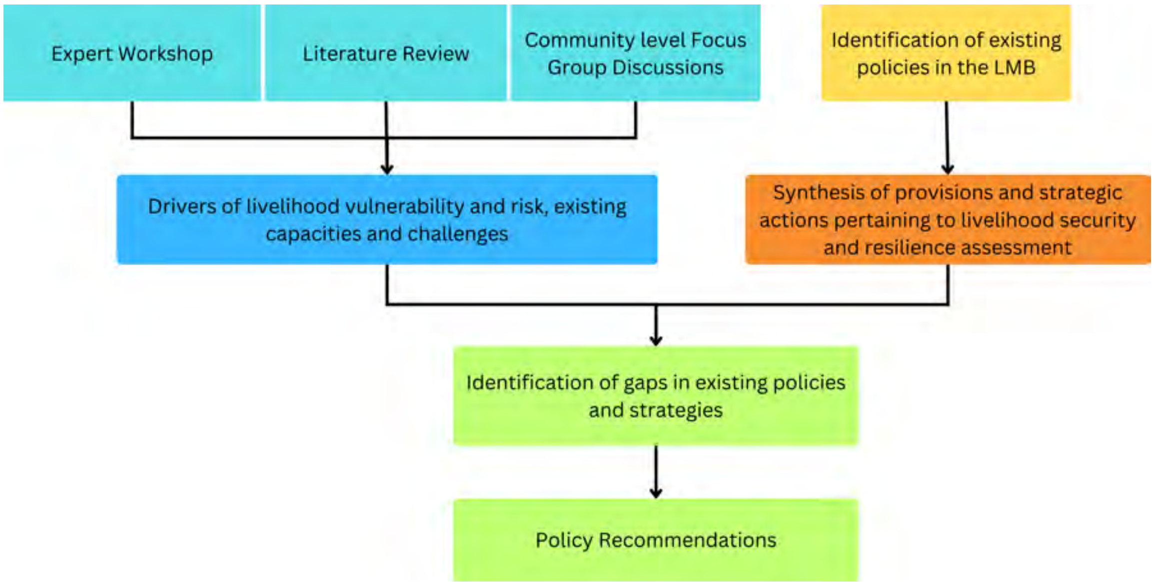

FIGURE 1. Methodological flowchart of the study for this paper.

2. METHODOLOGY

Figure 1 shows the methodological flowchart of the study.

In the first stage, discussions were conducted with experts and community people living in the LMB who depended on agricultural livelihoods. An expert workshop was conducted in Thailand with twelve researchers and practitioners in natural resource management, climate change, disaster risk reduction, risk governance and agriculture from three LMB countries, viz. Thailand, Vietnam and Cambodia. In addition, workshops were conducted with community people, local authorities and researchers as participants in the three LMB countries (approximately 20 people from each country), where focus group discussions were carried out. Five key questions guided the discussions,

1. What are the primary livelihood activities in the LMB communities?
2. What factors pose threat to livelihood activities?
3. What capacities do communities possess that reduce impacts on livelihood activities?
4. What must be done to enhance the resilience of local livelihoods?
5. What are the desired outcomes of livelihood activities?

The purpose of these workshops was to identify the major drivers of risk and vulnerability to agricultural livelihoods, understand their impacts and identify existing capacities of the local communities and stakeholders in risk reduction. The information generated through the review and workshops has been discussed through the lens of the Sustainable Livelihoods Framework (SLF) (DFID, 1999).

The information generated was further validated through a review of existing literature. A semi-systematic review process was utilised to identify, synthesise and analyse the literature on livelihood resilience in the LMB. Literature was searched on Scopus and Web of Science with the keywords: 'livelihood', 'lower mekong', 'livelihood+impacts', 'livelihood+vulnerability', 'livelihood+resilience', and 'agriculture+vulnerability'. Similarly, in the second stage, existing policies in all four countries in the LMB region were reviewed to understand how these policies addressed the issues surrounding livelihoods and resilience. The synthesis of the data collected through the two stages is used to identify gaps in existing policies and strategies and develop recommendations.

3. RESULTS AND DISCUSSION

Table 1 demonstrates the outcomes of the expert workshop and focus group discussions based on the five key questions. Similarly, Figure 2 shows the outcomes of the expert workshop and focus group discussions through the lens of the Sustainable Livelihood Framework (SLF). The figure depicts the linkages between factors that induce vulnerability in agricultural livelihoods in the LMB, the capacity of the communities across five livelihood capitals, strategies and instruments that may enhance resilience and the desired livelihood outcomes.

Livelihood systems in the LMB communities predominantly exhibit an agrarian character,

TABLE 1. Outcomes of expert workshop and community-focus group discussions on livelihood resilience aspects in the LMB.

Questions	Cambodia	Thailand	Vietnam
What are the primary livelihood activities?	— Farming (Paddy) — Horticulture (Vegetables) — Textile industry	— Farming (Paddy) — Livestock — Aquaculture	— Farming (Paddy) — Small-scale food industries — Aquaculture
What factors pose threat to livelihood activities?	— Floods — Drought — Wind storms	— Drought — Floods — Tropical storms	— Riverbank erosion — Floods — Changes in river flow
What are the desired livelihood outcomes?	— The ability of farmers to increase farm production and income — Proper use of natural resources	— Household food security — Increased income and financial status	— Ensure continuous operation of farming and small-scale business activities — Improved psycho-social well being
What capacities do communities possess that reduce impacts on livelihood activities?	— Flood Control Structures Early Warning & Agro-advisory — Irrigation infrastructure — Hazard-resilient crop varieties — Agricultural storage structures	— Drought/flood-tolerant plant species — Crop diversification — Precision farming (technological interventions) — Early warning system, information and advisory	— Water resource planning — Land-use planning and zoning — Structural mitigation measures (embankments, dykes, dams) — Early warning system — Community co-operatives and networks
What must be done to enhance the resilience of local livelihoods?	— Strengthen market and supply chain — Financial security (insurance) for farmers — Capacity building and technological advancement in agriculture — Increase the capacity of local authorities	— Comprehensive stakeholder engagement in planning and decision-making — Inter-agency collaboration and knowledge sharing — Targeted policies for farmers/agricultural communities	— Strategies for livelihood diversification, relocation and resettlement — Implement skill development training and education activities. — Provide technical and financial support for housing and agricultural assets.

relying significantly on paddy farming, livestock rearing, aquaculture or associated small-scale businesses. Agriculture, fisheries and forest products contribute significantly to household and national income, making up more than 10% of the GDP of the countries (World Bank, 2022). More than 6.8 million people in the region are directly engaged in farming, while an additional 18 million work in the agricultural sector as farm labour. However, without intensive farming systems and technological advancements, the communities heavily rely on the ecosystem and natural resources for agricultural practices (such as irrigation, grazing, forest products, etc.) (Morton & Olson, 2018). This reliance increases their exposure and vulnerability to the increased frequency and intensity of natural hazards, including floods and drought, as well as the adverse impacts of riverbank infrastructure development and environmental degradation (Pal et al., 2023).

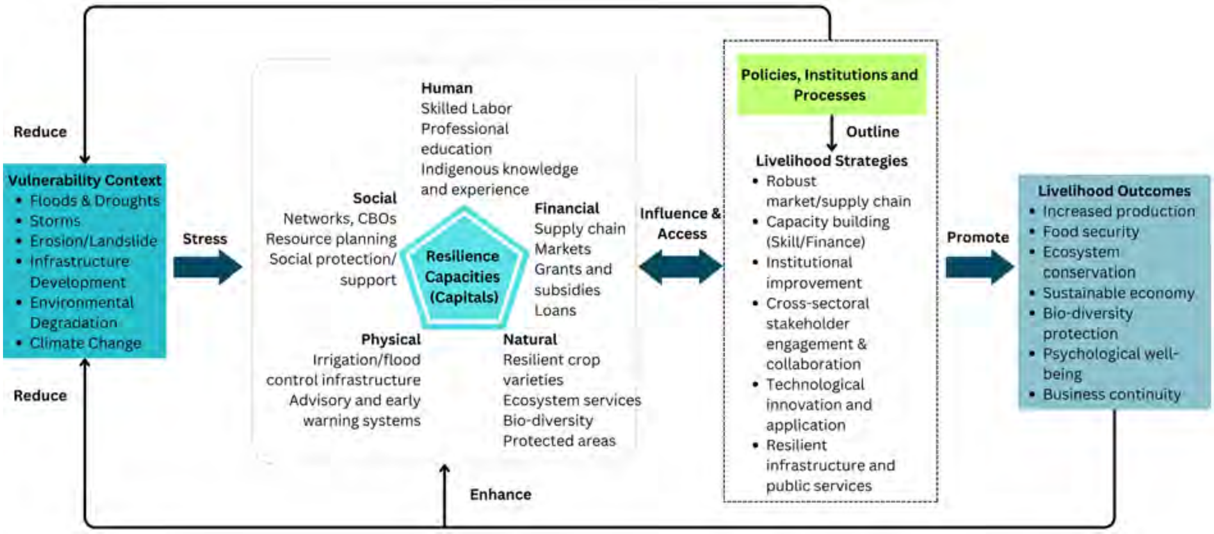

FIGURE 2. Understanding livelihood resilience perspective for the LMB region through the Sustainable Livelihoods Framework.

3.1. Factors impacting resilience of livelihoods in the LMB

LMB's agrarian livelihoods are highly dependent on natural resources and the environment. Hence, changes and variations in ecosystem services due to natural and anthropogenic factors have a direct impact on livelihood activities and outcomes, as discussed below.

3.1.1. Natural hazards

The LMB region is prone to both flooding and drought. While the regular flood cycle is a vital component of the local livelihoods, the increasing frequency and severity of floods in recent years have the potential to impact human and economic activities adversely. Floods destroy crops, livestock, and infrastructure, leading to substantial economic losses and food insecurity (Arias et al., 2019; Hoang et al., 2018; K. V. Nguyen & James, 2013). The average annual cost of floods in the LMB is estimated to range between US$ 60–70 million, with Cambodia and Vietnam suffering a higher proportion of losses (Christopher, 2012).

The LMB has also been experiencing frequent drought; the likelihood of annual meteorological drought is 0.40 to 0.45 per year in Lao PDR and Thailand and 0.30 to 0.35 per year in Cambodia and Vietnam (Christopher, 2012). Drought and low river flow have widespread impacts, including diminished agricultural productivity, environmental degradation, and reduced energy production, among others that have a direct impact on the local livelihoods (Abhishek et al., 2021; Thilakarathne & Sridhar, 2017). Although the exact cost estimates are not available, the MRC estimates drought impacts to be more significant than floods, and appropriately so, with individual drought such as the 2004–05 drought in Cuu Long Delta in Vietnam costing about US$ 45 million.

3.1.2. Riverbank infrastructure development

The construction of dams, embankments and other riverbank infrastructure projects in the LMB region has significantly altered the natural flow of rivers (Pokhrel et al., 2018). As of 2023, more than 90 hydropower projects have been constructed in the LMB region, along with other synergistic infrastructure and services such as irrigation, transportation and disaster management (MRC, 2014). However, while there are several economic gains, such infrastructure development disrupts the ecosystem and natural resources such as a decline in fisheries, forests, wetlands and mangroves that are estimated to cost up to US$168 billion by 2040 (MRC, 2014). Disrupted river ecosystems and altered river flow negatively impact the livelihoods of communities dependent on fishing, agriculture and other water-based activities.

3.1.3. Environmental degradation

The pressure exerted by population growth and socio-economic development in the LMB has posed considerable challenges for the river basin, ecosystem and communities. The increasing population (expected to rise to about 83 million in 2060) coupled with rapid industrialisation and urbanisation will lead to environmental degradation, including deforestation, soil erosion and water pollution, which further compounds the challenges faced by agricultural communities in the LMB (Thu Trang & Loc, 2021). Unsustainable land and water management practices, as well as the use of agrochemicals, have led to a decline in agricultural productivity and biodiversity loss, threatening the long-term livelihood security of these communities (T. D. Dang et al., 2018; Pokhrel et al., 2018; Spruce et al., 2020). Studies show that dam construction has severely disrupted the sediment flow in the LMB rivers, reducing the volume of sediment by more than half between 1994 and 2014 (WWF, 2018), further exacerbated by unsustainable sand mining to fulfill the increasing demand in the construction industry. Similarly, the LMB has also experienced dramatic changes in land use and land cover (LULC); one study found that between 1988 and 2017, about 21% of the area in the Mekong Basin had undergone LULC changes, attributed mainly to changes in forests into shrimp farms, cultivable lands and built-up area (Li & Hong, 2022).

3.1.4. Vulnerability to climate change

The LMB ecosystem is highly complex, dynamic and fragile and is recognised as one of the region's most vulnerable to the impacts of climate change. These impacts have gradually become evident, affecting the livelihoods of millions relying on the river's natural resources. According to research conducted by the MRC, the average annual basin-wide increase in temperature could be between 0.4 °C to 3.3 °C by 2060, while average annual rainfall may vary between 16% reduction (in dry climate scenario) or 17% increase (in wet climate scenario) (MRC, 2017). Similarly, Talberth and Reytar (2014) estimate an annual net economic cost of nearly US$ 364 billion due to climate change by 2030 in the LMB countries; losses in labour productivity are expected to be the most significant, followed by impacts of sea level rise and reduction of agriculture and fisheries production.

The cumulative effect of floods, droughts, riverbank infrastructure development, and environmental degradation and climate change have significant impacts on the traditional livelihood activities of agricultural communities in the region (Kura et al., 2017; Myint, 2014; Thu Trang & Loc, 2021). Many farmers and fishers struggle to sustain their livelihoods, experiencing reduced income, limited market access and increased vulnerability to poverty (Nguyen & Sean, 2021). The loss of livelihood activities also has broader socioeconomic implications, as it undermines the region's food security, exacerbates inequality and perpetuates rural-urban migration.

3.2. Livelihood resilience capacities

The livelihood resilience concept introduces five major capitals (assets): Human, Financial, Natural, Physical and Social as shown in Figure 1 above. In agricultural communities such as the LMB, the human capital, determined by the size of the household and its labour force has significant implications on livelihoods, especially given the challenges of labour shortages resulting from migration and a shift towards more formal sectors of trade (Huy & Khoi, 2011). Human capital in the LMB is enhanced by the availability of skilled labour in the agricultural sector, and the proficiency and expertise of the community's workforce. This is achieved by introducing professional and formal education and specialised training to community members (Tran et al., 2023). In addition, using indigenous knowledge and experience can facilitate in enhancing sustainability of livelihoods (Phu, 2023).

Similarly, LMB communities also rely on financial capacities to secure livelihoods. Communities rely on access to markets and supply chains (Wong, 2006) and broader economic and financial instruments to strengthen their capacity to invest in agriculture and generate income. This is supported through accessibility to grants, subsidies and loans, which, in many cases, are explicitly targeted to the agricultural sector. Considering the LMB communities' heavy reliance on natural resources for their livelihoods, natural capital plays a significant role. To combat the impacts of natural hazards, climate change and anthropogenic factors, farming communities have been using improved and resilient crop varieties (Ho et al., 2021), implementing crop diversification strategies (Tung, 2017), polyculture and composite farming to reduce risks. Similarly, the demarcation of protected areas including community-based conservation activities has helped safeguard biodiversity and ecosystem services, ultimately improving agricultural outputs.

The LMB countries have also mainly invested on physical infrastructures to control and mitigate risks. Infrastructure such as flood control structures designed to mitigate the impact of flooding events, early warning and advisory systems for timely communication of potential threats, irrigation infrastructure supporting agricultural activities, and strategies for optimal land allocation and use through land-use planning and zonation has helped control hazards, reduce exposure of agricultural land and activities towards hazards and increase security. Finally, social capital, including the strength and extent of community networks and collaborative ventures through co-operatives, is essential to enhancing economic and social outcomes by reducing and transferring risks across a wider group of people. Similarly, LMB communities rely on cultural and religious activities to foster cohesion, unity and collaboration to withstand and cope with the impacts of natural hazards. This is complemented by social protection and security schemes implemented by the government and other organisations.

3.3. Policies and strategies on livelihood security and resilience in LMB

Lower Mekong Basin countries have developed and implemented several policies and strategies aimed at multi-dimensional socioeconomic development. They focus on sustainable agriculture, water resource management, climate change adaptation and community-based approaches. These efforts aim to improve food production, enhance income generation, and build resilience to climate and environmental challenges, benefiting local communities in the region. A brief synopsis of major policies and strategies, their strategic objectives or goals directed towards agricultural livelihoods and the provisions regarding vulnerability, risk or resilience assessment is given in Table 2.

3.3.1. Emphasis on promoting agricultural livelihoods

In Thailand, the National Strategy (2018–2037) is oriented towards augmenting societal resilience and addressing agricultural and food security concerns by integrating agricultural management practices. This includes initiatives to increase agricultural productivity, foster employment within the agricultural sector and elevate farmers' per capita income. Additionally, the 20-year Agriculture and Co-operatives Strategy (2017–2036) is directed towards fortifying the resilience and competencies of individual farmers and farmer institutions, concurrently advancing the productivity and quality benchmarks of agricultural commodities. Similarly, the Agricultural Development Strategy outlined in the Twelfth National Economic and Social Development Plan (2017–2021) focuses on strengthening agricultural production. It emphasises developing and maintaining water storage systems, strategically planning crop planting aligned with water availability and safeguarding potential agricultural land. The strategy seeks to broaden opportunities for farmers to access land, thereby supporting their livelihoods. Concurrently, the Climate Change Master Plan (2015–2030) is designed to guide agencies and organizations in formulating mechanisms, tools and action plans dedicated to climate change adaptation across multiple sectors, including agriculture, rural development and livelihoods.

The Agriculture Restructuring Plan 2021–2025 of Vietnam aims to enhance agricultural products' quality, added value, and competitiveness while prioritising environmental and ecological protection. By doing this, the plan seeks to elevate rural populations' income, ensuring food and livelihood security. Similarly, the Sustainable Agriculture and Rural Development Strategies for the Period 2021–2030 with a Vision Toward 2050 outlines strategies to improve socio-economic and environmental dimensions of agriculture with an emphasis on increasing farmer's incomes and quality of life. Moreover, it also aims to enhance the resilience of agricultural livelihoods through diversification, poverty alleviation programs and equitable development across all regions. Resilience building of agricultural livelihoods is also outlined in Vietnam's 5-Year Socio-Economic Development Plan (2016–2020), which concentrates on agricultural restructuring, increasing the efficiency of agricultural production to enhance the lives of farmers and overall rural development. Finally, the National Strategy for Climate Change Until 2050 prioritizes urgent solutions to reduce vulnerability and enhance resilience against climate change impacts. The strategy emphasises sustainable livelihood models, incorporating training, profession transition, technology assistance, and funding sources to support residents in areas vulnerable to climate change and its associated impacts.

In Cambodia, the National Strategic Development Plan 2019–2023 acknowledges the pivotal role of agriculture in contributing to multiple dimensions of national development. It aims to fortify the role of the agriculture sector in overall socio-economic development through employment, food security, poverty reduction and rural development. In concordance, the National Environment Strategy and Action Plan 2016–2023 envisions promoting the agriculture sector as a critical driver of economic development and aims to foster

TABLE 2. Policies and strategies developed by LMB countries for enhancing livelihood security and resilience in the region.

SN	Policy/Strategy	Goals/objectives on resilience of agricultural livelihoods	Provisions regarding vulnerability, risk and resilience assessment
Thailand			
1	National Strategy (2018–2037)	Developing agricultural and food security by integrating agricultural management, increasing agricultural productivity, increasing employment in the agricultural sector, and improving farmers' per capita income.	None
2	20-year Agriculture and Co-operatives Strategy (2017–2036)	Strengthening the farmers and farmer institutions. Increasing the productivity and quality standards of agricultural commodities.	None
3	Agricultural Development Strategy in the Twelfth National Economic and Social Development Plan (2017–2021)	Strengthening agricultural production by developing and maintaining water storage systems, planning the crop planting systems to match the availability of water, protecting potential agricultural land and expanding opportunities for farmers to access land for their livelihood.	Preparing maps on the risks from climate change that show the agricultural areas affected by the climate change for the community to jointly solve the problems, that show the vulnerable areas to floods, drought, landslides, problems from saltwater intrusion, transmission of plant and animal diseases, etc. Vulnerability assessments of agricultural land and coastal areas are needed to update their risks and vulnerability for use in the preparation of the adaptation plan for the agriculture sector.
4	Climate Change Master Plan (2015–2050)	Action planning for resilience and adaptation to climate in high-priority sectors (including agriculture) Develop effective and comprehensive early warning measures such as pest and meteorological forecasting for the agricultural sector. Establish a climate-based agricultural insurance scheme.	Assess the impact of climate change on food security at national and local levels, considering the effects that future domestic and international demand for food will have on the food security, livelihood and nutritional quality of food available. Develop agricultural risk maps that will aid in forecasting the occurrence of disasters such as outbreaks of plant and animal diseases, flooding, drought, landslides, saltwater intrusion, and other extreme weather events.

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TABLE 2. *Continued.*

SN	Policy/Strategy	Goals/objectives on resilience of agricultural livelihoods	Provisions regarding vulnerability, risk and resilience assessment
Vietnam			
1	Agriculture Restructuring Plan 2021–2025.	Continue to restructure the agricultural sector towards sustainable agricultural development, improve quality, added value and competitiveness of agricultural products; environmental and ecological protection; improve income for people in rural areas; ensure food security and national defence.	None
2	Sustainable Agriculture And Rural Development Strategies For The Period 2021–2030 With A Vision Toward 2050	Develop agriculture effectively and sustainably in terms of economy, society and environment. Improving income, life quality, role and position of people involved in agricultural production; creating non-agricultural careers to develop diversified livelihoods, reduce poverty sustainably for rural people and ensure equal development opportunities among regions.	Build a system of warning, forecasting and determining risks as the basis of synchronous solutions, and proactively protect production against risks of epidemics, natural disasters, environmental pollution, etc.
3	5-Year Socio-Economic Development Plan 2016–2020	Concentrate on agricultural restructuring, improving the efficiency of agricultural production and new rural development associated with improving farmers' lives.	None
4	National Strategy for Climate Change Until 2050	Implement urgent solutions for reducing vulnerability and increasing resistance against climate change impact; at its highest priority, ensure safety and livelihood for inhabitants in regions that are potentially heavily affected. Develop sustainable livelihood models, prioritise training, profession transition, technology assistance, and funding source approach for inhabitants of areas prone to climate change and its impacts.	Assess impact, vulnerability, risk, loss, and damage caused by climate change in the planning and investment in infrastructure development of coastal and island industrial parks, urban areas, residential areas, and relocation areas on the basis of classifying areas with disaster risks and climate change scenarios. Assess and classify areas based on climate change risks and natural disasters; produce natural disaster warning maps; develop and build a national database on climate change.

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TABLE 2. *Continued.*

SN	Policy/Strategy	Goals/objectives on resilience of agricultural livelihoods	Provisions regarding vulnerability, risk and resilience assessment
Cambodia			
1	National Strategic Development Plan 2019–2023.	Promote the agriculture sector and rural development, the strategic goal is to strengthen the role of the agriculture sector in generating jobs, ensuring food security, reducing poverty and developing rural areas.	Formulating guidelines for local risk assessments and their use in local development planning, with a complement of traditional, indigenous and local knowledge and practices, and science and technology.
2	National Environment Strategy and Action Plan 2016–2023	Promotion of the agriculture sector in supporting economic growth, ensuring equity, reducing poverty, securing food security, and promoting the development of the rural economy.	Promote the application of informed environmental decision-making processes and tools, and proper assessment and monitoring based on scientific evidence and knowledge.
3	Cambodia Climate Change Strategic Plan 2014–2023	Increase capacity to address climate-induced opportunities in agricultural production systems, ecosystems and protected areas such as (i) Agricultural diversification (e.g. crops, livestock etc.), (ii) Increase in productivity (e.g. crops, fisheries, livestock, forestry etc.), (iii) Opportunity for new cropping, (iv) Watershed and ecosystem management.	Use existing vulnerability and risk assessments and conduct new ones where necessary to prioritise adaptation measures for key regions of Cambodia, such as coastal zones, highlands, rural and urban areas.
4	Plan of Action for Disaster Risk Reduction in Agriculture 2014–2018	To enhance the capacities and resilience of farmers and communities to threats and disasters affecting agriculture and rural livelihood.	Improve, in coordination with other relevant stakeholders, the existing risks and vulnerability assessment methodologies from an agricultural perspective.
Lao PDR			
1	9th Five-Year National Socio-Economic Development Plan. (2021–2025)	Enhanced well-being of the people, including poverty alleviated in rural and remote areas, and people's livelihoods, cultural values, and media work improved; equal access to socio-economic development opportunities promoted and the rights of women and children protected.	Update disaster risk information at the central level and encourage localities to assess risks and create disaster risk maps; and support the development of provincial disaster risk reduction strategies and disaster preparedness plans for ten provinces, 20 districts and 80 villages.

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TABLE 2. *Continued.*

SN	Policy/Strategy	Goals/objectives on resilience of agricultural livelihoods	Provisions regarding vulnerability, risk and resilience assessment
2	Agriculture Development Strategy to 2025 and Vision to 2030.	To enable more inclusive and efficient agricultural and food systems by the creation of employment, income generation for people, environmental protection and contribute to stability and balance of ecological system.	Carry out the study and collection of information to identify and map out risky areas where natural disasters often occur and may occur, such as downstream areas along the rivers that are at risk on flooding, areas that are at risk on drought, areas that often affected by the outbreak of animal and plant diseases, areas that are at risk on soil erosion and other risks by applying modern techniques or technologies in the determination and assessment of events such as the use of satellite image, aerial photos/maps, applying modern warning systems and others.
3	Natural Resources and Environment Strategy 2016–2025.	Development and management of natural resources and environment, and to ensure sustainable social economic development, and build capacity for climate change adaptation and mitigate the risks of natural disaster. Reduce the risk and impact of natural disasters to livelihood, agricultural products, public and private investment.	Implement research programs to study and disseminate the updated climate change scientific data and develop maps of vulnerable and high-risk disaster areas to support in policy and strategy planning, national socio-economic development plans of line sectors at central and local levels and for people's livelihood.
4	National Strategy on Climate Change 2010	Develop the capacity of the country in mitigating and adapting to changing climatic conditions in a way that promotes sustainable economic development, reduces poverty, protects public health and safety, enhances the quality of Lao PDR's natural environment, and advances the quality of life for all Lao people.	Undertaking a country-specific, sector-based research on the vulnerability, impacts and adaptation options of the agricultural sector in Lao PDR at the macro-scale as well as the village level.
5	Plan of Action for Disaster Risk Reduction and Management in Agriculture 2014–2016	Prevent and reduce the impacts of natural disasters and climate change on farming communities and the agricultural sectors, and contribute to enhanced resilience of livelihoods for sustainable and fair food and nutrition security in Lao PDR.	Upgrade climatic risk and vulnerability assessment tools and methods, provide agro-climate information products along agricultural cropping cycles and ensure timely delivery of hazard-specific early warnings targeted to the needs of farmers and other agriculture-dependent communities.

sustainable agricultural practices in the country. Similarly, the Cambodia Climate Change Strategic Plan 2014–2023 aims to address climate-induced challenges in agricultural production systems, ecosystems and protected areas. It outlines strategies such as agricultural diversification, improving agricultural practices for increased productivity, exploration of new cropping opportunities, and ecosystem management. Complementing these initiatives, the Plan of Action for Disaster Risk Reduction in Agriculture 2014–2018 seeks to enhance the capacities and resilience of farmers and communities. The focus is on mitigating threats and disasters affecting agriculture and rural livelihoods, aligning with broader national strategies for sustainable development.

The well-being of rural and remote populations in Lao PDR is emphasised in the 9th Five-Year National Socio-Economic Development Plan (2021–2025), focussing on poverty reduction, improvement of livelihoods and enhancement of cultural values. A more specific policy document, the Agriculture Development Strategy to 2025 and Vision to 2030 aims to establish more inclusive and efficient agricultural and food systems. The strategy emphasises strengthening the agricultural sector to increase employment opportunities and household income in rural communities and foster environmental protection and ecosystem conservation. Sustainable livelihoods are also embedded within the Natural Resources and Environment Strategy (2016–2025), which is centred on developing and managing natural resources and the environment. The strategy emphasises reducing risks and impacts from natural disasters on livelihoods, agricultural products, and public and private investments. Concurrently, the National Strategy on Climate Change 2010 also has specific provisions directed towards promoting sustainable economic development and livelihoods in the country by enhancing capacity to mitigate and adapt to climate change. Finally, the Plan of Action for Disaster Risk Reduction and Management in Agriculture 2014–2016 provides a much more concentrated action on preventing and reducing the impacts of natural disasters and climate change on farming communities and the agricultural sector to contribute to enhanced resilience for sustainable and equitable food and nutrition security in the country.

3.3.2. Evidence of livelihood vulnerability, risk and resilience assessment actions

Although existing policies have emphasised strengthening agricultural livelihoods in the LMB countries, there is limited evidence of robust assessment frameworks and approaches to understand the current levels of livelihood resilience.

Thailand's National Strategy and the 20-Year Agriculture and Co-operatives Strategy lack explicit consideration of vulnerability, risk, and resilience assessment. At the same time, the Twelfth National Economic and Social Development Plan and Climate Change Master Plan emphasise integrating vulnerability assessments, specifically in mapping and assessing impacts on national and local food security. These plans outline developing risk maps to assess the potential impact of climate change on agricultural regions to natural hazards such as floods, drought, landslides, saltwater intrusion, and the transmission of plant and animal diseases.

In Vietnam, the Agriculture Restructuring Plan and the 5-Year Socio-Economic Development Plan do not explicitly address vulnerability, risk or resilience assessments. On the other hand, the Sustainable Agriculture and Rural Development Strategy prioritizes risk determination as the foundation for comprehensive solutions. This includes proactive measures to safeguard water production against epidemics, natural disasters and environmental pollution. The National Strategy for Climate Change has a much more comprehensive provision for assessing impacts, vulnerability, risk, loss, and damage, including integrating disaster risk classifications into infrastructure development planning for coastal and island industrial parks, urban areas, residential areas and relocation zones. The strategy also emphasises developing natural disaster warning maps and the establishment of a national database on climate change.

Cambodia's National Strategic Development Plan incorporates explicit provisions and guidelines for localised risk assessments to inform local development planning through scientific and technological interventions and with traditional, indigenous and local knowledge. The National Environment Strategy and Action Plan advocates utilizing evidence-based assessment and monitoring tools for informed environmental decision-making, including sustainable agricultural practices. Similarly, the Cambodia Climate Change Strategic Plan prioritises both existing vulnerability and risk assessments and supplemental information through new evaluations to assess, identify and prioritise adaptation measures across different sectors and regions, including agriculture. The Plan of Action for Disaster Risk Reduction in Agriculture is much more targeted towards agricultural risk mitigation and aims to enhance existing agricultural risk and vulnerability assessment methodologies through collaboration with relevant stakeholders.

In contrast to previous countries, the Socio-Economic Development Plan of Lao PDR has specific provisions for developing central-level disaster risk information, encouraging localities to assess risks, and crafting disaster risk maps. The Agriculture Development Strategy also involves applying modern techniques like satellite imagery, aerial photos, and advanced warning systems to study and map high-risk agricultural areas prone to natural disasters. Similarly, the Natural Resources and Environment Strategy and the National Strategy on Climate Change have specific provisions regarding sector-specific research on climate change data and developing vulnerability maps to identify disaster-prone areas. These strategies also outline several adaptation options for the agricultural sector at both macro and village levels. Finally, Lao PDR's Plan of Action for Disaster Risk Reduction and Management in Agriculture has specific provisions on using climate risk and vulnerability assessment tools to generate agro-climate information products and deliver hazard-specific warnings and advisories tailored to the needs of farming and agriculture-dependent communities.

A synthesis of the extant policies within the Lower Mekong Basin (LMB) countries, namely Thailand, Cambodia, Lao PDR, and Vietnam shows the importance of agricultural livelihoods in the region, demonstrated by the diverse array of strategic objectives, provisions and guidelines embedded within their sectoral development plans (agriculture, environment) and the disaster risk management and climate change strategies. Similarly, in line with the paradigm shift in risk management in global frameworks such as the SDGs, SFDRR and IPCC, the current policies also incorporate several actions on vulnerability, risk and resilience assessments, albeit in different sectors and scales. However, a disjoint can be seen in assessing the vulnerability, risk, and resilience of livelihoods from a multi-dimensional perspective. Present assessment guidelines and initiatives predominantly concentrate on physical assessments, neglecting the identification of underlying attributes and interlinkages within livelihoods within intricate socio-economic and ecological systems of the LMB region.

The current policies exhibit a gap in comprehensive strategies and action plans for the integrated assessment of vulnerabilities and resilience concerning agricultural livelihoods. It seems imperative to broaden the comprehension and understanding of livelihoods by exploring multi-faceted aspects. The role of five capitals (human, social, natural, financial and physical) on livelihood outcomes and the influence and impact of policies, institutions and support mechanisms in building livelihood resilience can only be adequately measured through a robust assessment framework that integrates these factors, within the specific local paradigm of the LMB. Such a framework can be a benchmark for planning, developing, and implementing targeted strategies and actions conducive to fortifying and enhancing resilience within the agricultural sector.

3.4. Importance of resilience assessment, framework and tools

Addressing the complex challenges faced by agricultural communities living in the LMB requires a comprehensive and multi-dimensional approach (Pal et al., 2023). Efforts must be made to enhance livelihood security and disaster resilience through sustainable land and water management practices, improved infrastructure planning, strengthened early warning systems, and the promotion of alternative income-generating activities (Gunawardana et al., 2021; Myint, 2014; Phoumin & Minh Thu, 2020).

Considering the widespread impacts of natural and anthropogenic hazards across multiple sectors in the LMB, there has been an increasing recognition of assessment to measure the vulnerabilities and capacities of communities. An interdisciplinary approach to address the grounded solutions can provide the basis for integrated multi-hazard resilience assessment frameworks. The results obtained through these frameworks will provide valuable information for decision-making by capturing the unique challenges these communities face and identifying opportunities for intervention.

3.4.1. Implications for disaster management

Assessment frameworks integrating livelihood and resilience can significantly affect effective disaster management in the LMB (Cimellaro et al., 2010; Hansson et al., 2020; Lecegui et al., 2022; Tariq et al., 2021). By providing a comprehensive understanding of vulnerabilities in the existing livelihood systems, these frameworks enable policymakers and practitioners to prioritise resources, design targeted interventions and develop robust strategies that can promote sustainable livelihoods, thereby enhancing the resilience of the communities. For instance, identifying livelihood and economic activities prone to failure during floods and drought can inform investments in strengthening these activities (McCallum et al., 2016; K. V. Nguyen & James, 2013). Integrating the established theoretical principles of sustainable development, resilience and climate change into these frameworks, policymakers and development agencies can anticipate and address emerging risks and uncertainties associated with future hazards.

3.4.2. Promoting sustainable development

Resilience assessment frameworks also contribute to sustainable development in the LMB. By considering multiple dimensions of resilience, these frameworks help recognise the interlinkages between disaster risk reduction, poverty alleviation and environmental sustainability. For instance, by evaluating the impacts of riverbank infrastructure development on communities' livelihoods and ecosystems, these frameworks can guide infrastructure planning and design that promote sustainable development (Hishan et al., 2021; Phoumin & Minh Thu, 2020). Additionally, by assessing the social and economic factors that influence resilience, such as access to education, healthcare and markets, these frameworks can inform policies that address systemic vulnerabilities and promote inclusive development.

4. CONCLUSION & POLICY RECOMMENDATIONS

The livelihoods of LMB communities face considerable exposure to environmental and anthropogenic hazards and stressors. Events such as floods and droughts have a profound impact on their way of life, mainly since a substantial portion of the population depends directly on the river's ecosystem and basin hydrology for their economic activities. To effectively manage risks and enhance disaster resilience in the LMB, it becomes crucial to recognise the intricate interlinkages and interactions between livelihoods and resilience perspectives. By understanding and addressing these connections, efficient actions can be taken to mitigate the impact of disasters and safeguard the well-being of the communities in the region.

Enhancing the disaster mitigation process is best achieved by empowering local communities to build their inherent capabilities for handling impacts effectively. This necessitates appropriate policy interventions to address disparities, which can be identified through a comprehensive study utilising critical dimensions and indices. Such studies enable a thorough understanding of the community's adaptation behaviour, livelihood risks, and potential sustainable approaches. However, ensuring these policies, strategies, and interventions are firmly rooted in scientific evidence is equally crucial. This requires robust assessment processes to gather reliable data, providing a solid foundation for guiding decision-making and enhancing the overall effectiveness of disaster management efforts.

The following key recommendations have been made to enhance resilience assessments in the LMB region, to aid development and risk management planning for sustainable livelihoods and disaster resilience.

- **Incorporate specific actions on agricultural livelihood resilience assessment in the LMB:** While agricultural production and associated livelihoods have been prioritised in several policies and strategies in the LMB countries, this paper identifies that a comprehensive assessment of livelihood resilience has not been prioritised yet. Considering the ever-increasing need and acknowledgment of the role of livelihood security in attaining overall disaster and climate resilience, specific actions must be included within the policies to act as a formal pathway.
- **Harmonise resilience assessment frameworks and toolkits:** It is crucial to establish a standardised and harmonised approach to resilience assessment across LMB communities. This can be achieved by developing a comprehensive tool that incorporates the various dimensions across multiple disciplines into a singular framework. By harmonising these tools, policymakers can ensure consistency, comparability, and effective communication of resilience information between different communities and stakeholders.
- **Promote community participation and ownership:** Resilience assessment frameworks and toolkits should prioritise community participation and ownership. Communities in the LMB are the ones most affected by disasters, and their local knowledge and perspectives are invaluable in understanding their vulnerabilities and designing appropriate resilience strategies.

Policymakers should actively engage communities throughout the assessment process, involving them in data collection, analysis, and decision-making. This participatory approach will foster a sense of ownership and empower communities to take proactive measures for disaster risk reduction.

- **Enhance data availability and accessibility:** Reliable and up-to-date data is essential for effective resilience assessment and planning. Policymakers should invest in data collection systems, including early warning systems, hazard monitoring networks and socio-economic databases. Furthermore, efforts should be made to ensure the accessibility and usability of data for stakeholders involved in resilience planning. This can be achieved through data-sharing platforms, user-friendly interfaces and capacity-building programmes that enable communities to interpret and utilise the data effectively.
- **Integrate climate change adaptation into resilience assessments:** Climate change poses significant challenges to disaster risk management in the Lower Mekong Basin. Resilience assessment frameworks and toolkits should incorporate climate change adaptation measures to address future risks. This includes considering projected climate scenarios, assessing climate-related vulnerabilities and identifying appropriate adaptation strategies. By integrating climate change considerations into resilience assessments, policymakers can enhance the long-term effectiveness of disaster risk management and planning efforts.
- **Strengthen institutional coordination and collaboration:** Effective resilience assessment and planning require close coordination and collaboration among various stakeholders, including government agencies, non-governmental organisations, community-based organisations and international partners. Policymakers should establish mechanisms for interagency coordination, ensuring that different sectors and levels of government work together seamlessly. Additionally, fostering collaboration between researchers, practitioners and policymakers can facilitate knowledge exchange, innovation and the adoption of best practices in resilience assessment and planning.

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Blue carbon ecosystems in the Coral Triangle: A perceptive approach to climate adaptation

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ABSTRACT

This paper offers a comprehensive synthesis of nine research papers from the Asia-Pacific Network for Global Change Research (APN) project titled "Enhancing Capacities of Local Stakeholders in Coral Triangle in Managing Blue Carbon Ecosystems for Climate Mitigation and Adaptation." These papers are organised into four key thematic areas: (1) assessing the status of mangrove degradation and its underlying factors, (2) exploring community perceptions of seagrass ecosystems and their associated services, (3) analysing local perspectives on sustainable tourism and its influence on blue carbon (BC) ecosystem services, and (4) discerning trends in research and coastal management strategies for BC ecosystems. The findings presented within these papers illuminate the intricate challenges surrounding BC ecosystems in the Philippines and Indonesia, underscoring a range of human-induced pressures and natural vulnerabilities. These studies emphasise the significance of incorporating community perceptions and socio-economic dynamics into the BC ecosystems' conservation and management strategies framework. The comparative insights derived from these papers hold vital implications for local stakeholders and policymakers. Practical training in Geographic Information Systems (GIS) can empower local communities to enhance their capacity-building efforts in the future. This is valuable guidance for shaping future BC ecosystem management plans and programs, particularly in a rapidly changing climate.

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HIGHLIGHTS

- Mangrove degradation, primarily driven by aquaculture expansion, calls for targeted conservation efforts.
- Seagrass ecosystems, often overlooked due to their submerged nature and limited public awareness, demand increased academic and practical attention for their preservation.
- Successful blue carbon initiatives hinge on active engagement with local communities and stakeholders, underscoring the importance of participatory approaches.
- Effective protection and conservation require aligning local regulations with national law enforcement, fostering coordinated efforts toward ecosystem preservation.
- Engaging local communities not only promotes sustainable management but also enhances livelihoods, highlighting the symbiotic relationship between conservation and well-being.

1. INTRODUCTION

Wetlands cover 6% of Earth's surface and hold approximately 12% of the world's carbon (Erwin, 2009). Among wetlands, mangroves play a particularly crucial role in carbon storage in their biomass and within their soils, contributing significantly to global carbon cycling (Zhao et al., 2022). The Ramsar Convention is an intergovernmental treaty that aims to protect, manage, and restore wetland ecosystems, including mangroves, seagrasses, and intertidal marshes. This convention can be strengthened by identifying and designating new Ramsar Sites, improving existing site management, and reducing the threats that lead to coastal wetland degradation and loss (Beers et al., 2020). In line with the objectives of the Paris Agreement established under the United Nations Framework Convention on Climate Change (UNFCCC), the term 'blue carbon' was coined in 2009 within a rapid response assessment report as part of a unique inter-agency collaboration (Alongi, 2018). Notably, the Asia-Pacific Network for Global Change Research (APN) has played a pivotal role in supporting global change research, especially related to climate mitigation, through its funding of collaborative projects across various sectors. APN, in this context, provided funding for the project titled "Enhancing Capacities of Local Stakeholders in Coral Triangle in Managing BC Ecosystems for Climate Mitigation and Adaptation". This project, which has now concluded, adopted a transdisciplinary approach involving communities, practitioners, and scientists, intending to empower local communities and ensure the sustainable use of BC ecosystems, as outlined on the APN website (2021).

This paper serves to summarise all the published papers produced within the framework of the APN-funded project, which has successfully concluded. In general, these publications offer valuable insights into the spatial distribution of existing management strategies and the common challenges faced in managing BC ecosystems across Indonesia and the Philippines. They underscore the importance of bridging science and policy to ensure the conservation and sustainable management of BC ecosystems. Additionally, they highlight how communities perceive BC ecosystem services through their awareness, utilisation, and management activities. This collective knowledge is a pivotal resource for informing future strategies and policy decisions in the era of climate change.

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2. THE FOUR GENERAL CATEGORIES OF THE PAPERS ON BC ECOSYSTEMS

The nine papers are divided into the following categories: (1) assessing the status of mangrove degradation and its underlying forces (2 papers); (2) exploring community perceptions of seagrass ecosystems and their associated services (3 papers); (3) analysing local perspective on sustainable tourism and its influence on BC ecosystem services (2 papers), and (4) discerning trends in research and coastal management strategies for the BC ecosystems (2 papers).

2.1. Assessing the status of mangrove degradation and its underlying forces

Two papers in this section analysed the perceptions of local coastal communities and their involvement in mangrove management. They also studied the driving forces behind mangrove forests and the degradation of their BC stock in the Philippines and Indonesia. Quevedo et al. (2022a) presented the importance of mangrove ecosystems in Eastern Samar province, Philippines, for bridging terrestrial and marine ecosystems, providing ecosystem services and sequestering carbon. It has provided valuable insights into the dynamics of mangrove cover change (MCC) and emphasised the importance of considering local community perceptions and socio-economic factors in mangrove conservation. This study investigated MCC dynamics in the study area, utilising primary and secondary data. Primary data collection involved household surveys conducted in three coastal villages. These surveys gathered information on respondents' perceptions of MCC, including observed changes, drivers, and timelines. The survey also asked respondents to rank the importance of various drivers of MCC. Multiple sources were employed to collect secondary data, including population density, typhoon track archives, remote sensing data on mangrove cover, mangrove-related policies, and mangrove awareness. These sources were used to complement and validate the primary data. The results revealed that the mangrove cover in the study sites had generally declined over time. The community perceptions collected aligned with observed changes in mangrove cover, as indicated by remotely sensed data. The overall trend showed a decrease in mangrove cover from approximately 752 hectares in 1990 to around 558 hectares in 2016, followed by a gradual increase to about 630 hectares in 2019. Anthropogenic drivers attributed to human activities, such as converting mangrove areas to fishponds, were identified as significant drivers of MCC, especially in the earlier periods (1960s to early 2000s). Underlying factors like poverty and weak policy implementation influenced these activities.

Moreover, natural threats such as typhoons were also recognised as contributors to mangrove loss, with Typhoon Haiyan in 2013 having a particularly significant impact (Quevedo et al., 2020a). The perceived effects of recent typhoons were more potent than those of older ones, possibly due to individual experiences and the increasing intensity of recent typhoons linked to climate change. In addition to typhoons, rising sea levels significantly threaten coastal ecosystems. Their physical effects include the inundation of low-lying wetlands and drylands and an increased risk of flooding (Perez et al., 1999). The Philippines is particularly susceptible to sea level rise and extreme rainfall, which severely affect human life, infrastructure, agriculture, and natural ecosystems (Hong et al., 2022). Similarly, coastal areas in Jakarta are experiencing severe land subsidence, further exacerbating the threats posed by rising sea levels and increasing risks for local communities (Esteban et al., 2017).

Furthermore, addressing these challenges requires urgent and strategic action, with mangrove reforestation playing a vital role in mitigating climate change, protecting coastlines from high tidal waves, and reducing flood risks (Alsaaideh et al., 2013). The study also examined how socio-demographic attributes and awareness of mangrove ecosystem services influenced the recognition of MCC drivers. This research emphasises that understanding local perceptions of MCC and its drivers provides valuable insights for developing sustainable mangrove management strategies. Science-based approaches to mangrove reforestation can enhance resilience against natural threats, while community perceptions can complement traditional data sources in the analysis of MCC.

Using the Driver-Pressure-State-Impact-Response (DPSIR) framework as a holistic tool for identifying and establishing causal links between various indicators in environmental management (Kohsaka, 2010). Quevedo et al. (2023a) applied the framework to identify both the threats and management efforts related to mangrove ecosystems across all 27 provinces of Indonesia. The methodology involved data collection from Scopus and Web of Science databases and included a screening process to select relevant peer-reviewed articles. The selected articles are then analysed using the DPSIR framework to identify drivers, pressures, impacts, and responses to mangrove ecosystems. The results exposed that Central Java has the highest number of publications related to mangroves, followed by East Kalimantan and South Sulawesi. In contrast, some provinces have very few or no articles on the topic of mangroves. The analysis also displayed increased articles discussing mangrove degradation and management in recent years.

Furthermore, this study provided an overview of Indonesia's regional and provincial trends in mangrove degradation and management efforts. With its high population density, the Java region experiences indirect anthropogenic drivers, like population growth, leading to societal pressures on mangroves. Aquaculture expansion is a prominent driver in Kalimantan, resulting in mangrove loss. Papua province enforces stricter mangrove management due to large-scale oil palm plantation development, while the Maluku islands face societal and institutional pressures and indirect anthropogenic forces. Sulawesi has witnessed significant mangrove conversion for aquaculture, while Sumatra deals with issues like oil palm plantation development and the impact of aquaculture on mangroves. Natural drivers, such as earthquakes and tsunamis, are documented in provinces that experience vigorous seismic activity, and climate change, particularly sea level rise, affects mangroves and coastal communities in Jakarta and Central Java. The study suggested that the future of Indonesia's mangroves depends on achieving a balance between economic development and sustainability. Essential measures include policies that promote sustainable aquaculture and mangrove conservation and the implementation of payment for ecosystem services and financial valuation, particularly within BC. Moreover, it is recommended to foster collaboration with stakeholders, including non-governmental organisations (NGOs), and to incorporate eco-tourism concepts.

Building on these findings, a systematic assessment using the DPSIR framework can further highlight the vulnerabilities of Indonesia's mangrove ecosystems and guide sustainable management strategies. Drivers such as population growth, urbanisation, industrial expansion, weak policy enforcement, climate change, and seismic activity contribute to increasing pressures. These pressures manifest as aquaculture expansion, oil palm plantations, deforestation, pollution, and coastal infrastructure development, leading to widespread mangrove degradation. As a result, the state of mangroves has been significantly affected, with shrinking forest cover, declining biodiversity, and reduced carbon sequestration capacity, making these ecosystems increasingly fragile. The impacts of these changes include coastal erosion, increased flooding, declining fishery productivity, higher carbon emissions, and socioeconomic displacement of coastal communities.

Despite ongoing conservation efforts, such as mangrove reforestation programs, national policy frameworks, and community-based restoration initiatives, gaps remain in law enforcement, sustainable land-use planning, and long-term community engagement. Addressing these vulnerabilities requires strengthening legal frameworks, promoting sustainable aquaculture, integrating local ecological knowledge into conservation strategies, and embedding mangrove conservation into disaster risk reduction plans. A balanced approach reconciling economic development with environmental sustainability is essential to protecting Indonesia's mangroves from intensifying human pressures and climate-related threats.

2.2. Exploring community perceptions of seagrass ecosystems and their associated services

In this section, three papers discuss the significance of seagrass ecosystems and their role in providing various ecosystem services.

Quevedo et al. (2022b) compared local perceptions of rural and urban areas through household surveys to understand how different contexts influence people's awareness and attitudes toward seagrass ecosystems in the Philippines. The study provided insights into seagrass conservation at a local scale, where specific conservation and management strategies are needed. Overall, respondents in rural areas displayed higher awareness and utilisation of seagrass ecosystem services and had a stronger connection to these services than those in urban areas. For instance, significant differences were observed in awareness levels of services like nurseries, the frequency of seagrass bed utilisation as an income source, and awareness of coastal management-related strategies, which were significantly higher in rural areas than in urban areas. This difference in perception can be attributed to the direct experience of rural communities with natural events like typhoons, during which seagrass meadows have been observed to provide protection. Urban respondents were more concerned about pollution from domestic waste and were aware of seagrass meadows as recreational sites, possibly due to their proximity to tourist destinations. The findings of this paper highlighted that the concept of seagrass BC is poorly understood and not mainstreamed in local coastal management plans (Quevedo et al., 2020b).

The study emphasised the need to increase awareness of BC among local stakeholders, especially those who rely on seagrass habitats for their livelihoods. It also highlighted the importance of community engagement in seagrass conservation efforts and the potential for citizen science initiatives. Partnerships between residents, practitioners, and policymakers could lead to context-based seagrass management plans and programs in rural and urban settings.

Rifai et al. (2023a) analysed community perceptions of seagrass ecosystem services in Indonesia's Karimunjawa National Park (KNP), a protected area with various seagrass species. The research aimed to provide insights and recommendations for improving seagrass ecosystem management from a social perspective. Data were collected through household interviews in three coastal villages within KNP, and respondents were selected randomly to represent various demographic groups. The respondents displayed high awareness of some seagrass ecosystem services, such as their role as nurseries for marine organisms and in water purification. However, awareness of other services, such as carbon sequestration and coastal protection, was relatively low. Moreover, respondents had misconceptions regarding the carbon storage capacity of seagrass ecosystems. A significant proportion believed that most of the carbon was stored in seagrass biomass, while, in fact, most of the carbon was held in the sediment. The results indicated that higher education is associated with greater awareness levels.

Therefore, the study underscores the importance of enhancing community awareness regarding seagrass ecosystem services, particularly carbon sequestration, and the necessity for customised conservation and education efforts. Additionally, it highlights the role of community perceptions in shaping conservation strategies and the potential for Payment of Ecosystem Services (PES) schemes to bolster seagrass conservation in Indonesia's Komodo National Park.

Rifai et al. (2023b) introduced the concept of seagrass restoration as a nature-based solution (NbS) to address climate change and promote ecosystem health. NbS is actions that protect, manage, and restore natural ecosystems to benefit human well-being and biodiversity. Seagrass restoration aligns with NbS principles, and the paper provided evidence of how seagrass restoration fits the criteria set by the International Union for Conservation of Nature (IUCN) for NbS. This study highlighted the potential for implementing seagrass restoration as a NbS in Indonesia, particularly in addressing climate change mitigation and adaptation. The paper acknowledged challenges, such as the lack of a national budget and low community awareness about seagrass restoration. The study underscored the need for collaboration among stakeholders, including the scientific community, government, local communities, and NGOs, to address these issues. Capacity building, awareness campaigns, realistic restoration designs, and payment for ecosystem services are proposed as potential solutions. The paper advocates for recognising seagrass restoration as a valuable tool in Indonesia's efforts to combat climate change. It encourages more attention, funding, and collaboration to restore and protect these critical marine ecosystems.

While community awareness is crucial in shaping conservation strategies, translating this awareness into concrete actions is essential for ensuring the health and sustainability of seagrass ecosystems. Building on Rifai et al.'s (2023a, 2023b) findings, addressing knowledge gaps, particularly regarding seagrass carbon sequestration is paramount. To complement these insights, effective monitoring and restoration efforts are vital for maintaining ecosystem services and promoting long-term sustainability.

Community awareness efforts should particularly emphasise the significance of monitoring and restoration as key strategies in seagrass conservation. Regular monitoring is crucial in assessing ecosystem health, identifying early signs of degradation, and informing adaptive management strategies to sustain seagrass ecosystems over time. Involving local communities in seagrass monitoring through citizen science initiatives collects valuable data, fosters a sense of ownership, and enables timely responses to emerging threats. Furthermore, restoration activities, such as replanting seagrass beds and mitigating human-induced damage, should be prioritised at the grassroots level to restore ecosystem services and ensure the long-term viability of seagrass habitats.

A comprehensive and inclusive approach to seagrass monitoring and restoration can lead to more effective and sustainable conservation outcomes. Communities should be equipped with the necessary tools and knowledge to monitor programmes and track changes in ecosystem health actively. Citizen science initiatives, where local residents contribute to data collection and restoration efforts, can further foster a sense of stewardship and long-term commitment to seagrass conservation. To strengthen these efforts, prioritising education, collaboration, and financial incentives is crucial for enhancing ecosystem conservation and contributing to climate change mitigation on a global scale. Recognising seagrass restoration as a vital NbS will help drive policy changes, secure funding, and reinforce community-led conservation initiatives. Finally, integrating traditional ecological knowledge with scientific research can empower coastal communities to protect and restore these critical marine ecosystems for future generations.

2.3. Analysing local perspective on sustainable tourism and its influence on BC ecosystem services

The tourism expansion has brought significant economic advantages to the public and private sectors, particularly in coastal regions. However, its rapid growth has also led to environmental degradation, including the loss of seagrass and mangroves due to coastal developments, pollution, and increased human activity (Daby, 2003; Spalding & Parrett, 2019). Understanding the interactions between tourism and these habitats is essential, as mangroves and seagrasses are vital blue carbon ecosystems contributing to climate mitigation. Unlike other sectors, tourism relies on and impacts these ecosystems, making it a crucial area for developing sustainable management strategies that balance economic growth with conservation.

This section contains two papers on the impacts of tourism, mainly on mangroves and seagrass.

Quevedo et al. (2021a) provided valuable insights into residents' perceptions of tourism benefits and impacts in rural and urban settings in the northern part of Palawan province, Philippines, with a focus on the importance of BC ecosystem services, including mangroves and seagrass beds. The study conducted household surveys in coastal villages and covered various aspects, including awareness of BC ecosystem services, perceived benefits, tourism impacts, environmental changes, and sustainable tourism measures. Participants rated their awareness of the benefits of mangroves and seagrass and their opinions on sustainable tourism measures using a Likert scale. The study also explored residents' perceptions of the impact of tourism on their personal and community well-being, encompassing social, cultural, economic, and environmental dimensions. Additionally, it examined changes in habitat cover, conservation efforts, accessibility, and seafood stocks related to mangroves and seagrasses. The study found that respondents in both areas recognised the importance of protecting natural resources for the sustainability of the tourism industry. For example, residents in both areas demonstrated a high awareness of the benefits of mangroves, such as coastal protection. In rural areas, the functions of seagrass ecosystems were recognised more, possibly due to awareness campaigns conducted by NGOs in the area. On the other hand, residents generally have positive perceptions of the economic benefits of tourism, such as its potential to generate income and employment opportunities. However, there was also recognition that tourism could lead to rising prices of goods and services and increased competition for local jobs, which could have adverse effects. Overall, this research provided a valuable foundation for local governments to develop policies and strategies for sustainable tourism. These should balance economic development with environmental protection and the well-being of residents. The study highlighted the importance of community awareness and engagement in achieving these goals and underscores the role of NGOs in facilitating this process.

To assess the residents' perceptions of the impact of tourism on coastal ecosystems in Karimunjawa, Indonesia, Lukman et al. (2022) involved 47 respondents and employed a questionnaire-based survey that focused on sustainability dimensions: socio-cultural, economic, and environmental. Chi-square tests were used to evaluate associations between residents' perceptions, the prioritisation of coastal management, and their involvement in the tourism sector. The results indicated that respondents had a positive perception of tourism's socio-cultural and economic impacts and negative perceptions regarding its impact on the environmental domain, especially among those involved in the tourism sector. Education level was negatively correlated with environmental perceptions, indicating that higher education levels led to more negative perceptions. The study emphasises the need for comprehensive coastal ecosystem management, involving the local community and addressing environmental concerns while also recognising the economic benefits of tourism. Further research was recommended to delve into the intricacies of these perceptions and involve various stakeholders in policy discussions.

2.4. Discerning trends in research and coastal management strategies for BC ecosystems

Two papers in this section provide information on the status and challenges of published research and the management strategy concerning the BC ecosystem.

Quevedo et al. (2023b) identified that since the concept of BC was introduced in 2009, there has been substantial research progress in various aspects, such as BC quantification, mapping, economic opportunities, and management. However, the paper emphasises that several challenges remain, as indicated by ten fundamental questions in BC science, mainly focusing on the question related to management actions for BC sequestration. To address these challenges, the study conducted a comprehensive literature review, which included peer-reviewed articles, technical reports, policy briefs, books, conference presentations, dissertations, theses, and news articles. This approach aimed to provide a more comprehensive perspective on BC research, including earlier developments and contributions from civil society that may have been overlooked in previous reviews. To support scholars in shaping their research agendas, avoiding redundancies, and assisting coastal managers and practitioners in developing evidence-based BC management strategies, the authors collected BC-related documents from various databases, such as Scopus, Web of Science, and others. They retrieved 4,206 potential documents and conducted a rigorous screening process to narrow the selection to 1,179 relevant documents. The study revealed that the number of BC-related documents has increased from 2009 to 2021, with peer-reviewed articles dominating the literature. The analysis of co-occurrence networks showed that BC research is multidisciplinary, covering both natural and social sciences. The geographic distribution of BC research is led by the United States and Australia, with a robust co-authorship network. While Asia, particularly China, has shown a significant research output, collaborations with other countries are still limited, especially among developing countries.

The paper highlighted the growing importance of social and management perspectives in BC research and points out the continued growth and significance of BC research. It also presented a roadmap for future research agendas to advance the field. By addressing these research agendas, BC science can continue to evolve, become more inclusive, and contribute to more effective coastal management and policy development.

Quevedo et al. (2021b) examined coastal management plans in selected municipalities in the Philippines, focusing on mangrove and seagrass ecosystems. The study employed content analysis to assess the management plans and discussed the clusters derived from the analysis. Eight groups were identified: environmental profiles, ecosystem services, carbon sequestration, tourism, natural and anthropogenic threats, laws and policies, and management activities. The analysis revealed that management activities received the most attention, while carbon sequestration received the least. It is worth noting that the concept of BC has not been fully integrated into these plans, and management strategies primarily concentrated on mangrove forests, with limited attention given to seagrass meadows. The emphasis on mangrove forests is due to their coastal protection services, which became particularly evident after the super typhoon Haiyan in 2013. The lack of attention to seagrass ecosystems suggests a need for increased research and collaboration with mangrove conservation efforts. The results demonstrated that the coastal management plans do not account for indirect drivers such as urbanisation, which can impact mangrove and seagrass ecosystem losses. Most discussions focused on direct drivers like human-induced disturbances and natural events. Future investigations could involve in-depth interviews with local government units and the application of frameworks to understand these drivers better. This study can serve as a reference for local policymakers to improve their management plans, especially by focusing on the integrated management of seagrass ecosystems and enhancing knowledge about BC ecosystems.

3. PROMISING FUTURE CAPACITY-BUILDING APPROACH: A CONCEPTUAL FRAMEWORK FOR COMMUNITY ADAPTATION

This review addresses a critical research gap: How do capacity-building programmes enhance local communities' adaptation capacity in managing mangrove and seagrass ecosystems in Indonesia and the Philippines? While previous studies highlight the role of local communities in conservation, there is limited understanding of the impact and limitations of such programmes in fostering long-term resilience. Specifically, this review investigates how Geographic Information Systems (GIS)-based training can empower local communities to overcome governance and implementation challenges in blue carbon ecosystem management.

3.1. Conceptual framework: Behaviour change and community adaptation

We draw from environmental psychology and climate adaptation frameworks to guide this discussion. The Theory of Planned Behaviour (TPB) (Whitmarsh et al., 2021) posits that attitudes, perceived control, and social norms influence individuals' actions. Applying this to community-based conservation, effective adaptation strategies require technical training and behavioural shifts that enhance local agency, promote collective responsibility, and ensure that communities view conservation efforts as valuable and achievable.

Furthermore, we propose a Theory of Change (ToC) framework (Deutsch et al., 2021) to illustrate how GIS training can improve adaptation capacity:

1. Knowledge and skill development: Training local communities in GIS equips them with the technical skills to map, assess, and monitor mangrove and seagrass ecosystems.
2. Participatory data collection and perception integration: Incorporating local knowledge into GIS databases ensures that conservation strategies reflect on-the-ground realities.
3. Data-driven decision-making: Reliable spatial data enables local stakeholders and policymakers to make evidence-based conservation and adaptation decisions.
4. Improved governance and community Empowerment: GIS training fosters collaboration between communities, researchers, NGOs, and government agencies, strengthening institutional capacity.
5. Long-term sustainability and adaptation capacity: With enhanced monitoring and governance structures, communities can anticipate environmental changes, assess climate risks, and implement sustainable conservation measures.

3.2. Policy barriers and supportive policy frameworks

National policies that either support or hinder conservation efforts heavily influence the effectiveness of GIS-based capacity-building programs. Policy barriers such as weak enforcement of environmental regulations, fragmented land-use planning, and a lack of integration of blue carbon into national climate strategies can undermine these initiatives. Furthermore, policies prioritising economic growth (e.g., unsustainable coastal development or agriculture) without considering ecological impacts may exacerbate pressures on mangrove and seagrass ecosystems.

In contrast, supportive policies that integrate blue carbon conservation into broader climate change adaptation and mitigation strategies can significantly enhance the success of these programs. National policies should promote sustainable land-use practices, empower local communities, and ensure that conservation strategies are evidence-based and collaborative. Strengthening policy integration and ensuring long-term financial and institutional support for capacity-building programs are critical for realising the full potential of GIS-based training in blue carbon ecosystem management.

3.3. Implications for capacity-building programs

GIS-based training programs offer a promising approach, bridging the gap between local knowledge and policy implementation. By enabling communities to track ecological changes, assess vulnerabilities, and contribute to data-driven governance, such programs enhance local agencies in climate adaptation. However, the effectiveness of these programs depends on long-term engagement, institutional support, and accessibility of resources.

Future research should evaluate the impacts of GIS training on decision-making and ecosystem resilience, as well as potential barriers such as resource constraints, policy integration challenges, and community engagement sustainability. Addressing these gaps will ensure that capacity-building programs bring tangible, lasting improvements in adaptation and conservation efforts.

4. CONCLUSION

This study highlights coastal communities' perceptions of blue carbon ecosystem services, emphasising their awareness of management policies, utilisation of ecosystem resources, and participation in conservation initiatives. The findings reveal that indirect anthropogenic drivers, such as population growth and economic development, exert significant pressure on BC ecosystems, particularly mangroves and seagrasses, crucial for climate change mitigation. Additionally, the study underscores the need for increased community awareness and engagement in conservation efforts, particularly concerning the carbon sequestration potential of seagrass ecosystems.

Building on these insights, the study presents a conceptual framework incorporating Geographic Information Systems (GIS) based training as a strategic tool to enhance community adaptation and governance in blue carbon ecosystem management. By equipping local communities with technical skills in spatial analysis, GIS training facilitates participatory data collection, supports evidence-based decision-making, and promotes stronger institutional collaboration. Applying behavioural change models, such as the Theory of Planned Behaviour (TPB), emphasises the necessity of fostering local agency, encouraging collective responsibility, and ensuring conservation efforts are considered valuable and attainable. The Theory of Change (ToC) framework further demonstrates how structured capacity-building programmes can drive long-term sustainability by improving governance, enabling adaptive management, and empowering communities to respond effectively to environmental changes.

Despite the promising potential of GIS-based capacity-building programmes, their success is contingent upon the broader policy landscape. Supportive policies can enhance these efforts, while several barriers exist such as fragmented policies, weak governance, and unsustainable development practices. Integrating blue carbon ecosystems into national climate change policies, promoting sustainable coastal development, and strengthening the enforcement of environmental regulations are critical steps to ensuring the long-term sustainability of these ecosystems. The effectiveness of capacity-building programmes also depends on institutional support and policy integration. Future research should focus on evaluating the long-term impacts of GIS-based training on decision-making, the resilience of BC ecosystems, and addressing policy-related barriers such as resource limitations and policy gaps. Strengthening these areas will ensure local communities actively contribute to blue carbon conservation, ultimately leading to more sustainable and climate-resilient ecosystem management strategies.

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Original article

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Integrated assessment of existing practices and development of pathways for the effective integration of nature-based water treatment in urban areas

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ABSTRACT

Water pollution poses a significant and escalating threat to urban environments, particularly in the rapidly expanding cities of Asia. Addressing this challenge requires implementing cost-effective solutions, and one such approach is the deployment of Nature-based Solutions (NbS) to treat septic tank effluents, canals and lakes. This study represents a pivotal step in this direction by formulating a comprehensive framework to assess the effectiveness and impacts of NbS. The research draws on six case studies spanning the Philippines, Sri Lanka and Vietnam, offering valuable insights into the practical application of NbS in diverse urban contexts. Furthermore, the study has yielded practical guidelines for the construction and installation of three key NbS components: Constructed Wetlands (CWs), Constructed Floating Wetlands (CFWs), and Green Roofs (GRs). These guidelines were implemented through trial implementations, enhancing our understanding of their real-world performance. Moreover, stakeholder engagement played a vital role in this endeavour, as such gatherings provided essential data on public acceptance and the influence of policies and governance structures. The knowledge and insights from these interactions contribute significantly to the collective understanding of effectively replicating and implementing NbS for water treatment in urban environments. The project successfully trained 72 early career professionals and students from project partners and stakeholders. It produced 23 publications, including a book, book chapters, journal articles, perspectives, resource materials reports and four short videos on NbS. These outcomes were achieved through the collaborative efforts of project partners and stakeholders, engaging in 29 events such as quarterly, national and regional meetings, field trips, focus group discussions, socio-economic surveys and extensive field trials.

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KEYWORDS ASSESSMENT FRAMEWORK, CONSTRUCTED WETLANDS, CONSTRUCTED FLOATING WETLANDS, ECOSYSTEM, GREEN ROOF SYSTEMS, NATURE-BASED SOLUTIONS

HIGHLIGHTS

- A matrix was developed to evaluate the effectiveness of NbS for water treatment.
- A comprehensive guide to implementing selected NbS was produced.
- Extensive stakeholder engagement provided valuable insight to those NbS.
- Trials confirm the feasibility of replicating the selected NbS.
- A methodology to compute cost-benefit analysis has been developed.

1. INTRODUCTION

Urbanisation, population growth and climate change collectively pose a formidable threat to water quality on a global scale. Nowhere are these impacts more pronounced than in the growing urban landscapes of developing nations. Within these urban environments, canals and rivers bear the brunt of pollution, stemming from the untreated discharge of effluents from septic tanks and other sources and the dumping of solid waste into those waters. For example, in 2021, the Ministries of Natural Resources and Environment and Health in Vietnam reported alarming statistics. Approximately 9,000 lives are lost annually due to inadequate sanitation and compromised water quality. Additionally, nearly 250,000 individuals find themselves hospitalised each year, grappling with acute diarrhoea resulting from the consumption of contaminated domestic water. Moreover, a staggering 200,000 people are reported to suffer from cancer, a consequence attributed to water pollution (Dang et al., 2022; https://www.unicef.org/vietnam/stories/world-water-week-2021-meet-our-expert).

Fortunately, NbS for water treatment offers a cost-effective lifeline to enhance the quality of surface waters in our cities. Practices such as constructed wetlands (CWs), constructed floating wetlands (CFWs), green roofs (GRs) and maturation ponds (MPs) have demonstrated their efficacy. Yet, their widespread adoption remains hindered by several key challenges. These include a lack of comprehensive understanding regarding their effectiveness and impact on community acceptance, policy formulation, governance and financial backing.

A collaborative two-year initiative from 2021 to 2023, supported by the Asia Pacific Network for Global Change Research (APN), has explored these pressing issues deeply. Headed by the authors of this paper, the project set out with the overarching goal of augmenting knowledge and capabilities essential for integrating nature-based water treatment technologies into urban water management and planning within Asian cities. Its specific objectives encompassed a spectrum of critical aims, including (i) assessing the potential of nature-based water treatment in enhancing water quality and human well-being while simultaneously fortifying the livability and resilience of urban centres in Sri Lanka, the Philippines, and Vietnam, (ii) advancing the understanding of how natural water treatment technologies can be effectively conceived, maintained, replicated and scaled across diverse Asian cities, (iii) strengthening the research capabilities of participants from partner countries to engage in transdisciplinary action-research, particularly in response to critical sustainability challenges and (iv) elevating the awareness of local stakeholders about the profound potential of nature-based water treatment in addressing these critical sustainability challenges. These objectives were realised through a multifaceted approach driven by collaboration among various stakeholders. This approach included (i) the development of a comprehensive framework to evaluate the effectiveness and impacts of NbS for water treatment, (ii) the formulation of comprehensive guidelines covering the suitability, construction, installation, operation, and maintenance of NbS and (iii) the practical testing and validation of NbS to showcase their replicability. Through these concerted efforts, this initiative has illuminated a promising path forward in urban water management, one rooted in NbS and enriched by shared knowledge and collaboration.

2. METHODOLOGY

Broader definitions of CWs, CFWs and GRs are provided below to facilitate subsequent discussions in the manuscript. CWs are engineered systems mimicking the process of natural wetlands using soil and plants to treat wastewater. In the CW, the plants are usually grass due to their resistance to harsh wastewater conditions, while the soil media or substrates used are gravel and sand for effective filtration and adsorption of the pollutants. Other pollutants and nutrients can be taken up by the plants for further treatment of the wastewater. At the same time, its deep and extensive root systems provide the environment for microorganisms, which can also remove other organic matter in the wastewater. Aside from this, CW provides ecological benefits such as the promotion of biodiversity conservation, aesthetics for tourism and even as a source of livelihood. CFWs, also referred to as floating treatment wetlands or floating wetlands, stand as remarkable human-engineered constructs meticulously designed to elevate aquatic plant growth above water surfaces. They aim to effectively remove pollutants from water bodies, delivering environmental and communal benefits. GRs, also called green roof systems, can be constructed by growing plants on a channel filled with suitable media, allowing the plants to grow. Wastewater can be passed through the media, and the plants will uptake the nutrients in the wastewater and purify it. GRs are one of the innovative architectural and urban development options based on sustainable development concepts that can increase urban green areas, improve environmental quality and generate sustainable urban development. Additionally, GRs also improve building insulation and reduce cooling costs.

The following methodology was carried out to achieve the three goals mentioned in Section 1:

(i) *Review of the status and utilisation of NbS in all three participating countries,* the *Philippines, Sri Lanka and Vietnam*. A comprehensive assessment of water quality in lakes and canals, wastewater treatment systems, water management, governance structures and pertinent policies was diligently undertaken. This rigorous evaluation aimed to examine the existing landscape and the utilisation of NbS for water and wastewater treatment across a triad of countries. Ultimately, the review enabled the project team to select appropriate NbS case studies in the three countries.

(ii) *Mapping the NbS in all three countries through web-based and geographic information systems (GIS)*. Static and dynamic maps were developed to show the locations of all existing NbS sites in Sri Lanka, the Philippines, and Vietnam. Static maps were produced so they could be printed or displayed as images. Dynamic maps are interactive maps that allow users to zoom in and out, click, select, search, and explore the data in different ways. The NbS for water treatment project sites in Sri Lanka, the Philippines and Vietnam were plotted on Google Maps and GIS mapping was also developed for dynamic mapping of NbS for water in the three countries.

(iii) *Stakeholder participation to acquire social and economic implications of NbS*. Various stakeholder meetings were integral to achieving the goals. These included regular partner meetings, five quarterly gatherings with experts in focal areas, focal group sessions, two annual national meetings per country, and two regional meetings (Vietnam 2022, Philippines 2023). All the information were documented and analysed for further use.

(iv) *Development of questionnaires to evaluate social and economic implications*. The spectrum of stakeholders engaged with NbS is diverse, including communities, regulatory bodies, policymakers, businesses, scientists, engineers, social scientists and teachers. Each stakeholder group holds significant viewpoints that must be comprehensively addressed to ensure successful replications. Partners in all three nations crafted questionnaires and held stakeholder interviews. Results obtained were analysed to gain a valuable understanding of stakeholders' views on various aspects. The composition of stakeholders and sample sizes were chosen using the practical guidelines on the topic developed by the United Nations Department of Economic and Social Affairs (2008). Further, the economic implications are calculated based on how stakeholders place a value, such as their willingness to pay for the ecosystem services provided by the NbS.

(v) *Developing a framework to assess the effectiveness and impacts of NbS*. A comprehensive evaluation framework for NbS effectiveness and impacts has been developed, focusing on CWs, CFWs, and MPs. This adaptable framework assesses NbS effectiveness, which is hinged on achieving

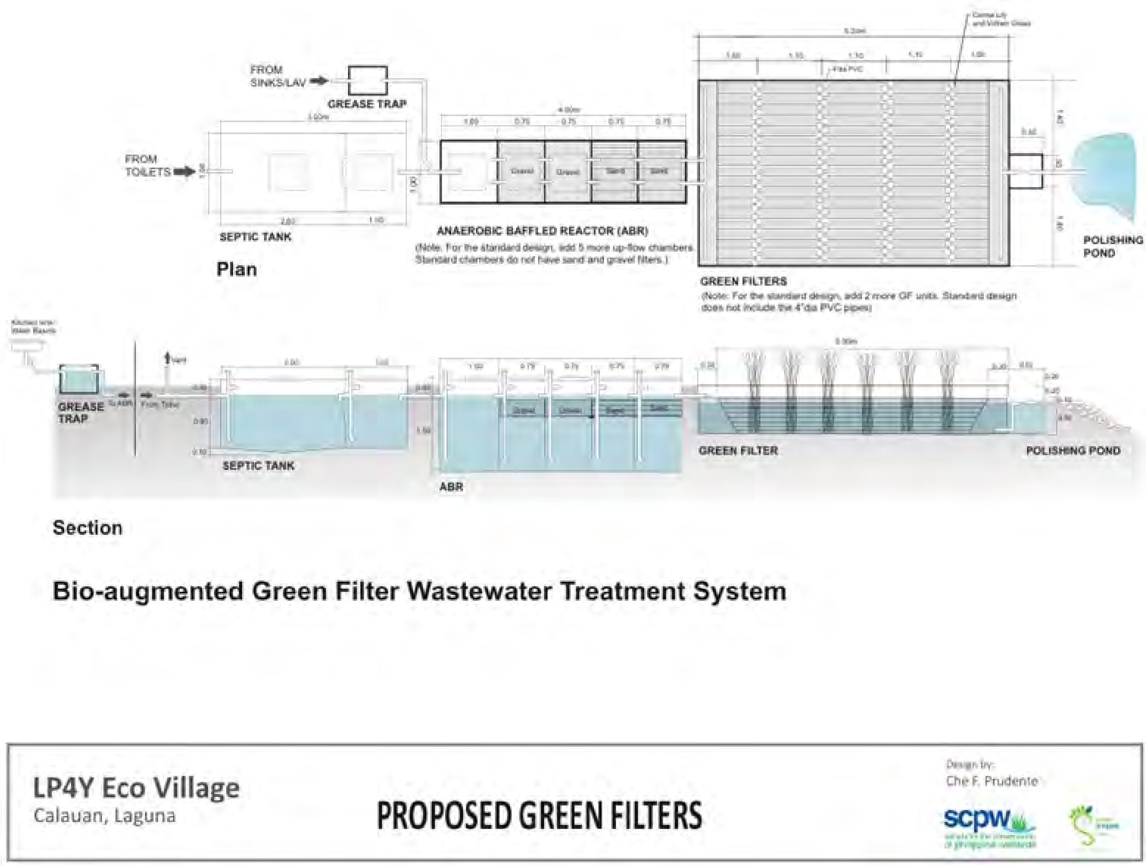

FIGURE 1. Proposed design of CWs in Green Village, Calauan Laguna.

objectives and problem resolution. Technical excellence and maintenance are essential for effectiveness, distinct from cost considerations. The framework zooms in on targeted water quality improvements, while broader environmental, social, and economic outcomes demand examination to capture NbS co-benefits, address undesirable effects, and provide sustainability evidence. Contextual factors such as institutional setup, governance, and policy enrich the assessment. The project sought to answer the following: Is a given NbS socially embraced across stakeholder spectra? Can policies accommodate NbS implementation and adjustments?

(vi) *Developing guides to NbS.* A guide comprising suitability mapping, economic analysis, social acceptability, construction, installation, maintenance, operation and troubleshooting of CWs, CFWs, GRs, plant selection guide for CFWs and upscaling and replication pathways was developed.

(vii) *Trialling the NbS considered in the project.*

(a) CWs: In the Philippines, the CW framework and guide developed were piloted at Panguil Eco Park at Pangil and the Green Village at Calauan. The management of the Ecopark plans to construct CWs system for their septage treatment, while the latter has a working CWs for their septage treatment but would require rehabilitation. These two sites provide an excellent validation platform for the developed framework since one is new while the other exists. Further, since the eco-park trial site is a new construction of CW, the work based on the framework would involve social acceptability and focus group discussion activities. For the village, the work involved was retrofitting one of their existing CWs with the proposed design shown in Figure 1. The bio-augmented green filters, or CWs, were operated by adding an effective microorganism activated solution (EMAS) in the anaerobic baffled reactor (ABR). The EMAS is a solution composed of safe and naturally occurring aerobic and anaerobic microbes, such as lactic acid bacteria, fungi, and yeast (Talaat et al., 2015). Based on the existing studies, EMAS can improve the removal of physical (odour) and chemical constituents in wastewater. For example,

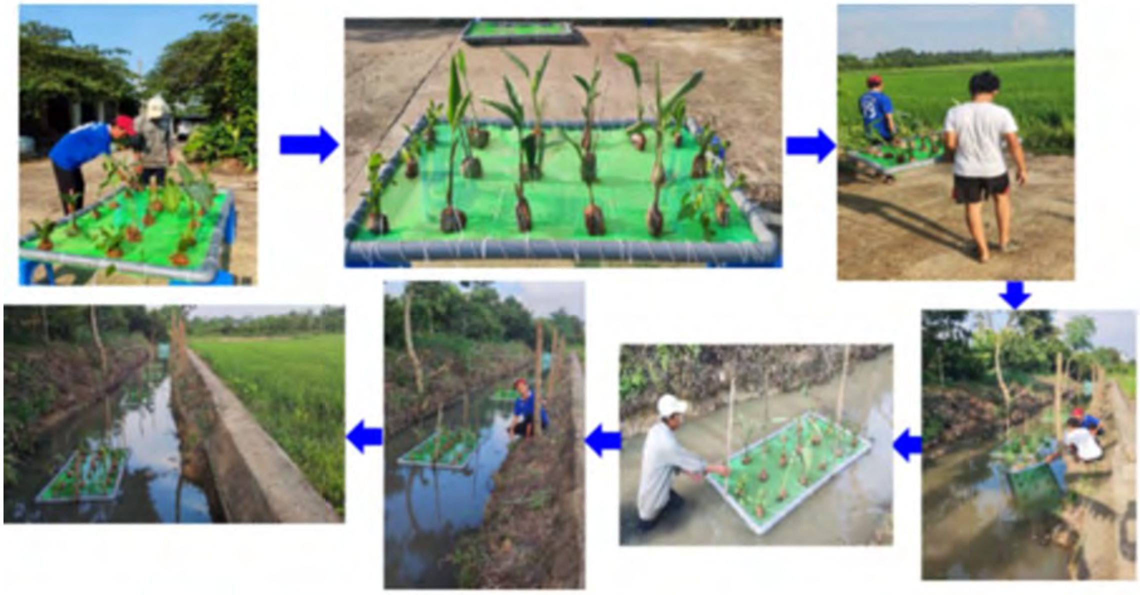

FIGURE 2. Photos of construction and installation of 6 CFWs in a canal adjacent to the agricultural seed centre in Vinh Long province, Vietnam.

60%–90% BOD of the wastewater can be removed by introducing EMAS (Safwat & Matta, 2021). A design with similar concepts was also proposed for the eco-park.

(b) CFWs in Vietnam: CFWs were replicated at an Agricultural Seed Center in Vinh Long Province. Six CFWs were installed in a canal adjacent to the seed centre, which receives water containing fertilisers from the rice fields. The canal's length to width to depth dimensions are 40 m × 3.5 m × 1.5 m. The determination of the panel size is influenced by ease of installation and maintenance considerations. The recommended raft size adheres to a length-to-width ratio of 2:1 (Schwammberger et al., 2019). Accordingly, the length-to-width dimension of each unit is 2 m × 1 m, and thus 12 m^2 floating wetland area was used to treat the water in the canal of 140 m^2. Therefore, the CFWs covered 8.5% of the canal surface. The choice of materials for constructing the raft was guided by their buoyancy and durability in water, aiming to withstand prolonged exposure without sustaining damage. Materials fitting these criteria include bamboo, foam sheets, plastic bottles and jars, PVC pipes, and coconut coir mats. A mixture of four ornamental species, including *Canna x generalis, Heliconia psittacorum, Echinodorus cordifolius* and *Cyperus alternifolius,* were planted at a density of nine plants/m^2. Figure 2 shows the construction and launching of six CFWs in the canal. The system has been operational for over three and a half months.

(c) CFWs in Sri Lanka: The CFWs implemented at Kandy and Kurunegala lakes, pivotal to the framework's development, yielded significant insights into their operational performance. The evaluation process informed an important enhancement to the design, introducing a coir pith mat with a geomembrane outer layer. This revision aimed to curb erosion of the original growth media (coir pith mat), optimising system durability. Thus, a trial was conducted to evaluate the performance of modified CFW. Seven units of CFWs, each having approximately 14 plants, were installed at a site in Kurunegala Lake in June 2023. The dimensions of a floating wetland unit were 1.98 m × 0.58 m (= 1.14 m^2) (Figure 3).

(d) GRs: The GR systems established at Ho Chi Minh City University, Vietnam, were found to be applicable in households where septic tank effluent is channelled to the GR system. Figure 4 shows the plan and sectional view of the GR system installed on the roof of the selected household. The plant bed has a length × width × height of 2000 mm × 200 mm × 170 mm. The working volume of the plastic influent tank was 60 L. The system

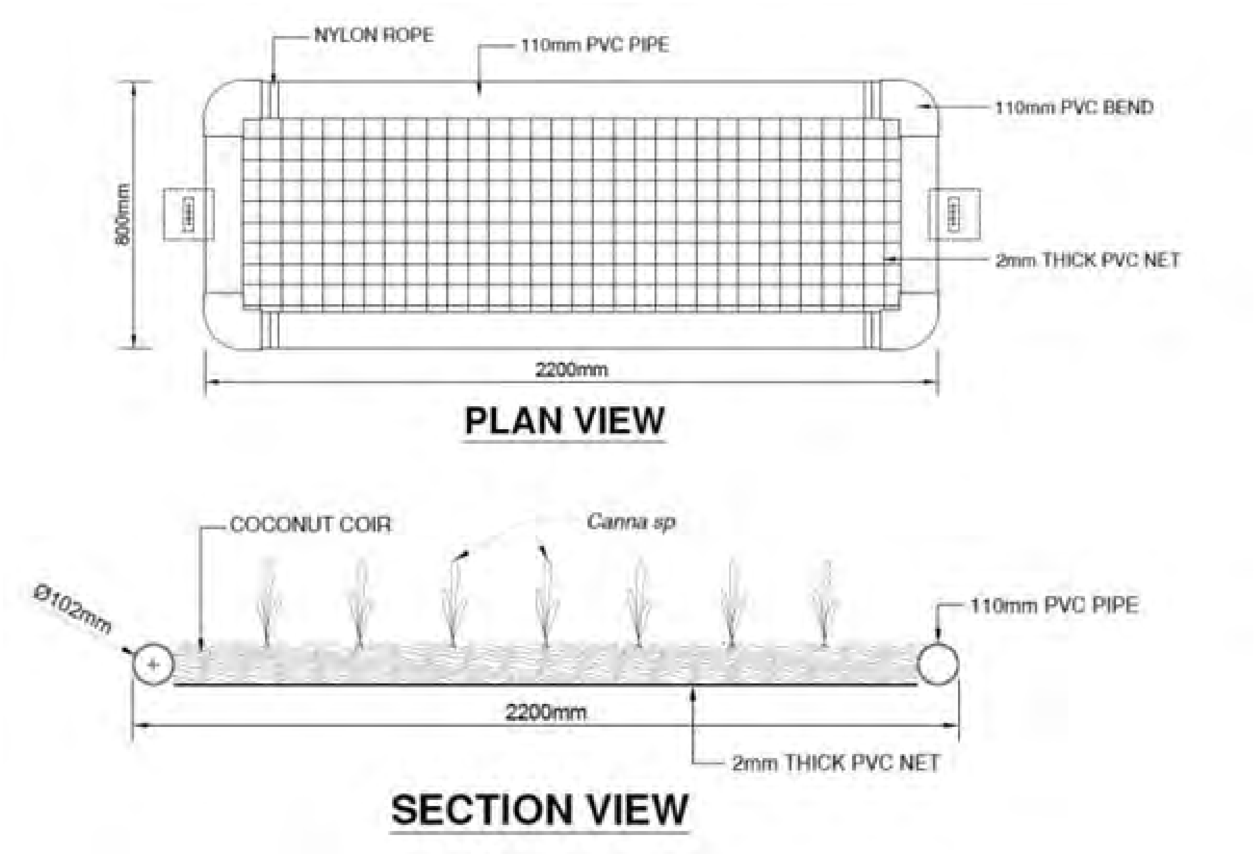

FIGURE 3. Schematic diagram of CFWs trialled at Kurunegala Lake in Sri Lanka.

had two substrates: a charcoal layer of 70 mm depth (26 L) at the bottom and a coconut shell layer of 30 mm depth (11 L) at the top of the plant bed; both layers covered 1880 mm length of the plant bed as 60 mm on both ends of the plant bed were filled with rocks to facilitate uniform flow at the inlet and outlet of the plant bed. *Vernonia elliptica* and *Portulaca grandiflora* were planted in the GR system with densities of 40 and 20 plants/m^2 and an average initial height of 30 and 5 cm, respectively. The installation process of the trial system included five steps, namely (i) installation of the tray (plant bed), pipes, and influent tank; (ii) adding charcoal to the tray; (iii) adding coconut shell to the tray; (iv) adding rocks to the tray; and (v) adding plants in the GR system. Sixteen plants of *Vernonia elliptica* and eight plants of *Portulaca grandiflora* were planted to observe the performance of the system. This trial has been operational for over two months.

3. RESULTS AND DISCUSSION

3.1. Understanding the status and utilisation of NbS in all three participating countries

Background information about the critical water management challenges in each country and promising locally appropriate NbS technologies at each pilot site guided the selection of the specific NbS examined in more depth throughout the project (Jegatheesan et al., 2023c). The results from the project add to the existing knowledge as summarised below and disseminated in more detail in the form of insightful book chapters (Dang et al., 2022; Pachova et al., 2022; Velasco et al., 2022; Weragoda et al., 2022). The reviews inform that all three countries have severe problems with surface water quality.

Urban canals in Ho Chi Minh City and Can Tho City have become conduits for untreated domestic and industrial wastewater, presenting significant environmental challenges. For instance, the Hoa Binh Canal, which exhibits chemical oxygen demand (COD) levels of 115 ± 66 mg/L, biological oxygen demand (BOD) levels of 76 ± 33 mg/L, and total suspended solids (TSS) levels of 58 ± 25 mg/L during low tides, and COD levels of 100 ± 63 mg/L, BOD levels of

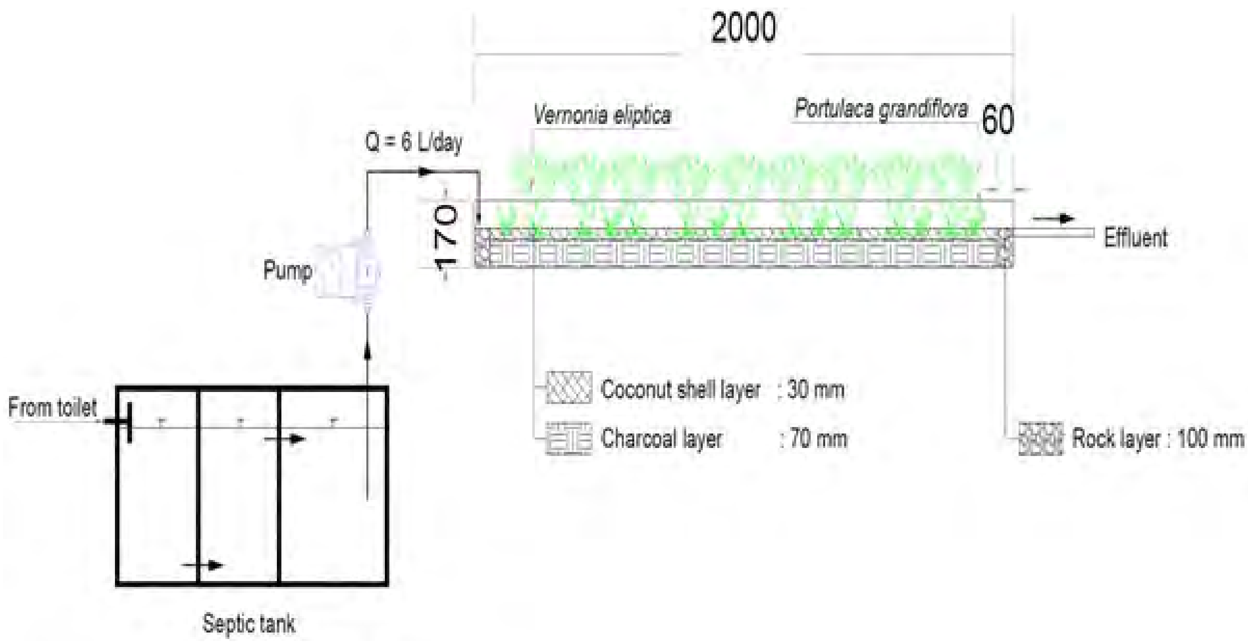

FIGURE 4. Schematic diagram of a GR module trialled to treat grey water generated at a household.

67 ± 41 mg/L, and TSS levels of 46 ± 32 mg/L during high tides. Industrial discharges introduce a range of pollutants, including polychlorinated biphenyls, polycyclic aromatic hydrocarbons, insecticides, polybrominated diphenyl ethers, and perfluoroalkyl substances, into these canals. Notably, there's also evidence of metal(oid) accumulation in the canal ecosystems. The canals are characterised by high turbidity, NH_4^+–N, PO_4^{3-}–P, and low dissolved oxygen levels, exacerbating water quality concerns. Waste stabilisation ponds have been implemented as a treatment system to address these challenges. Our case study focused on the Binh Hung Hoa wastewater treatment plant, which incorporates various treatment components such as aerated lagoons, sedimentation ponds, MPs and sludge drying beds. It serves as a pivotal case study in the development of the NbS framework outlined in this study. Furthermore, pilot and demonstration scale CFWs have shown promise in treating canals, lakes, and rivers, underscoring the underutilisation of such NbS in the region, as highlighted by Dang et al. (2022).

The review of the Philippines paints a concerning picture: in 2019, approximately 12% of the country's rivers were deemed biologically dead, and 47% of the monitored freshwater bodies failed to meet water quality standards, particularly concerning faecal coliforms (71%), without even considering unmonitored water bodies. To put this into perspective, out of the total 410 waterbodies assessed, only 167 met the required water quality standards, while 151 fell short and 92 remained unmonitored. A significant contributor to this issue is the large population segment lacking connections to sewer systems, with 77% of households relying on septic tanks, which directly correlates with the poor water quality observed in surface water bodies. Alarmingly, even 58% of groundwater resources are tainted. Despite these challenges, promising policies and plans are emerging, such as the ambitious goal to provide 40% of the population with access to septage treatment plants and 3% with sewage treatment plants by 2022. This initiative is part of a broader effort outlined in the Philippine Development Plan, which mandates the establishment of sewerage systems in all 17 highly urbanised cities (Velasco et al., 2022).

CW emerges as an excellent solution to address this pressing issue, curbing the discharge of untreated septic tank effluents into waterways. The study draws on a compelling case study—a CW operational since 2006 in Bayawan City, capable of treating 540 m³ of septic tank effluent daily. This CW serves as a model system, attracting numerous townships and cities to visit, learn, and replicate its success. This case study has been instrumental in shaping the framework and guide for addressing these challenges, as detailed in the guidebook from the Philippines (Velasco et al., 2023a).

In the context of Sri Lanka, although sanitation coverage impressively reaches 99% in Southeast

Asia, the public sewer system covers a mere 2%. This disparity has detrimental consequences on the water quality of surface waters. Wastewater treatment primarily relies on onsite sanitation methods, with 87.4% of the wastewater undergoing treatment through septic tanks, up-flow anaerobic filters, subsurface wetlands, and disinfection systems. This study examines two key lakes in Sri Lanka as case studies: Kandy Lake and Kurunegala Lake, both of which have implemented CFWs to enhance water quality. Kandy Lake, situated near the world-famous Temple of the Tooth, spans 0.18 km^2 (18 ha) and serves as a recreational haven while fostering a harmonious environment for the local community and tourists.

On the other hand, Kurunegala Lake, covering 0.46 km^2 (46 ha), plays a crucial role in meeting the high water demands of the surrounding community. Despite their significance, both lakes grapple with water quality issues from catchment run-off and discharge from households and hotels. Kandy Lake has witnessed a recurring five-year cycle of fish kills. At the same time, Kurunegala Lake has experienced occasional eutrophication in recent times, prompting stakeholders to take action to improve water quality. These case studies underscore the importance of stakeholder coordination, ongoing water quality monitoring, and the diligent maintenance of CFWs, as elaborated in Weragoda et al. (2022) research.

3.2. Mapping the NbS in all three countries

This NbS mapping was carried out to disseminate information on existing NbS for water treatment and management in all three countries, where six NbS applications in Sri Lanka, 42 in the Philippines, and nine in Vietnam were mapped. The following links can be used to access those mappings (Velasco et al., 2023b):

(i) https://www.google.com/maps/d/edit?mid=1Hb5pryV-7KXRSDL1MkIYO905KzuK5hGO&usp=sharing

(ii) https://naturebasedsolutions.github.io/Map-of-Existing-NbS-for-wastewater-treatment-projects-in-the-Philippines-Sri-Lanka-and-Vietnam/

The development of those two mappings is detailed in the guidebook published by the project team members (Jegatheesan et al., 2024), and the generation of these web-based and GIS maps aims not merely at encapsulating knowledge within geographic markers. Instead, it envisions an expansive horizon where the public can engage, contribute, and expand these maps by adding existing and new NbS projects in other countries.

3.3. Stakeholder participation in acquiring social and economic implications of NbS

Various stakeholder meetings garnered a wealth of insights, shaping project direction effectively. The following were the major outcomes of those meetings, which contributed to realising project objectives and have been published as perspectives on our APN project webpage (Devanadera et al., 2023; Jegatheesan et al., 2023a; Mowjood et al., 2023, Trang et al., 2023a).

The Philippine perspective offers valuable insights into the challenges, opportunities, and policy options for replicating and upscaling NbS for wastewater treatment in the country, as outlined in the perspective (Devanadera et al., 2023). In Sri Lanka, the perspective underscores the importance of identifying key regulators, beneficiaries, and custodians of lakes. It emphasises the need for central coordination in lake management and celebrates the project's success in creating a collaborative platform for stakeholders. The Central Province Governor's office has committed to taking a leadership role in lake management, as outlined in the perspective (Mowjood et al., 2023). From Vietnam, the perspective highlights opportunities for replicating CFWs and GRs, showcasing the project partners' expertise in constructing and installing NbS. Additionally, it identifies opportunities for developing governance and policies to facilitate NbS implementation, as detailed in the perspective (Trang et al., 2023a).

The first regional meeting was held at RMIT University in Ho Chi Minh City in August 2023. A field trip to Can Tho City was also made to investigate the performance of the CFWs of the Bung Xang Canal. During the regional meeting, the presentation by Can Tho University on the installation of CFWs in Bung Xang Canal and subsequent activities, such as water quality monitoring and focus group meetings, led to an excellent brainstorming session. The following suggestions were the outcomes of that session: CFW plants are readily available at no cost in Can Tho City, but they need to be purchased in Ho Chi Minh City. This raises the question of whether it would be financially viable to transport these plants to other urban areas from Can Tho City. The potential for carbon sequestration through floating wetlands presents an opportunity for climate change mitigation, warranting detailed calculations.

Students are actively engaged in learning the construction, operation, and maintenance of floating wetlands, as well as conducting essential water quality and biomass analyses. Their training extends to developing strategies for evaluating biodiversity, and this knowledge can be disseminated effectively. Utilising AutoCAD, an enhanced visual representation of the canal with integrated floating wetlands is being developed, with the canal banks undergoing adjustments to illustrate the transformed view following the installation of these floating wetlands. Lessons learned from Sri Lankan partners are guiding the reconfiguration of floating wetlands across the canal, optimising their placement for enhanced effectiveness and impact.

The presentations from the Philippines provided the basis for the development of the integrated framework and the socio-economic analysis of CW. Various key national government agencies in the Philippines favourably adopted the framework. The team then emphasised that the framework should clearly state the participation of the stakeholders in the construction and implementation of CWs. For the socio-economic analysis, the Philippine team established the background methodology focusing on the following: (i) apply economic analysis of CW projects using contingent valuation and shadow pricing methods, (ii) apply financial analysis of CW projects using financial cost-benefit analysis and real options approach, (iii) evaluate how risks and uncertainties affecting the decision-making process for CW projects, and (iv) provide policy support for the utilisation of CWs in the Philippines gearing towards a more sustainable environment and climate-resilient communities. In addition, a representative from Bayawan City provided very valuable and inspiring experiences on the successful implementation of their CW in treating septage from one of their villages.

Similarly, the presentation on GRs by Ho Chi Minh City University drew the following feedback: The study focusing on GRs has assessed the suitability of oyster shells and charcoal as growth media for plants, with variations in hydraulic loading rates ranging from 200 to 500 $m^3/ha \cdot d$. Depending on the plant species employed in the roof garden, a notable 52–78% removal of COD can be achieved. Additionally, the study observed effective removal rates for phosphorus, ranging from 34–73%. It's worth noting that some Ca^{2+} ions may leach into the treated effluent from the oyster shells, warranting consideration in system design and management. This led to investigating the use of coconut shells instead of oyster shells.

The presentation on CFW by the Sri Lankan team led to the following outcomes: Evaluation of floating wetland cell shapes revealed that the rectangular shape outperforms the honeycomb shape. Further assessments indicated that approximately 30% of the lake's surface area should be covered by floating wetlands to achieve water quality improvement. CFW plants were ranked based on their efficiency in nutrient and pollutant removal, with *Canna Sp.* exhibiting an impressive dry weight growth of 3,100 g/m^2 per year. When addressing project challenges, the team recognised the need for a viable business model and the importance of segmenting stakeholders to influence funding bodies effectively. The team also contemplated the involvement of different actors in project implementation.

Additionally, the team critically evaluated the scope of NbS and explored hybrid systems that combine NbS with grey solutions. The following feedback was given during the discussions: To visualise the impact of floating wetlands, generate contour plots of lake concentrations, considering both inlet and outlet points of CFWs as well as other areas within the lake. The analysis also should use the previously developed hydrodynamic model and examine thermal and concentration stratification to validate water quality data. Incorporating drone technology, aerial perspectives of the lake and its CFWs can be obtained. Leveraging the NbS webpage and forging connections with external organisations will enhance project visibility and collaboration. Furthermore, the importance of establishing a network for students across partner institutions to sustain NbS-related activities beyond the APN project was emphasised when the Sri Lankan team initiated this effort.

Project members from Europe have provided valuable insights into the extensive activities related to NbS being carried out across Europe. Remarkably, there are currently 35 Horizon 2020 projects with a combined funding of 240 million euros dedicated to NbS research in the region. Understanding the driving forces behind these initiatives and how to develop a replicable model for Asia is a key focus. Additionally, policy guidelines for fostering the creation of nature have become a hallmark of this research. Notably, efforts in Europe, such as the removal of tiles and their replacement with plants in two cities, exemplify how Water Matters and smaller-scale applications in conservation

FIGURE 5. FGDs on Social Acceptability for Wastewater Treatment using CWs (from left to right: GK Fisherman's Village Block Leaders, Barangay LGU of Maninihon, and Barangay LGU of Villareal in Bayawan City) (adapted from Devanadera et al., 2023).

and treatment can contribute to a sustainable water future. The discussion also raised an essential question: where is the most effective platform to disseminate information to the public? Clinics and healthcare professionals were identified as promising channels. The concept of nature-based thinking emerged, emphasising that the transformation of urban cities begins with addressing and transforming existing challenges. This approach calls for the development of policy papers and the identification of often-hidden human connections. Collectively, these insights have empowered the project team to adopt a global perspective while taking local actions to promote NbS for water treatment effectively.

3.4. Development of questionnaires to evaluate social and economic implications

For successful replications of NbS, a major factor is the effective dissemination of information regarding their traits, encompassing their effectiveness and impacts. It is imperative to gain a profound understanding of stakeholders' perspectives. In capturing the perspectives of these diverse stakeholders, it is crucial to meticulously design questionnaires that are tailored to their specific interests and concerns. Additionally, conducting interviews using these questionnaires can be a valuable approach to gather in-depth insights and responses that will contribute to the overall success of NbS replications.

The project conducted interviews on various aspects of NbS using the following questionnaires (Jegatheesan et al., 2023b):

- Suitability mapping of CWs in the Philippines
- Socio-economic survey for wastewater treatment using CWs in the Philippines
- Socio-economic assessment of the impact of NbS: Kandy Lake in Sri Lanka
- Assessment of the impacts of water resources in Bung Xang Canal on residential life and the application of CFWs in Can Tho City, Vietnam
- Assessment of environmental problems and solutions for water quality management in urban, Ho Chi Minh City, as well as the application of GRs to treat septic tank effluent in Vietnam
- Socio-economic and community awareness of wastewater treatment using NbS in Vietnam

3.4.1. *Outcomes from the survey in the Philippines on the implementation of CWs*

Three (3) Focus Group Discussions (FGDs) were conducted during field visits on 16 August 2022 and 9 February 2023. The FGDs included (1) block leaders of the GK Fisherman's Village, (2) Barangay (village) officials and staff in Barangay Maninihon, and (3) Barangay officials and staff in Barangay Villareal, all from the City of Bayawan (Figure 5).

The study encompassed Key Informant Interviews (KIIs) with CW personnel and a social acceptability survey involving 270 residents from GK Fisherman's Village. Results indicate 94% awareness of CWs in the village (Table 1). The study found that CWs proved cost-effective in curbing water pollution and enhancing community health. Factors influencing social acceptability were identified as community involvement, awareness, trust, safety, and perceived benefits. The thematic analysis emphasised the need for political support, dedicated management, technical expertise, and land availability for CW sustainability. The study recommends generating tangible economic benefits and expanding beyond regulatory services to meet community provisioning needs. Presently, the CW is primarily perceived for wastewater treatment.

TABLE 1. Survey Results on the Social Acceptability of CWs in Bayawan City* (adapted from Devanadera et al., 2023).

	Mean	Verbal Interpretation
Level of Social Acceptability to CWs	4.37	Very High
Participation in the operation of CW	3.49	High
Perceived level of safety of CW operations	4.24	Very High
Trust in the Government's CW operations	4.40	Very High
Perceived Benefits of CW	4.27	Very High
Perceived Risk of CW	2.39	Low

* 5-point Likert scale range and interpretation (Pimentel, 2010) - Very high: 4:21–5.00; High: 3.41–4.20; Neutral: 2.61-3:40; Low: 1.81–2.60; Very Low: 1.00–1.80.

3.4.2. *Outcomes from the survey conducted in Vietnam on the implementation of CFWs*

Thirty business households and another thirty non-business households living closer to Bung Xang Canal were invited to participate in the interview (Trang et al., 2025). The survey outcomes indicated that there was an average of 58.33% who agreed to pay a fee to clean the canal water. An average of 35–48.33% agree to pay a fee for landscape creation and for the cleaning of water in this area with a monthly fee of VND 10,000 to 15,000, which is equivalent to USD 0.42–0.63/month (1 USD = 23,700 VND). The willingness to pay (WTP) was computed using the following formula obtained through multiple regression analysis:

$$WTP = -0.191 * DORWQ + 0.117 * Age + 0.155 * EDU + 0.349 * Know$$

Where: DORWQ is perception of water quality in the canal (Measured using five-point Likert scale from Very poor = 1 to Very good = 5), EDU is level of education (1 = No education, 2 = Primary, 3 = Secondary, 4 = High school, 5 = Graduate/Postgraduate) and Know is the awareness of the 10% fee for environmental protection per 1 m^3 of potable water usage (1 = aware of the fee and 0 = not aware of the fee). The values for Age were defined as 1 = <20 years, 2 = 21–30 years, 3 = 31–40 years, 4 = 41–50 years, 5 = 51 years and above.

Respondents also believed poor water quality in the canal could affect their daily activities, health, business, and aesthetic values. They also knew about the NbS for water treatment, particularly the CFWs. Unfortunately, they did not want to participate in any design and installation activities of the CFWs. Thus, the survey clearly indicates the need for environmental education and the provision of incentives to create awareness of the benefits of NbS in treating polluted water.

3.4.3. *Outcomes from the survey conducted in Vietnam on the implementation of GRs*

The purpose of the survey is to understand the quality of the living environment and existing green roof systems and propose solutions to manage green roof systems in Ho Chi Minh City. Thirty households living in Ho Chi Minh City (including residents, students from many universities, workers, etc.) were invited to participate in interviews. Survey results show that 100% of households agree that water and air pollution in Ho Chi Minh City is mainly due to industrial waste. At the same time, respondents said that poor living environment quality can affect their living habits and health.

On the other hand, some individuals believe that the activities of households, restaurants, markets, and schools cause water and air pollution in Ho Chi Minh City. A total of 45% of respondents said air quality was poor, while 50% said water bodies were poor.

In addition, they also know NbS for water treatment, especially GRs. On average, '50% agree to pay installation and maintenance fees for green roof systems with fees of 1,185,000 VND (50 USD/system) and 237,000 VND (10 USD/1 month), respectively. However, due to a lack of resources and rooftop space, only 10% of families were willing to participate.

3.5. Developing a framework to assess the effectiveness and impacts of NbS

Effectiveness in NbS is gauged by goal attainment and problem resolution, with an emphasis on technical design and operational maintenance. Unlike efficiency, it neglects costs, focusing on specific targets such as water quality, possibly excluding broader environmental, social, and economic outcomes. Examining these aspects is vital for recognising co-benefits, addressing negative consequences, and building a basis for scalability. Institutional setup, governance, and policy context play a pivotal role in determining effectiveness, impacts, and potential expansion. The text offers indicators and methods for assessment. A schematic diagram outlining the factors influencing NbS effectiveness and impacts (contributions to Sustainable Development Goals, SDGs) is developed in this study, as shown in Figure 6 (Jegatheesan et al., 2023c). This definition guided the creation of a matrix (Table 2) as well as identifying objectives and problem-solving across three NbS cases in the study.

To assess the effectiveness of an NbS, we propose a comprehensive evaluation approach. First, we will examine whether the NbS meets established design criteria, improves water quality, and adheres to effective operations and maintenance protocols. For design assessment, we plan to develop specific criteria tailored to the type of NbS under consideration based on literature data. The design of the NbS will then be tested against these criteria to determine its status and overall effectiveness. Figure 6(b) illustrates similar procedures for assessing water quality and operations and maintenance protocols. By integrating these outcomes, we can comprehensively evaluate the effectiveness of NbS.

Similarly, to assess the impact of the NbS, we will examine its resource generation, pollution reduction, contributions to climate change resilience and adaptation, and benefits to human and ecosystem health. For instance, to evaluate resource generation, we will develop methods to quantify the production of flora and fauna, additional water resources, and benefits from recreational activities. These resources will be measured and, where possible, assigned monetary values. Similar methods are proposed for assessing other impact factors, as depicted in Figure 6(c).

The matrix provided served as a tool for assessing the effectiveness and impacts of the environmental initiatives considered in this study, including CFWs in Kandy and Kurunegala lakes in Sri Lanka and Bung Xang Canal in Can Tho, Vietnam, the CW in Bayawan City, Philippines, and the MP in the Binh Hung Hoa wastewater treatment plant in Vietnam. This comprehensive evaluation yielded invaluable insights that would have been challenging to consolidate otherwise. The assessment provided the following outcomes:

(i) Contribution to climate resilience was evident, although quantification was not made. Lakes and MP contribute to the reduction in heat islands, and CW and CFWs contribute to carbon sequestration.

(ii) Social acceptance of NbS was notably high across the studied regions. In Sri Lanka, the establishment of a wetland education club in a Kandy school prior to the project, the utilisation of lake environments for picturesque photoshoots against the backdrop of CFWs in both Kandy and Kurnegala lakes, and the subsequent formation of lake management committees under the patronage of city mayors post-project initiation were exceptional achievements. In Vietnam, the keen interest of locals in replicating CFWs with support from Can Tho University and the replication of GRs with backing from Ho Chi Minh City University stood out as significant outcomes. The Philippines saw strong support from various stakeholders and the Society for the Conservation of Philippine Wetlands (SCPW), facilitating community education and training while fostering a drive for replication. The CW in Bayawan City Fisherman Village has emerged as a model, drawing mayors and policymakers from other cities to observe its successful operations. Furthermore, the efficient operation of the landfill and its associated CW exemplifies the versatility of such systems. Bayawan City stands as a model city, exemplifying cleanliness and contributing to the health and well-being of both the community and the ecosystem.

(iii) Regarding the policy and governance of NbS, each of the three countries has unique experiences and challenges. It is crucial to establish well-defined roles and responsibilities among various stakeholders to ensure the effective operation of NbS initiatives. Additionally, there is a pressing need for the formulation of comprehensive national-level policies and guidelines to facilitate the successful implementation and replication of NbS for water treatment across these regions. The guidebook produced from this study will be an excellent resource for such use.

(iv) The Benefit-Cost Ratio (BCR) was calculated by comparing the total costs to the total benefits over the expected lifespan of each Nature-based

TABLE 2. Matrix for the development of an assessment framework (adapted from Jegatheesan et al., 2023c).

Category / Aspect for evaluation	Objective	Targeted outcomes	Potential impacts
Technical	• Meeting good design standards • Good operation and maintenance practices	• Complete design details • Adequate staffing • Regular maintenance	• Ease of replications • Reduction in maintenance cost
Environmental	• Improved water quality • Climate resilience and contribution to combat climate change • Balanced ecosystem	• Increased dissolved oxygen • Reduced concentrations of nutrients and other organic and inorganic pollutants • Reduced concentration of biological contaminants • Sustainable operations under extreme weather conditions • Reduction in heat islands • Sufficient footprint of the treatment system • Increased species and increased number of each species (both flora and fauna)	• Reduction in downstream treatment costs due to the removal of physical, chemical and biological pollutants • Attenuation of peak flow • Increase in the lag period • Level of decrease in temperature around the NbS • Increase in flora and fauna
Social	• Increased visibility and acceptance • Willingness to participate and pay • Improved health and sanitation	• Adequate promotional tools • Adequate information of costs-benefits • Use of the surroundings of the NBS for health benefits	• Increase in in-kind contribution • Reduction in medical costs
Economics	• Harvesting of resources • Increased tourism	• Increased income due to resources and tourism	• Increase in income due to the production of resources • Increase in income due to tourism
Policies and governance	• The existence of an organised governance structure • Appropriate policies and procedures in place	• Efficient line of communication	• Ease in troubleshooting

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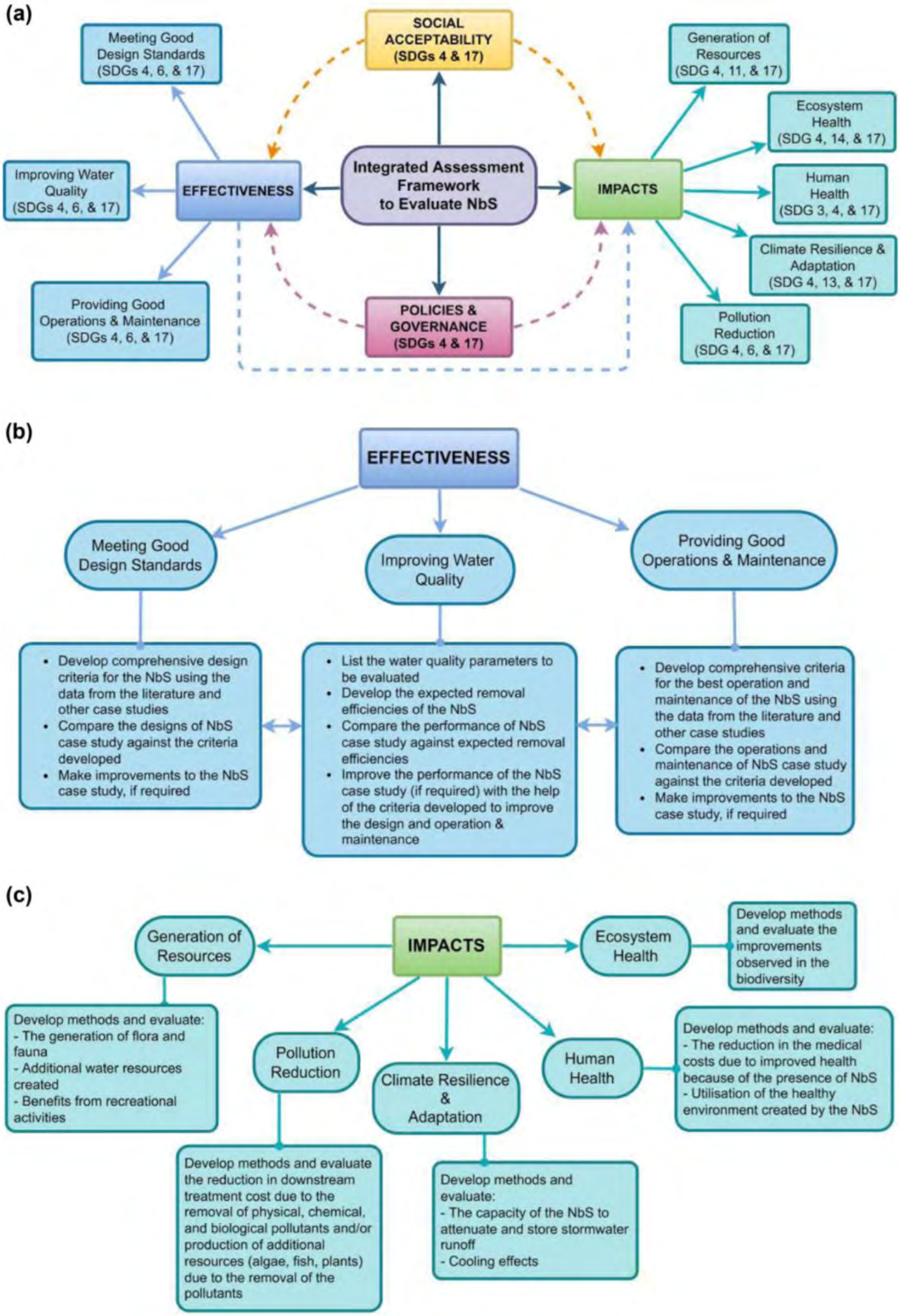

FIGURE 6. Factors affecting the effectiveness and impacts of NbS for water treatment: (a) Components of the proposed integrated assessment framework to evaluate NbS and the contributions of those components to SDGs, (b) Procedures to assess the effectiveness of NbS and (c) Procedures to assess the impacts of NbS (adapted from Jegatheesan et al., 2023c).

Solution (NbS) type. Notably, the BCRs for different projects varied: 1.43 for the Binh Hoa wastewater treatment plant, 3.0 for the CW in Bayawan City, 3.47 for the CFWs at Kurunegala Lake, and an impressive 10.84 for the CFWs at Kandy Lake. It's important to note that in the case of the Binh Hoa wastewater treatment plant, the exact contribution of NbS (combining grey and green technologies) remained unclear due to data limitations. Generally, higher pollutant removal corresponded to higher BCRs, as seen with the CFWs at Kandy Lake. However, it's worth mentioning that the benefits weren't solely attributed to the CFWs in the case of the lakes. A BCR of 3.0, as suggested by Irwin et al. (2018), can serve as a valuable benchmark when establishing NbS for water treatment projects.

3.6. Guides to selected NbS considered in the project

A comprehensive guide for implementing and scaling CWs, CFWs and GRs has been prepared and has been published as a book (Jegatheesan et al., 2024). This comprehensive book encompasses the mapping of current NbS in partner nations, suitability mapping, economic analysis, social acceptability, guides to implement CWs, GRs, and CFWs, and to select plants for CFWs. Upscaling and replication pathways of those NbS have also been discussed. On our APN project webpage, succinct overviews of the guides for CWs, GRs, CFWs, and plant selection for both, alongside brochures and videos, can be found (Bui et al., 2023; Hemalal et al., 2023; Trang et al., 2023b,c; Velasco et al., 2023a). These resources serve as conduits to share project knowledge and facilitate NbS replication. Table 3 summarises the purposes of the guides and the components considered for each purpose.

3.6.1. Guide Framework for the Implementation of CWs in the Philippines

A framework to guide CW and its implementation will improve its replicability. The guide developed in this study includes suitability mapping, design, construction, operation and maintenance, as well as social acceptance and economic evaluation. A CW treating 540 m^3/d of septic tank effluent, which has been operated in Bayawan City, Philippines, since 2006, is used as a case study to establish the framework mentioned above.

3.6.2. Guide to construct and install GRs

To construct and install GRs, the following should be carried out systematically: (i) evaluate the public acceptance and relevant policies and governance, (ii) conduct a suitability study, (iii) select plants and growth media, (iv) construct the channel, fill with media and plant selected species, (iv) supply wastewater to the channel. One of the great applications of such GRs will be treating septic tank effluent, which is reaching the canals in Vietnam without much treatment and polluting the water bodies. All the above have been discussed in the guide prepared for this study.

3.6.3. Guides to CFWs (Sri Lanka and Vietnam)

The following methodical sequence of steps must be undertaken to harness the fullest potential of CFWs, embracing a holistic approach: Assessment and selection of site, selection of plant species, sizing and shaping the floating rafts, choosing appropriate materials and tools for making rafts, steps to design rafts, deploying and anchoring the rafts and following proper operation and maintenance protocols. The guide developed in this study comprised the above, providing valuable information to the users.

3.6.4. Guide for CFW plant selection

Choosing suitable emergent plant species is crucial for CFWs as the plants play a significant role in removing the pollutants that are entering the water body and maintaining the overall health of the ecosystem. The suitability of plants will depend on the plant-related and non-plant-related characteristics of the species. The plant selection process will have the following components: (i) a systematic literature review on CFWs, (ii) a preliminary screening process, and (iii) allocating weighted scores to the plants. The preliminary screening process will check whether the plant is available locally, non-invasive, perennial, terrestrial and adapted to submerged conditions. Weighted scores will consider improving water quality and biodiversity while providing aesthetic and economic values. The above is captured in the guide developed for this study.

3.6.5. Upscaling and replication pathways

Scaling pathways are essential to replicate NbS. The definitions of four types of scaling pathways and several actions employed in the project on those scaling pathways are shown in Table 4.

TABLE 3. Purposes of the guides developed in this study and the components considered for each purpose.

Purpose	Components
1. Understanding Local Context	• Assess the specific environmental, social, and economic conditions of the urban area. • Identify local water challenges and the potential role of NbS in addressing these issues.
2. Design and Planning	• Develop NbS tailored to the local environment using evidence-based design criteria. • Consider multifunctionality, ensuring the NbS addresses water treatment while also providing co-benefits like biodiversity enhancement and recreational spaces.
3. Implementation Strategies	• Engage stakeholders, including local communities, in the planning and implementation process. • Use adaptive management techniques to respond to changing conditions and feedback during the implementation phase.
4. Monitoring and Evaluation	• Establish robust monitoring protocols to assess the effectiveness of the NbS in improving water quality and achieving other environmental objectives. • Use data from monitoring to refine and optimise the NbS over time.
5. Operations and Maintenance	• Develop clear guidelines for the ongoing maintenance of NbS to ensure long-term functionality. • Train local authorities or community members to maintain these solutions.
6. Scaling and Replication	• Identify opportunities for scaling successful NbS to other areas within the urban environment. • Share lessons learned and best practices to facilitate replication in different contexts
7. Economic and Policy Considerations	• Assess the cost-effectiveness of NbS compared to traditional grey infrastructure. • Advocate for policy support and integration of NbS into urban planning frameworks.
8. Case Studies and Best Practices	• Case studies from various cities highlighting the successful implementation of NbS and the lessons learned • Best practices are distilled to guide future projects, emphasising the importance of adaptability and stakeholder engagement.

3.7. Trial outcomes of NbS considered in the project

The outcomes of the trials conducted in all three countries demonstrate the feasibility of replicating CWs, CFWs and GRs. The community support was evident for such NbS for water treatment. The following sections describe the outcomes of each trial.

3.7.1. CWs trials in the Philippines

In the Philippines, the SCPW proposed CWs for septage treatment at Green Village in Calauan Laguna and Panguil River Eco-Park in Pangil Laguna. These two different sites would provide a great validation platform for the developed framework since the former is where the CW was retrofitted, while the latter is a new construction of CW.

3.7.1.1. Green Village trial site

The Green Village site has an existing CW system that treats septage from the toilets in the village, which serves as a youth camp centre for training and other events. Initial site visits were made to check

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TABLE 4. Four Scaling Pathways: Definitions and actions taken in the project (Jegatheesan et al., 2024).

Scaling deep	**Scaling up**	**Scaling out or wide**	**Scaling across**
Definition: Enhancing the performance and impacts of existing measures by deepening understanding and relations with the broader socio-ecological ecosystem.	Definition: Integrating relevant concepts, guidelines and tools in governance and planning to improve the enabling environment for both sustaining existing interventions and supporting the establishment of new ones.	Definition: Replication of existing good practices and examples in different geographic locations and socio-economic contexts.	Definition: Expansion of prevailing methods and strategies into different realms. This involves adapting and redefining existing interventions or incorporating components of those interventions into various sectors.
Actions carried out in the project: • Improvements of existing demonstration projects through closer engagement of local stakeholders and searching for additional partners and resources, as were the case in the trials of CFWs and GRs and large-scale application of CWs. • Community engagement activities, such as CW training conducted at the Pangil, Laguna, establish and eventually deepen the relationships with the stakeholders.	Actions carried out in the project: • Commitment to establishing a regular stakeholder consultation group by the Sri Lankan project partners, forming lake management committees, and fostering stakeholder exchanges in Sri Lanka. • Co-development of guidelines for the establishment of nature-based water treatment solutions with local policymakers for use by local authorities of the Philippines project partners as transpired during the national consultative meeting in 2022.	Actions carried out in the project: • Integration of guidelines in planning and potential up-taking by other cities in the Philippines • Development of the local network of NbS in Sri Lanka. • In Vietnam, one of the staff members at the Agricultural Seed Centre in Vinh Long province adopted the CFWs to improve the water quality of the canal adjacent to the centre. At the same time, the GR is being implemented in one household in Ho Chi Minh City.	Actions carried out in the project: • Transitioning from MP as NbS due to their large size and limited control to more manageable and replicable GR trials in urban settings. • In Sri Lanka, the impact of constructed floating wetland trials extended to educational settings, as seen in integrating these trials into a school environment alongside the formation of a youth researchers exchange group. • An unconventional form of scaling across emerged from addressing water pollution caused by bird droppings in Sri Lanka's lakes, a pertinent concern under the project's objectives. • Biofilm carrier trials and plant tests in CFWs in Sri Lanka • Green roof substrate improvements in Vietnam • Bokashi cultivation in the Philippines

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FIGURE 7. Initial condition of one of the CWs systems at Green Village.

the existing conditions of the CW system (see photos in Figure 7). Upon initial assessment, the proposed design was not followed. The primary issues identified were the accumulation of a substantial layer of soil within the CW, the planting of no viable vegetation, and the absence of valves to control flow and sampling. Further, when the CW plot was dug up, it was found that there was no concrete flooring. To address the identified issues, a retrofitting plan was devised with some enhancements implemented as follows:

(i) Cement flooring was added to the base of the CW and the outlet box to mitigate the risk of wastewater leakage. This prevents potential seepage, ensuring the wastewater is contained within the designated area.
(ii) The substrate layers were replaced, incorporating both gravel and sand. Then, the plants were replaced with vetiver grass due to their high treatment efficiency.
(iii) The height of the CW was increased by adding two levels of concrete hollow blocks (CHB) along its perimeter to prevent the transport of soil into the CW.
(iv) To properly manage the wastewater flow and to facilitate wastewater sampling, gate valves were installed at both the inlet and outlet pipes.

Presented in Figure 8 are the photos taken during different stages of the retrofitting and the initial wastewater sampling (no results to date). Since this is an existing system, utilisation of the guide began with the retrofitting step, where the research on the CW design was carried out based on the retrofitting specifications and continued with the use of the monitoring table to assess CW efficiency. Lastly, a manual on the operation and maintenance of the CW system will be developed to help Green Village's management implement it.

3.7.1.2. Panguil Eco Park trial site

The other trial site, the Panguil Eco Park, spans 12.5 km and plays a vital role in local life, monitored by the Laguna Lake Development Authority (see Figure 9 for the site photos). The plan to incorporate CW and other sustainable options in the treatment of their septage is given by Ma. Cheryl F. Prudente (Executive Director/Vice-President for Green STEPS, Inc., Green Simple Technologies for the Environment, People and the Society, Inc.), in partnership with SCPW (with an existing project on "Living Lakes, Biodiversity, and Climate Project"). This plan was endorsed by the mayor of the locality, Mayor Gerald A. Aritao, during the visit on 24 January 2023. Mayor Aritao committed to proceeding with the project and, together with

FIGURE 8. Retrofitting and sampling activities carried out at the CWs in the Green Village.

SCPW, will create a Memorandum of Agreement with SCPW to ensure the smooth implementation of the activities and its sustainability, even after the project has been completed. Then, on 18 March 2023, the team returned to the site to inspect the septic tanks (wherein two tanks are no longer properly working and will be replaced). This will be used to provide the design for the CW, which is based on Cheryl Prudente's conceptual design. In this case, the guide will be tested starting with the first step (pre-construction).

The developed CW framework will be piloted at this site. In July 2023, SCPW conducted capacity-building activities on wetlands, Nature-based Solutions (NbS), constructed wetlands (CW), and the cultivation of Effective Microorganisms (Bokashi) for use in CW systems and by the local community. Social acceptability surveys and focus group discussions determined the community's promising stance on CW for the park's septage treatment. However, the need for a working CW would be highly relevant for the constituents to accept the system readily.

3.7.2. CFWs trial in Vietnam

Several important outcomes emerge from this trial. One of them was the knowledge transfer, where the staff and students of Can Tho University were able to teach the locals about constructing and installing the CFWs in the canal. Additionally, the students came to conduct water quality monitoring biweekly and plant growth assessment monthly. In addition to adhering to the testing methodology and guidelines outlined in the guidebook, innovative techniques were implemented for securing plants onto the rafts of the floating wetland units. This

FIGURE 9. Site photos of Panguil Eco Park, Pangil Laguna, Philippines.

adjustment was necessitated by the limitations posed by the hydroponic plastic cups previously utilised in the Bung Xang Canal CFW systems, which hindered optimal root growth. As a result, three alternative methods were explored for plant placement:

(i) Coconut Coir and Nylon String: One method involved employing coconut coir to secure the plant roots, fastened in place with nylon string.

(ii) Coconut Shell and Nylon String: Another approach utilised coconut shells as a root-holding medium, firmly tied to the raft netting with nylon string.

(iii) Coconut Coir and Net Encapsulation: The third technique entailed using coconut coir to secure the roots, with the plant encapsulated within a rolled net to maintain its upright position.

These innovative methods were introduced to address the root growth constraints posed by the previous hydroponic cups, ultimately aiming to optimise plant growth within the CFWs.

3.7.2.1. Plant growth

The plant growth during this trial exhibited promising results. As illustrated in Figure 10, the plants displayed healthy growth one month after the rafts were initially deployed. Nevertheless, a challenge was encountered when a substantial number of insects began to attack the plants, as shown in Figure 11a. To mitigate this issue, during the 7th week of the trial, proactive measures were undertaken by pruning and removing the sections of plants that had been infested. These infested plant portions were then relocated far from the pilot site.

In recent developments, a significant recovery of the plants was observed approximately at the 10th week post-pruning, as illustrated in Figure 11b. However, upon visual assessment, it became apparent that the growth of these plants was somewhat less robust when compared to those situated in the Bung Xang Canal. This disparity in growth may be attributed to the relatively low concentration of essential nutrients, particularly nitrogen and phosphorus, in the canal water. It is anticipated that a potential improvement in plant growth will progress, primarily driven by the expected increase in nutrient concentration within the canal water during the new rice crop cycle, as indicated in Figure 12. This shift is anticipated to positively impact the overall health and growth of plants.

3.7.2.2. Water quality monitoring

Table 5 presents the findings regarding water quality within the canal, specifically the water drainage from the rice fields before it is discharged into the river. The results affirm that the inlet water quality is good, falling well within the established Vietnamese surface water quality standards, with values consistently within or below the permissible limits. Notably, a modest but positive shift was observed when comparing the water quality at the inlet point (prior to the passage through the 6 CFWs) to that at the outlet point (post-passage through the CFWs). This improvement is discernible through reductions in the con-

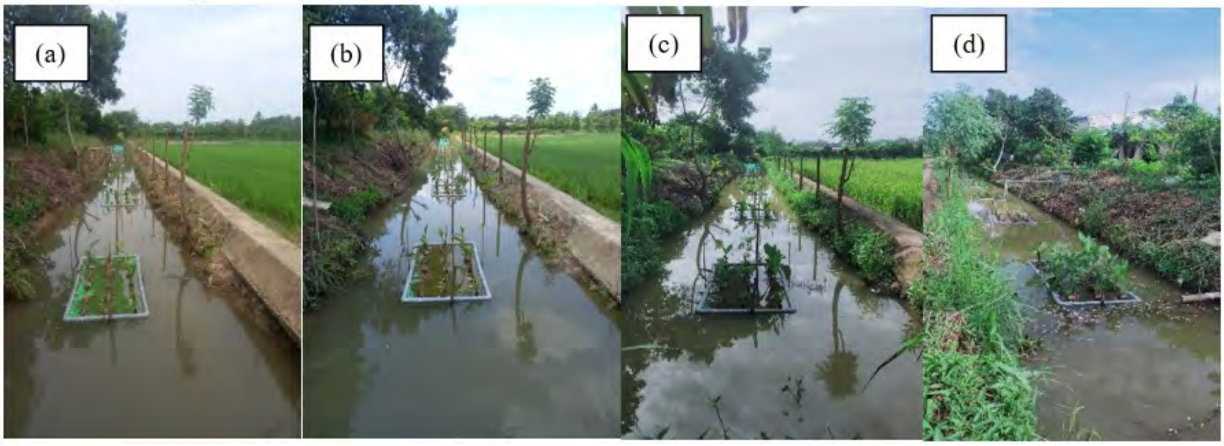

FIGURE 10. Plant growth performance at the launching day (a), after two weeks (b) and after one month (c, d).

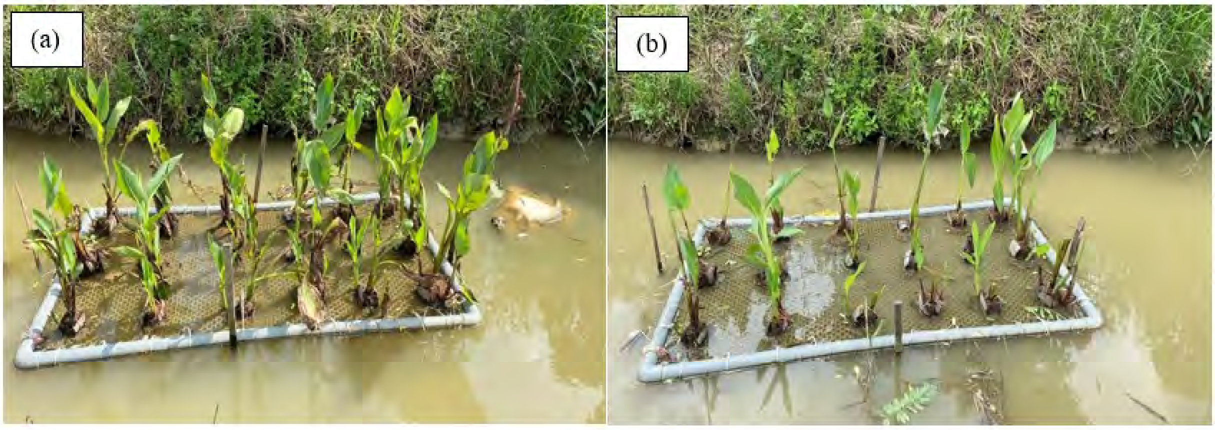

FIGURE 11. Infested plants by insects (a) and after pruning infested parts (b).

FIGURE 12. Plant growth with a new rice crop cycle releases more nutrients into the canal.

centrations of total dissolved solids (TDS), electrical conductivity (EC), Nitrate-Nitrogen (NO^{2-}–N), Nitrate-Nitrogen (NO^{3-}–N), Ammonium-Nitrogen (NO^{4+}–N), Phosphate-Phosphorus (PO^{43-}–P), and Total Phosphorus (TP) in the outlet water.

3.7.3. CFWs trial in Sri Lanka

During the trial, despite the plants being in their vegetative stage, their average height ranged from 30 to 50 cm, demonstrating robust growth even in the absence of regular maintenance. These advance-

TABLE 5. Water quality at the inlet and outlet of the canal (after passing through the CFWs) and in the river.

Parameters	Sampling points			QCVN 08:2015/BTNMT			
	Inlet	Outlet	River	A1	A2	B1	B2
Temperature (°C)	29.0–31.1 (30.2 ± 0.9)	28.1–31.2 (30.0 ± 1.3)	28.5–31.6 (30.3 ± 1.5)	–	–	–	–
pH	6.2–6.8 (6.6 ± 0.3)	6.1–6.7 (6.3 ± 0.3)	6.1–6.7 (6.4 ± 0.3)	6–8.5	6–8.5	5.5–8.9	5.5–8.9
DO (mg/L)	3.9–5.0 (4.3 ± 0.6)	3.1–4.5 (3.9 ± 0.6)	3.0–5.0 (4.2 ± 0.9)	≥6	≥5	≥4	≥2
TDS (mg/L)	**170–560 (350 ± 161)**	**110–400 (285 ± 127)**	110–400 (278 ± 122)	–	–	–	–
EC (μS/cm)	**250–720 (508 ± 225)**	**190–720 (430 ± 257)**	190–660 (418 ± 232)	–	–	–	–
COD (mg/L)	12.0–40.0 (29.4 ± 12.1)	25.6–40.8 (35.6 ± 6.8)	28.8–48.0 (36.6 ± 8.6)	10	15	30	50
Alkalinity (mg$CaCO_3$/L)	94.8–160.0 (122.9 ± 31.0)	82.5–197.8 (123.9 ± 50.6)	82.5–197.8 (123.9 ± 50.6)	–	–	–	–
NO^{2-}–N (mg/L)	**0.001–0.031 (0.017 ± 0.012)**	**0.003–0.027 (0.013 ± 0.012)**	0.002–0.037 (0.014 ± 0.016)	0.05	0.05	0.05	0.05
NO^{3-}–N (mg/L)	0.007–0.042 (0.021 ± 0.015)	0.010–0.051 (0.023 ± 0.019)	0.007–0.038 (0.021 ± 0.015)	2	5	10	15
NH^{4+}–N (mg/L)	**0.122–0.845 (0.463 ± 0.389)**	**0.119–0.590 (0.348 ± 0.248)**	0.323–0.418 (0.373 ± 0.039)	0.3	0.3	0.9	0.9
PO^{43}–P (mg/L)	**0.021–0.288 (0.129 ± 0.118)**	**0.038–0.135 (0.075 ± 0.045)**	0.028–0.087 (0.057 ± 0.025)	0.1	0.2	0.3	0.5
TP (mg/L)	**0.124–0.459 (0.288 ± 0.147)**	**0.063–0.365 (0.197 ± 0.134)**	0.151-0.883 (0.350 ± 0.356)	–	–	–	–

Note: Min–max (Mean ± standard deviation), number of samples = 4.

The classification of surface water sources for assessing and controlling water quality for different purposes of water: A1 - Good use for domestic water supply and other purposes, such as type A2, B1 and B2; A2 - Used for domestic water supply, but must apply the appropriate treatment technology, conservation of aquatic animals and plants, or other purposes, such as type B1 and B2; B1 - For irrigation purposes or other purposes requiring similar quality standards or for the purposes as type B2; and B2 - Water transport and other purposes with low-quality water requirements.

TABLE 6. Characteristic of influent and effluent (after passing through the GR system) grey wastewater.

No	Parameters	Units	Values		
			Influent	Effluent	Discharge standard*
1	pH	–	8.1 ± 0.6	7.9 ± 0.5	6.5 – 7.5
2	TSS	mg/L	38 ± 25	13 ± 7	100
3	COD	mg/L	59 ± 5	32 ± 6	–
4	NH_4^+–N	mg/L	40.0 ± 2.4	8.1 ± 1.2	10
5	TP	mg/L	0.6 ± 0.5	0.3 ± 0.2	10

* The national standard for domestic wastewater (QCVN 14:2008/BTNMT – Level B).

ments were guided by design criteria drawn from the project's comprehensive guide on CFWs. These improved CFWs are in the process of being installed at Kandy Lake. Additionally, biofilm carrier incorporation is being tested in the laboratory to evaluate their impact on plant growth and nutrient uptake in CFWs. It will be applied in a lake situated in the eastern province of Sri Lanka through a research study to further the development of pathways. Thus, the trials highlight that the design, fabrication, installation, maintenance, and performance assessment of CFWs in urban lakes for water pollution control are continuous and evolving processes that demand meticulous attention and well-informed decision-making.

3.7.4. GR Trial in Vietnam

The trial system was operated with grey wastewater that had the characteristics of 8.2 ± 0.1 pH, 38 ± 25 mg/L TSS, 59 ± 5 mg/L COD, 40.0 ± 2.4 mg/L NH^{4+}–N, and 0.6 ± 0.5 mg/L TP (Table 6). The operational parameters of the GR systems were fixed at a flow rate of 6.0 L/d, an organic loading rate of 9.0 ± 1.0 kg COD/ha/d, and a nitrogen loading rate of 0.6 kg N/ha/d. After treatment, the pollutant concentrations were measured at a TSS of 13 ± 7 mg/L, COD of 32 ± 16 mg/L, NH_4^+–N of 8.1 ± 1.2 mg/L, and TP of 0.3 ± 0.2 mg/L. The average removal efficiencies of TSS, COD, NH_4^+–N, and TP were 66 ± 8%, 46 ± 2%, 80 ± 5%, and 50 ± 6%, respectively. The treated water from the GR met the discharge standard limits stipulated by the Ministry of Natural Resources and Environment (QCVN 14:2008/BTNMT, level B). The treated water was thus discharged into the urban sewerage system. Data in Table 7 shows that plants are well adapted to grey wastewater entering the GR system. Growth of *Vernonia elliptica* and *Portulaca grandiflora* after 90 days is shown in Figure 13.

Thus, this study introduces an adaptable framework and guidelines tailored for diverse local contexts, drawing upon existing NbS applications in three countries. The establishment of a generic framework and guidelines refrains from prescribing specific NbS for individual countries, emphasising the necessity of tailoring approaches to address local nuances and requirements. While the study did not conduct an exhaustive ecohydromorphogeological investigation, it acknowledges the pivotal role of in-depth assessments in shaping decisions regarding suitable vegetation for the implemented NbS. These evaluations consider the unique environmental and geological characteristics of each region, enhancing the context-specific nature of the approach. Furthermore, the integration of field assessments, geological analyses, hydrological modelling, and community engagement is anticipated to yield a comprehensive understanding of fluvial geomorphology, the tectonic framework, and recharge potential through rain/stormwater harvesting at designated case study sites. This multidisciplinary approach aims to provide a nuanced and holistic perspective, facilitating the development of effective water management strategies.

4. CHALLENGES AND OPPORTUNITIES OF THE PROJECT GUIDING ADVANCES IN FUTURE-READY NBS SYSTEMS FOR WATER TREATMENT

The project faced notable challenges, particularly in collecting critical data on water quality, socio-economic impacts, and technical performance. These gaps underscore the need for systematic, NbS-specific data collection frameworks. Despite these obstacles, the project leveraged sev-

TABLE 7. Plant growth in the GR system.

Plant	*Vernonia elliptica*	*Portulaca grandiflora*
Initial average height (cm)	30 ± 2	5 ± 1
Average height after 3 months (cm)	90 ± 10	15 ± 5
Average plant growth (cm/day)	0.8 ± 0.2	0.1 ± 0.1
Average fresh weight (g/plant)	10.3 ± 0.5	1.3 ± 0.2
Density (Plant/m^2)	40	20

FIGURE 13. *Vernonia elliptica (left)* and *Portulaca grandiflora (right).*

eral scaling opportunities. For instance, floating wetlands and GRs were replicated across multiple sites in Vietnam, while (CWs) were implemented and retrofitted in the Philippines. In Sri Lanka, advancements included trials with biofilm carriers to enhance nutrient uptake and substrate improvements for GRs, demonstrating technical scalability. Similarly, in the Philippines, innovative materials like rice hull ash and recycled concrete were incorporated into (CWs), and the local government institutionalised wetland construction guidelines.

Emerging technologies further expand opportunities for improving NbS outcomes. Artificial Intelligence (AI) has been utilised to analyse complex datasets, optimising ecosystem services such as carbon sequestration and biodiversity conservation. Satellite technology supports real-time monitoring of NbS performance, while sensor technologies provide critical environmental data, such as soil moisture and air quality, to refine project interventions. Blockchain technology enhances transparency and accountability in data management, particularly in carbon credit tracking and project impact reporting.

Collaboration among regional partners was a key enabler for success. For example, Sri Lanka addressed local water management challenges by forming lake management committees, while the Philippines strengthened stakeholder engagement to support project implementation. These partnerships fostered the creation of a skilled regional network of NbS practitioners, promoting knowledge exchange and building technical and socio-economic capacities. This collaborative framework lays a strong foundation for advancing NbS replication and scaling across diverse contexts, driving sustainable outcomes.

5. CONCLUSIONS

This study successfully developed a framework for evaluating the effectiveness and impacts of NbS in water treatment, tested through case studies in the Philippines, Sri Lanka, and Vietnam. Key findings highlight climate resilience, cost-effectiveness, and social acceptance of CWs, CFWs and GRs, alongside their governance and policy implications. The developed guidelines address site suitability, installation, and operational considerations and were refined through stakeholder engagement and practical applications, yielding technical insights into retrofitting CWs, enhancing plant growth in CFWs, and optimising GR performance under specific conditions.

Challenges such as limited resources, space constraints, and the need for political and technical support were identified, emphasising the importance of environmental education and incentives to encourage adoption. This project recommends establishing knowledge hubs, fostering living labs and developing toolkits, complemented by training and capacity-building initiatives, to accelerate the replication of NbS. These efforts lay the foundation for scaling NbS and enhancing its role in sustainable water management.

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Videos produced from the project (see links below):

Integrated Constructed Wetlands Framework: Advancing Implementation in the Philippines (1 September 2023)

Constructing and Installing Green Roofs: A Guide and Demonstration (31 August 2023)

Guide for Selecting Plants for Constructed Floating Wetlands (CFWs) in Sri Lanka (31 August 2023)

Transforming Urban Water Treatment: Exploring Constructed Floating Wetlands in Vietnam (10 August 2023)

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Review

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Global warming impacts on marine diversity and key indicator species in East Asia

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ABSTRACT

Marine ecosystems in the northwest Pacific are known for their high biodiversity, with many marine species, from tiny plankton to huge macroalgae. Marine biodiversity is affected by irreversible global warming, mainly the increase of greenhouse gas emissions from anthropogenic activities. For the past several decades, marine ecosystems in East Asia have been changing due to the increase in sea surface temperature (SST), which has changed some important environmental factors, including rainfall patterns, extreme weather, and ocean circulation. Such modifications in the environmental parameters have altered the physiology, phenology, and distribution pattern of marine organisms. The SST increase has also altered population and community structure, and the functioning of the ecosystem. Certain subtropical and tropical fauna and flora are now extending their range of distribution from the warm southern area to the temperate regions, disrupting or modifying the biotic interactions in the temperate ecosystem. Collaborative conservation projects and responsible policies are crucial to safeguard the environmental value of East Asia's marine ecosystems for future generations and mitigate the negative effects of global warming on marine biodiversity. Conservation and management of East Asia's marine environments hold significant implications for global biodiversity and ecological balance, making them a pivotal focus in addressing climate change challenges in marine ecosystems.

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KEYWORDS EAST ASIA, MARINE ECOSYSTEMS, GLOBAL WARMING, MARINE BIODIVERSITY, POLEWARD MIGRATION

HIGHLIGHTS

- Global warming impacts marine ecosystems by elevating SST, extreme weather, and ocean circulation.
- Marine ecosystems in East Asia are diverse, vital, and teeming with marine life, nurturing unparalleled ecological significance.
- Global warming directly and indirectly impacts marine population dynamics, community structure, and ecosystem functioning.

1. INTRODUCTION

Over the past decades, numerous studies have contributed to understanding how global warming affects marine biodiversity on both global and regional scales (Tittensor et al., 2010). The SST level has gradually increased globally due to irreversible global warming, mainly driven by the alarming surge of greenhouse gas emissions from anthropogenic activities. In addition to the increase in SST, there have been substantial changes in climate extremes worldwide, encompassing reduced occurrences of cold days and nights, increased frequency of heatwaves, and alterations in the frequency, severity, and duration of compound extreme temperature and precipitation events (Albouy et al., 2020; Cheung et al., 2009; Worm & Lotze, 2016; You et al., 2022). The rapid increase in ocean temperatures, especially since 1991, has outpaced previous records, leaving scientists concerned about the implications for marine ecosystems (Cheung et al., 2009). Notably, changes in ocean temperature (Figure 1) significantly impact other important aspects of our planet's environment, including sea level, the extent of sea ice, and salinity which in turn changes precipitation and evaporation patterns, and their combined effect is already having a negative impact on marine life, leading to several unfavourable consequences (Albouy et al., 2020; Worm & Lotze, 2016).

The Northwest Pacific Ocean in East Asia comprises three large marine ecosystems (LMEs): the East China Sea, the Yellow Sea, and the East Sea (Rebstock & Kang, 2003). Even though it makes up only a small percentage of the ocean's surface, the East Asia marine ecosystem is known as the worldwide centre of marine biodiversity (Gonzales et al., 2019). It consists of a diverse range of coastal and oceanic habitats, holding unparalleled ecological significance as they stretch across the northwestern Pacific Ocean and harbour an impressive variety of marine life, supporting numerous species and contributing to marine diversity (Hu et al., 2022; Kang et al., 2000, 2012; Sugihara et al., 2009). Among these ecosystems, the coral reefs in East Asia stand out as one of the world's most biodiverse, nurturing a remarkable array of marine species by providing vital breeding grounds, shelter, and feeding areas for numerous fish, invertebrates, and other marine organisms (Muko et al., 2019; Nishihira, 2004). These coral reefs foster abundant marine life and act as natural barriers, safeguarding coastlines from erosion and mitigating the impact of extreme weather events (Veron, 2000). Additionally, East Asia's marine environments host a diverse range of macroalgae, playing a crucial role as primary producers through photosynthesis, and forming the foundation of the food web, thereby offering essential sustenance and habitat for various fish, invertebrates, and marine mammals (Lobban & Wynne, 1981; Lobban & Harrison, 1994; Vieira et al., 2016). The nutrient-rich waters of this region also nurture thriving phytoplankton blooms, attracting a diverse array of marine species, including fish, marine mammals, and seabirds (Hu et al., 2022; Jung et al., 2014).

Beyond local benefits in East Asia, the ecological importance of marine ecosystems extends globally as the region plays a crucial role in the migration patterns of many marine species, serving as a vital link in migration routes (Hu et al., 2022; Jung et al., 2014; Kang, Kim et al., 2020). Preserving and conserving these ecosystems becomes paramount

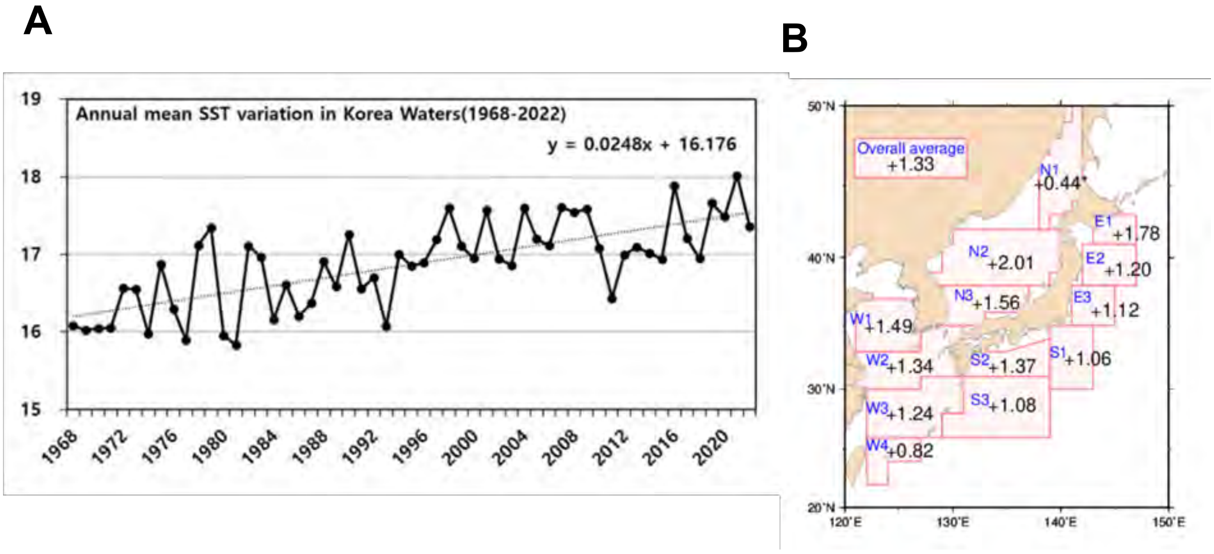

FIGURE 1. A: The long-term trends in annual mean sea surface temperature (SST) for Korean waters and the global average over the period 1968–2022 (unit: °C) (Cited from Han et al., 2023). B: Rates of increase in area-averaged annual mean SSTs around Japan from 1900 to 2023 (°C per century). Areas without symbols and those marked with [*] indicate statistically significant trends at confidence levels of 99% and 95%, respectively. N1 - Northeastern part of the Sea of Japan; N2 - Central part of the Sea of Japan; N3 - Southwestern part of the Sea of Japan; E1 - Sea off Kushiro; E2 - Sea off Sanriku; E3 - Eastern part of the sea off Kanto; S1 - Southern part of the sea off Kanto; S2 - Sea off Shikoku and Tokai; S3 - East of Okinawa; W1 - Yellow Sea; W2 - Northern part of the East China Sea; W3 - Southern part of the East China Sea; W4 - Sea around the Sakishima Islands (Source: Japan Meteorological Agency website https://www.data.jma.go.jp/gmd/kaiyou/english/long_term_sst_japan/sea_surface_temperature_around_japan.html).

for the sustainability of local marine life and coastal communities, and for maintaining worldwide biodiversity and ecological balance (Gonzales et al., 2019). In East Asia, safeguarding the rich biodiversity of marine environments requires collaborative efforts and responsible management practices to ensure these invaluable ecosystems thrive for generations. Unfortunately, marine ecosystems of East Asia face numerous threats, including overfishing, habitat destruction, pollution, and the impacts of climate change (Gonzales et al., 2019; Sekiyama, 2022; Zhang & Wang, 2019). Ensuring these invaluable ecosystems' long-term health and resilience requires concerted efforts at both regional and international levels. Collaborative conservation initiatives, sustainable fishing practices, and responsible coastal development are vital to preserving the ecological significance of East Asia's marine environments for future generations (Gonzales et al., 2019; Moore et al., 2018).

This review aims to present a comprehensive overview of the profound impacts of global warming on marine biodiversity in the East Asia region. Encompassing a range of essential aspects, the scope of this review will delve into the primary drivers of global warming and ecosystem-level impacts. Additionally, this review will specifically address the repercussions of rising sea temperatures on crucial habitats, focusing on coral ecosystems and other critical marine ecosystems in East Asia.

2. DRIVERS AND EFFECTS OF GLOBAL WARMING ON MARINE ECOSYSTEMS IN EAST ASIA

2.1. Primary drivers of global warming in East Asia

Global warming primarily results from anthropogenic activities, notably the emission of greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) from industrial processes, transportation, and deforestation, which contribute to the greenhouse effect, trapping heat in the Earth's atmosphere and causing a rise in global temperatures (Sekiyama, 2022; Zhang & Wang, 2019). Furthermore, the region's atmospheric and oceanic circulation patterns exacerbate global warming. For instance, the East Asian monsoon system can influence regional climate variability, affecting temperature and precipitation patterns, and changes in these circulation patterns can lead to altered weather conditions with subsequent impacts on the health and dynamics of marine ecosystems (Liu et al., 2023).

2.2. Effects of global warming on marine ecosystems in East Asia

In the 21st century, the majority of the oceans around the globe have shown a significant warming trend in increasing SST (Kim et al., 2011; Lee, Park et al., 2023). Numerous studies have documented rising SST, warming air temperatures, and changing precipitation patterns in East Asia (Lee, Park et al., 2023, Liu, 2020, Liu et al., 2023; Sekiyama, 2022; You et al., 2022; Zhang & Wang, 2019), and these observations align with global trends and indicate the progressive impact of global warming in the region (Zhang & Wang, 2019). In conjunction with anthropogenic interventions, extensive research has increasingly concentrated on the warming ocean as a central aspect influencing marine ecosystems (Jung et al., 2014). Climate models and projections for East Asia suggest that, if current emission trends continue, the warming trend is expected to intensify in the coming decades, leading to rising sea levels, shifting ocean currents, and altered weather patterns, thereby posing significant challenges to the region's coastal communities, marine biodiversity, and ecosystem dynamics (Cheung et al., 2009; You et al., 2022). Our understanding of how global warming affects atmospheric heatwave variabilities on both global and regional scales has greatly improved due to extensive research over several decades (Hong et al., 2021; Lee, Park et al., 2023; Wie et al., 2021). Extreme surface sea warming events, sometimes known as "marine heatwaves", are characterised by extremely high SSTs that continue for several days to many months. Over two decades, these events have become more frequent worldwide due to various atmospheric and oceanic variables (Hong et al., 2021; Wie et al., 2021). In contrast, investigations into ocean extremes represent a developing field, with only recent studies delving into these phenomena, both global distribution and trends (Zhang & Wang, 2019). Consequently, understanding the development of extreme hydrological, physical, and biological features during the past few decades, such as SST, low salinity, and phytoplankton biomass, is still uncertain (Lee, Park et al., 2023).

The rising SST trend not only impacts coral reefs globally but also negatively influences the coral reefs in East Asia, particularly evident through coral bleaching (Liu, 2020; Sully et al., 2019; Van et al., 2022). A serious hazard from rising sea temperatures is the potential for coral bleaching events, which can degrade the irreplaceable coral reef ecosystem, home to various marine animals (Sully et al., 2019). Given the crucial role that elevated sea temperatures play as the primary cause of mass coral bleaching, future projections indicate that the frequency and extent of bleaching events are anticipated to intensify as the SST continues to rise, posing an increasing threat to coral reefs worldwide (Liu, 2020; Sully et al., 2019; Van et al., 2022). Scleractinian corals also can be found in temperate regions, although they do not generally form a coral reef; in poleward, warm current-affected countries like Korea and Japan, corals have spread at higher latitudes (Lee et al., 2022; Sugihara et al., 2014).

Understanding how ocean circulation changes in a warming climate is a critical yet insufficiently elucidated aspect of scientific research (Peng et al., 2022). The complex ocean circulation system is pivotal in transporting heat and nutrients, significantly influencing marine ecosystem responses to greenhouse warming (Moore et al., 2018). Although previous research has mostly concentrated on the effects of changing winds on the upper ocean circulation, there are still many unknowns surrounding the anticipated changes in air circulation (Liu et al., 2023; Wie et al., 2021). The escalating SST, particularly on the upper surface, contributes to ocean stratification and hinders vertical circulation, transforming the upper surface into a vital heat storage location and source (Wie et al., 2021). Interestingly, less research has been done on how higher SST affects ocean circulation. However, increased SST can potentially exacerbate the surface subtropical gyre in a warmer climate and significantly change the SST (Peng et al., 2022). Understanding the larger effects of climate change on marine ecosystems and climate dynamics depends on understanding the intricate interplay between ocean circulation and temperature fluctuations (Jung et al., 2014; Moore et al., 2018; Wie et al., 2021). Increasing surface warming and sea ice loss lead to considerable nutrient trapping in the sea, according to a climate simulation extended to the year 2300. With a net transfer to the deep sea, this trapping causes a redistribution of nutrients on a global scale. Decreases of 24% and 41% in primary output and carbon export, respectively, are predicted by 2300 due to surface nutrient reductions north of 30°S (Moore et al., 2018).

According to research examining the relationship between marine biodiversity and climate change, a net gain in overall species richness is typically the result of slow changes in species composition. Such modifications directly impact the distribution (Serisawa et al., 2004), phenology, and physiology of organisms (Hong et al., 2021). Furthermore, by changing biotic interactions, climate change can significantly negatively affect populations, community structure, and ecosystem functions (Vergés et al., 2014). The generation of new biotic interactions as range-shifted species introduce themselves to native communities (Vieira et al., 2016), the elimination of current interactions when species leave their native ranges (Serisawa et al., 2004), or the modification of crucial behavioural, physiological, or other traits that mediate species interactions are all examples of indirect effects. In tropical locations, warming temperatures contribute to species loss and a decline in diversity, while temperate regions experience species turnover and, in some cases, net diversity increases as oceans warm. Observations in polar environments indicate declining trends in ice-dependent species due to the impacts of global warming (Cheung et al., 2009; Moore et al., 2018; Worm & Lotze, 2016). In East Asia, many studies highlight that, to date, the most compelling evidence for climate-driven changes in species distribution and diversity comes from long-term fish and plankton monitoring data (Kang et al., 2012), with an increasing number of studies investigating other groups, such as corals (Denis et al., 2015; Lee et al., 2022; Sugihara et al., 2014), and macroalgae (Vieira et al., 2016), to gain deeper insights into the impacts of climate change on their distribution and diversity in marine ecosystems.

Monitoring marine biodiversity on a global scale and understanding the distribution of invasive species is crucial for detecting changes in marine ecosystems. Environmental DNA (eDNA) has gained widespread popularity in the monitoring field and has experienced rapid advancements, particularly in the surveillance of aquatic invasive species (Vallejo et al., 2019). Recent developments in eDNA analysis, which extracts extra-organism DNA from various environmental samples, have made it possible to gather highly sensitive data about the diversity of fish in aquatic ecosystems in a less time-consuming, non-invasive, and cost-effective manner. Due to its benefits, eDNA has become a viable tool for biomonitoring, replacing or enhancing established techniques such as net sampling (Kawakami et al., 2023).

2.3. Effects on fish

Studies have investigated latitudinal shifts in the distribution of exploited fishes in the Yellow Sea, driven by the warming trends resulting from climate change, based on circulation model projections, temperature stratification in the Korea Strait (Figure 2) is anticipated to vanish by 2030 (Jung et al., 2014). By analysing long-term fisheries data and oceanographic observations, the mechanisms and implications of the latitudinal range shift of seven commercially important fish species in response to changing environmental conditions. Empirical relationships further indicate that five of the examined ranges of fish species are expected to shift poleward by 19–71 km from the 2000s to the 2030s (Jung et al., 2014). While the mean latitude of chub mackerel has not exhibited a significant overall northward shift (the catch distribution of chub mackerel has undergone a noteworthy change from the Korea Strait to the Yellow Sea in recent years (Jung et al., 2014)). Similarly, another study found that 12 fish species were classified as "winner" species due to their potential to thrive under changing environmental conditions, while nine out of 21 fish species could face reduced habitats by the 2050s, making them potential "loser" species in their ability to adapt to climate change. The study also predicted that 20 species' habitat changes would travel northward, with an average habitat median shifting distance varied from 110 to 206.5 km (Hu et al., 2022). These findings shed light on the potential implications of global warming on marine fish distributions in East Asia.

2.4. Effects on planktons and dinoflagellates

Phytoplankton, zooplankton, and dinoflagellates play crucial roles in marine ecosystems, affecting biomass, community composition, and population dynamics via food web relationships. The changing nutrient stress levels in the marine environment can influence their abundance and distribution, ultimately leading to shifts in the marine food web (Kang, Kim et al., 2020; Kim et al., 2008; Vergés et al., 2014). As nutrient stress increases, these primary producers and consumers may experience alterations in their secondary production, potentially impacting higher trophic levels and ecosystem dynamics (Vergés et al., 2014). Understanding these intricate relationships and responses to nutrient stress is vital for comprehending the

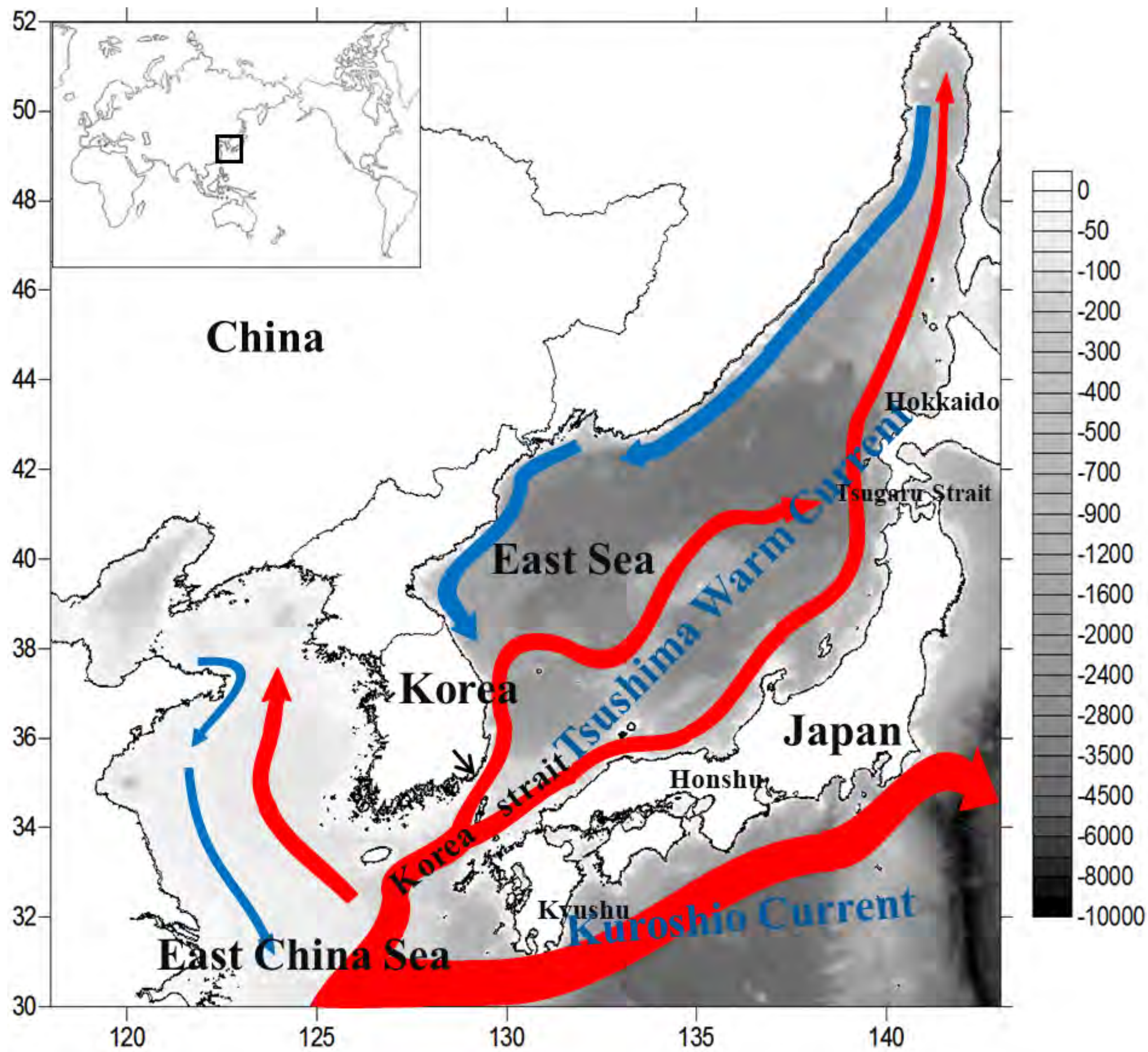

FIGURE 2. Map showing the major ocean currents in the northwest Pacific Ocean. The Kuroshio current and its branch, Tsushima warm current, are important for fisheries species in Korean waters (Cited from Jung et al., 2014).

resilience and stability of marine food webs in the face of ongoing environmental changes (Kang et al., 2012; Kang, Jang et al., 2020). The subtropical region in East Asia hosts a diverse array of tropical dinoflagellate species from the *Ornithocercus* and *Triposolenia* genera, with their populations exhibiting seasonal fluctuations, peaking in abundance during November. The direction and strength of the Jeju Warm Current (JWC), which flows into the strait, considerably impact this pattern. According to the study, these tropical dinoflagellates could be used as biological indicators to track the JWC's entry into the Jeju Strait. Furthermore, these dinoflagellates are assumed to have not yet established themselves on the coastal region of the south coast of Korea despite their constant northward advance toward the coastal areas in autumn and winter (Kim et al., 2008; Lee, Kim et al., 2023). In the Yellow Sea, long-term changes in phytoplankton and zooplankton in Jiaozhou Bay indicate an increase in warm-water plankton species, particularly dinoflagellates and gelatinous zooplankton, and a decrease in the size of the plankton community, while the overall health of Jiaozhou Bay has shown a positive upward trend (Wang et al., 2020).

2.5. Effects on corals and macroalgae

In East Asia, from Japan (Southern Kyushu and the Ryukyu arc) and up to Jeju Island in South Korea's southernmost part, this area is known as the northern limit of the range for many coral species, making it a unique site for studying the impacts of global warming on these organisms (Kang, Kim et al., 2020; Sugihara et al., 2009). The presence of a stable and thriving population of scleractinian corals (Figure 3) in the waters surrounding the sub-tropical region suggests that

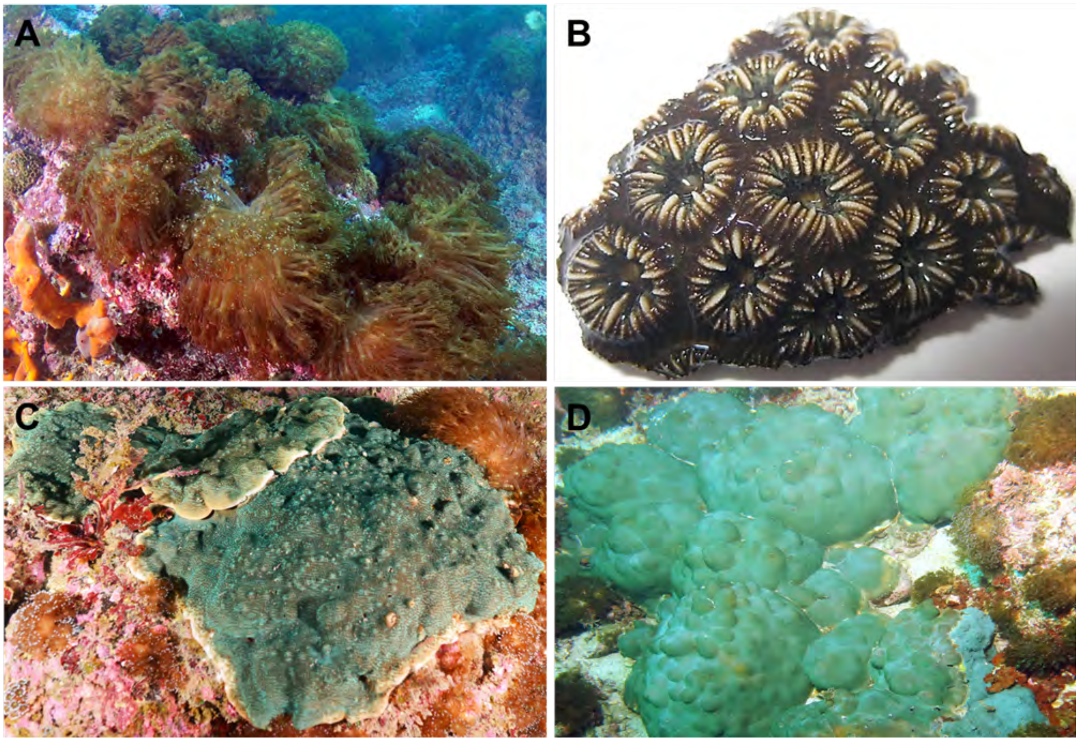

FIGURE 3. Notable scleractinian coral species are found around Jeju Island. A - *Alveopora japonica* (From northern Jeju); B - *Oulastrea crispata* (From southern Jeju); C - *Montipora millepora* (From southern Jeju); D - *Psammocora* sp. (From southern Jeju).

significant changes have occurred in the coastal ecosystem, leading to alterations in benthic composition, competition, and biodiversity (Sugihara et al., 2014; Denis et al., 2015; Vieira et al., 2016; Lee et al., 2022). Recent reports of sub-tropical fish species and new scleractinian coral species (Takatsuki et al., 2007; Denis et al., 2013; Kang, Jang et al., 2020) suggest that these coral communities have either migrated from tropical regions or expanded due to rising SST. Consequently, there has been an increase in scleractinian coral populations in the coastal benthic ecosystem (Vieira et al., 2016), leading to a shift from macroalgae to dominant coral ecosystems in some parts of Jeju Island (Figure 4) (Denis et al., 2015; Vieira et al., 2016; Kim & Kang, 2022). Remarkably, the northern coast of Jeju has reported up to 75% coverage of scleractinian corals, despite being considered marginal and unable to form reefs at high latitudes (Vieira et al., 2016). Additionally, when keystone species disappear, new species may be introduced from tropical locations, leading to further changes. Studies have shown that these changes have affected the benthic community dynamics in Korea, with the dominant coral species, *Alveopora japonica* experiencing high densities in some locations (Denis et al., 2013, 2015; Vieira et al., 2016). Increased abundance of *A. japonica* may contribute to the decline of brown macroalgae in Jeju Island. Anecdotal evidence has shown that until the 1980s, brown macroalgae were dominant in shallow subtidal rocky bottoms in Jeju, playing a vital ecological and economic role (Kang et al., 2012; Vieira et al., 2016). In the past few decades, high-latitude macroalgal communities, including Jeju, have suffered decimation due to temperature and other factors, leading to barren grounds with predominantly coralline algae covering the rocks and facilitating a coral takeover in numerous locations (Vieira et al., 2016; Lee et al., 2022).

Tropical coral reefs experienced the most severe bleaching event, highlighting their vulnerability to natural and human-induced disturbances. Rising SST poses an urgent global threat, triggering coral bleaching and potentially leading to widespread coral mortality (Kim et al., 2022; Nakamura et al., 2022). Following mass bleaching events, there was a significant reduction in spawning rates, ranging from 65% to 90%, in the subsequent period. The impact of bleaching on coral reproductive behaviour was profound, with many coral colonies experiencing disruptions in their normal reproductive cycles (Nakamura et al., 2022). In the temperate region,

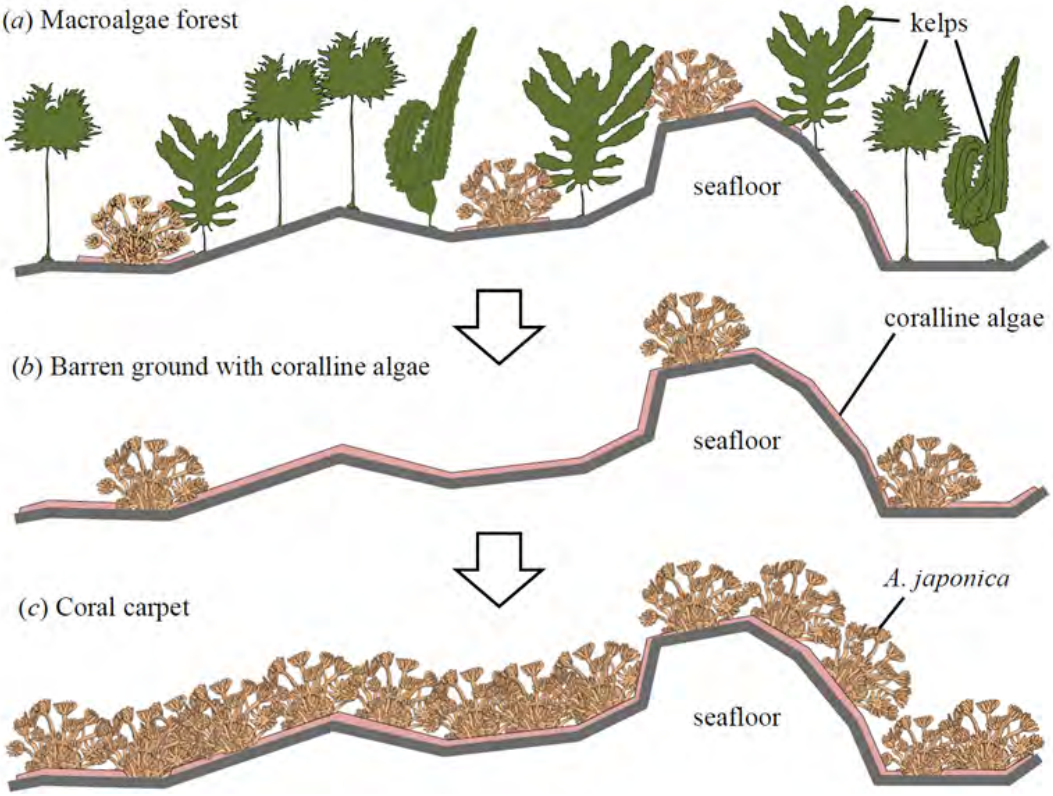

FIGURE 4. In Jeju Island, Korea, a regime shift from (a) macroalgal-dominated to (c) coral-dominated assemblages, with an intermediate (b) barren ground phase, is depicted in the schematic representation (Adapted from Vieira et al., 2016).

a recent study conducted a photographic assessment to evaluate the impact of a bleaching event on coral colonies. The results revealed that the bleaching affected 91% to 96% of the colonies, coinciding with higher summer temperatures, which likely significantly triggered the widespread bleaching (Kim et al., 2022). The high percentage of affected colonies highlights the severity of the bleaching and raises concerns about the resilience and recovery of the coral populations in the region (Gonzales et al., 2019; Van et al., 2022).

3. CONCLUSION

The impact of global warming in the East Asia region has been significant on marine biodiversity, with rising SST causing major changes. Global warming exerts a multifaceted effect on marine ecosystems, influencing various aspects such as temperature, rainfall patterns, extreme weather events, and ocean circulation. Such alterations can directly affect the physiology, distribution, and phenology of marine organisms. Furthermore, by interfering with biotic interactions, climate change has the potential to have indirect consequences that might have a considerable impact on populations, community makeup, and ecosystem functioning. The aforementioned indirect effects can take many different forms, including the emergence of new biotic interactions when species move into uncharted areas, the elimination of interactions as species move outside of their traditional ranges, or changes in important behavioural, physiological, or other traits that control species interactions. These complex interactions highlight the need for a comprehensive understanding of the cascading effects of climate change on marine biodiversity and ecosystem dynamics. Therefore, it is crucial to expand the scope to encompass a broader range of marine ecosystems and implement long-term monitoring of key indicators, thereby enabling the tracking of changes in species populations, including shifts in distribution, abundance, and size structure; in addition, efforts must be strengthened to detect and respond promptly to the spread of non-indigenous species.

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