Original article

APN Science Bulletin

2025, Volume 14, Issue 1, 200–227, e-ISSN 2522-7971

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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DOI 10.30852/sb.2024.2792

RECEIVED 11 June 2023
PUBLISHED (HTML) 30 May 2025
PUBLISHED (PDF) 30 May 2025

CITATION Jegatheesan, V., Velasco, P., Pachova, N., Trang, N. T. D., Bui, X.-T., Mowjood, M. I. M., Lecciones, A., Devanadera, M. C., Weragoda, S. K., Pham, H., Jinadasa, S., Nguyen, P.-D., Vo, T.-K. Q., Tran, C.-S., Thao, V. T. P., Trang, N. T. T., & Torrens, A. (2025). Integrated assessment of existing practices and development of pathways for the effective integration of nature-based water treatment in urban areas. *APN Science Bulletin*, *14*(1), 200–227. https://doi.org/10.30852/sb.2024.2792

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

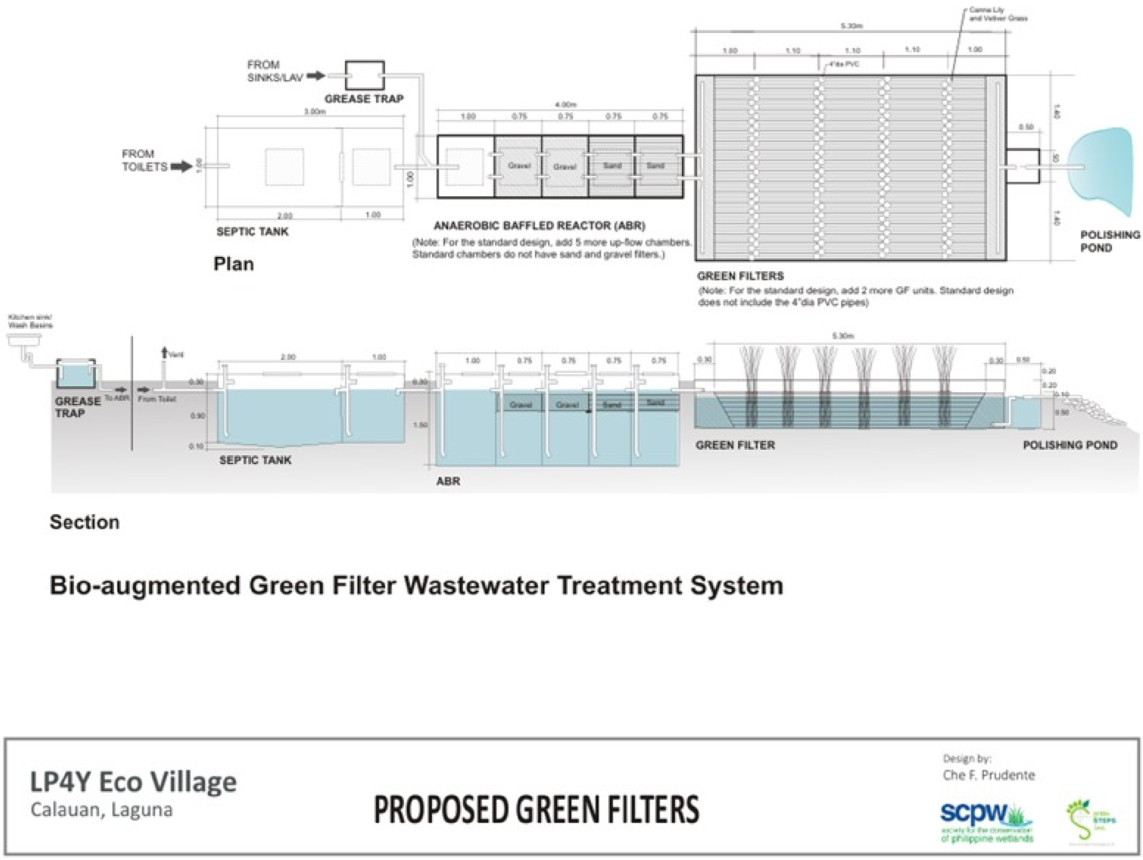

FIGURE 1. Proposed design of CWs in Green Village, Calauan Laguna.

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,

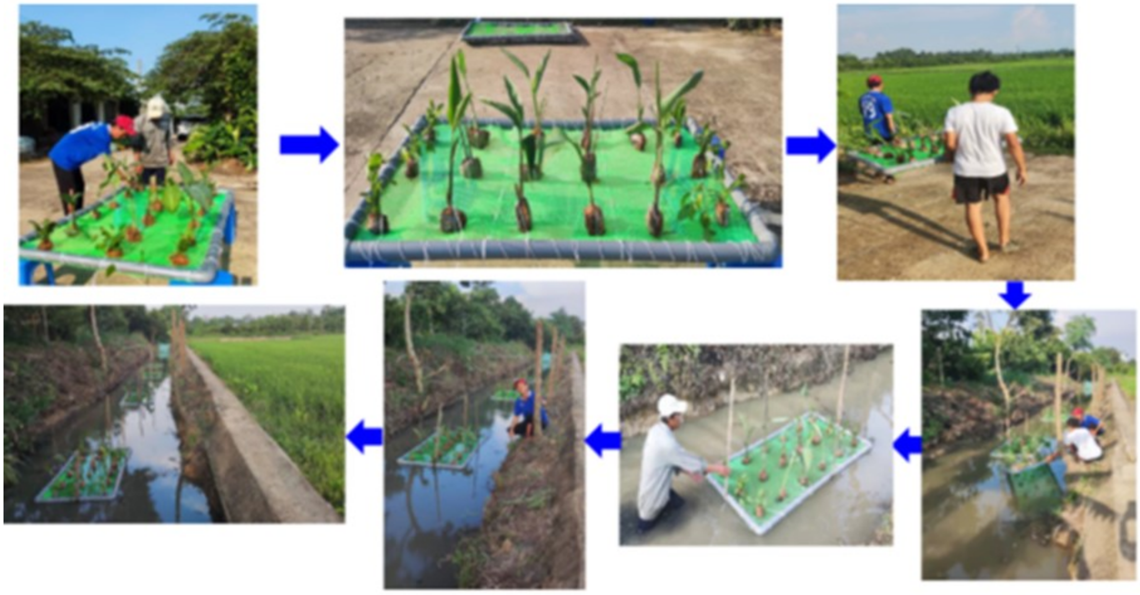

FIGURE 2. Photos of construction and installation of 6 CFWs in a canal adjacent to the agricultural seed centre in Vinh Long province, Vietnam.

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

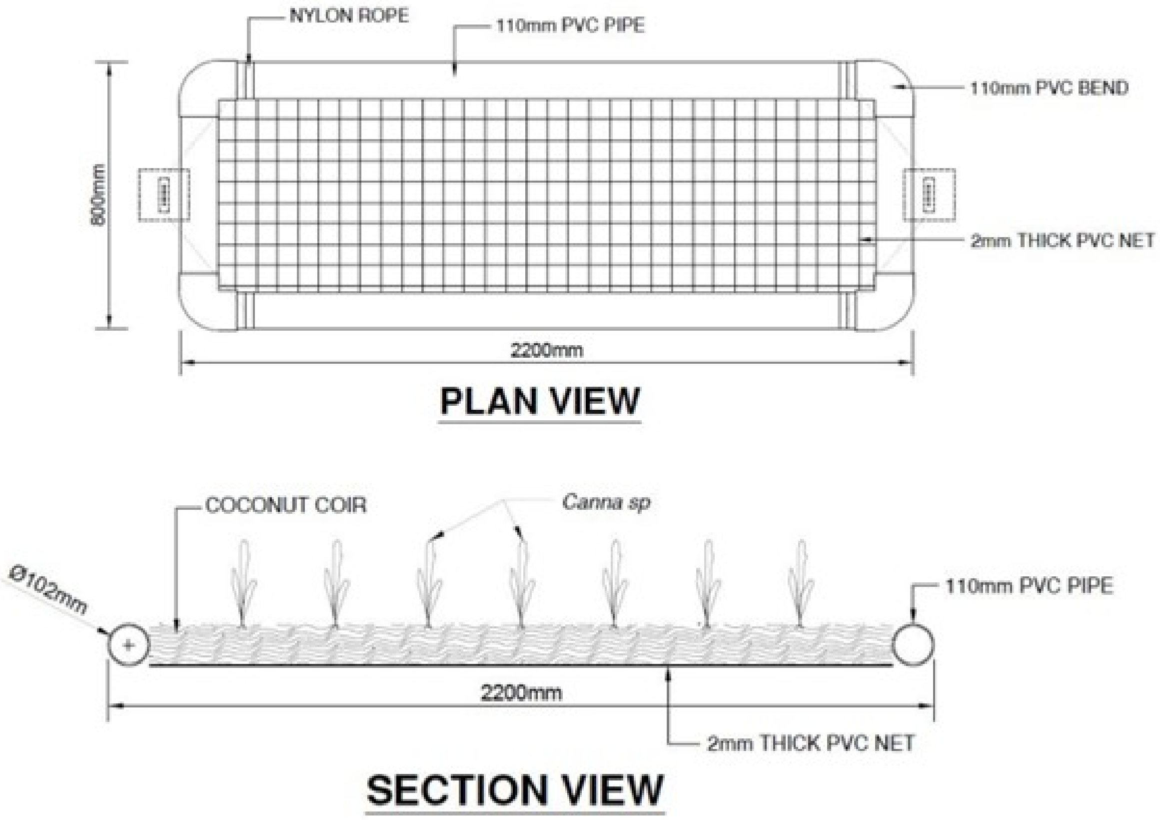

FIGURE 3. Schematic diagram of CFWs trialled at Kurunegala Lake in Sri Lanka.

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

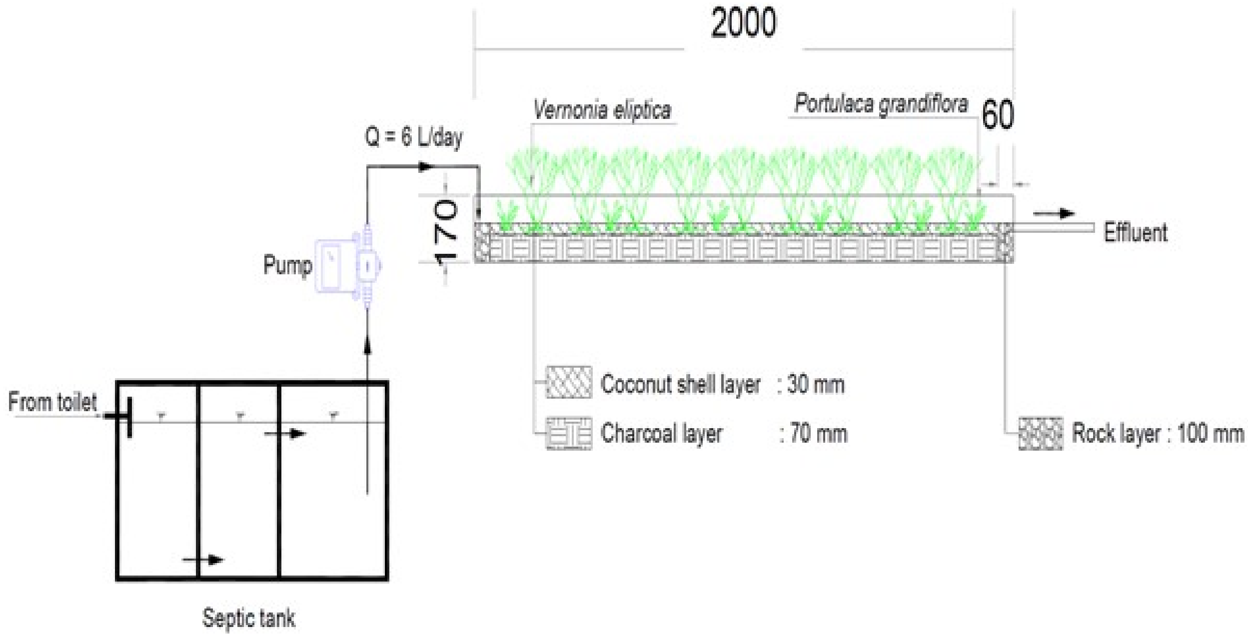

FIGURE 4. Schematic diagram of a GR module trialled to treat grey water generated at a household.

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:

$$\mathrm{WTP} = -0.191 * \mathrm{DORWQ} + 0.117 * \mathrm{Age} + 0.155 * \mathrm{EDU} + 0.349 * \mathrm{Know}$$

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

https://doi.org/10.30852/sb.2024.2792

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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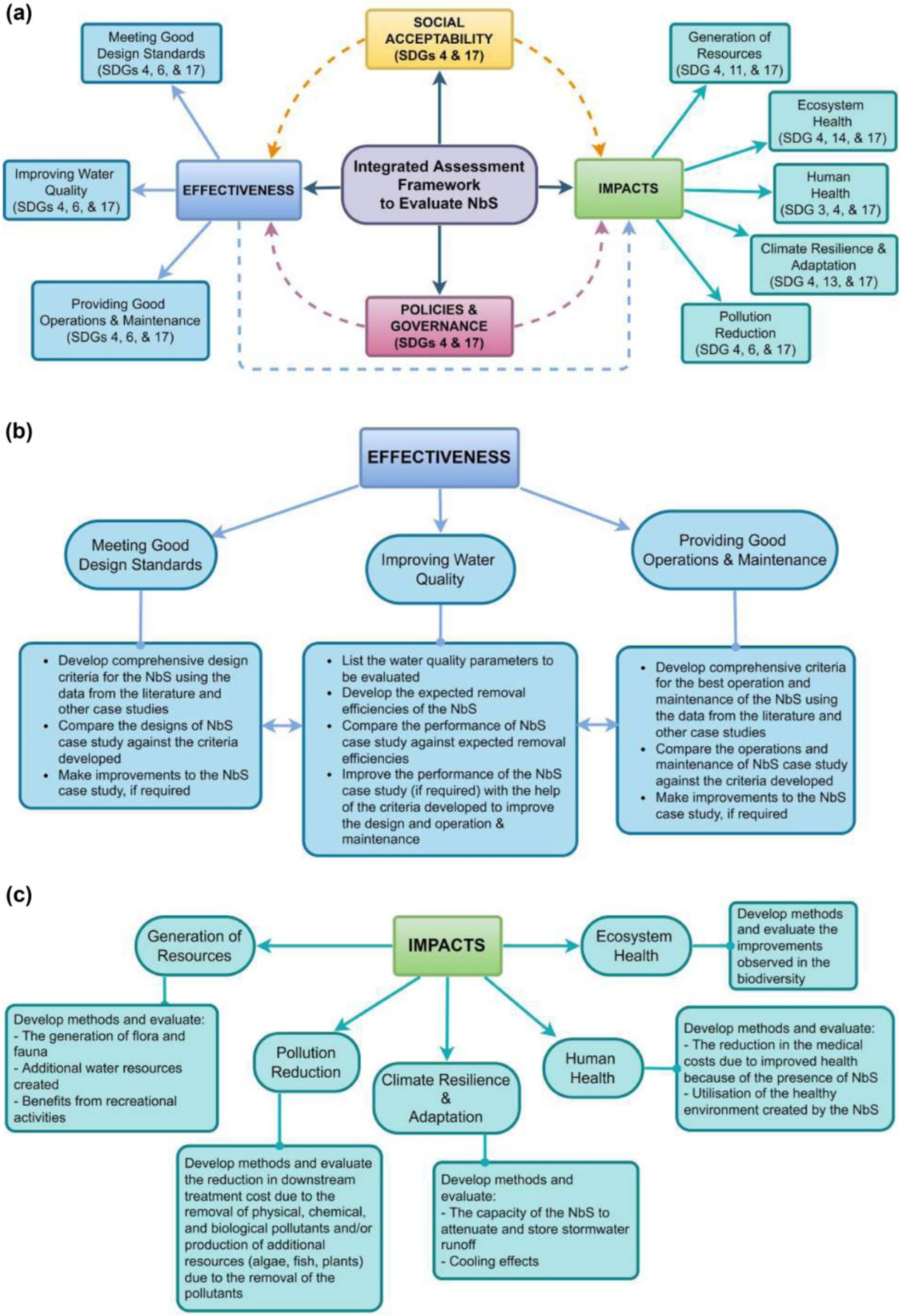

FIGURE 6. Factors affecting the effectiveness and impacts of NbS for water treatment: (a) Components of the proposed integrated assessment framework to evaluate NbS and the contributions of those components to SDGs, (b) Procedures to assess the effectiveness of NbS and (c) Procedures to assess the impacts 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

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

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

https://doi.org/10.30852/sb.2024.2792

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-

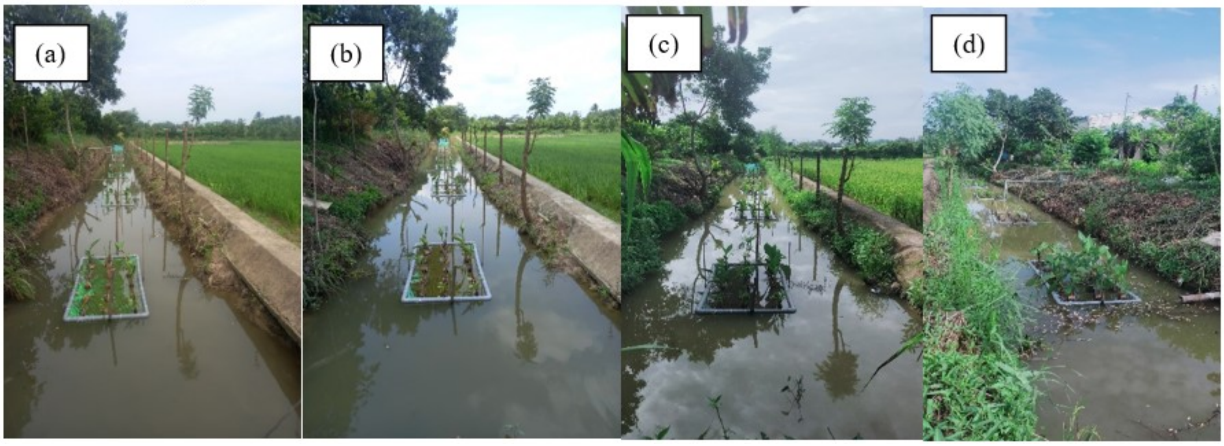

FIGURE 10. Plant growth performance at the launching day (a), after two weeks (b) and after one month (c, d).

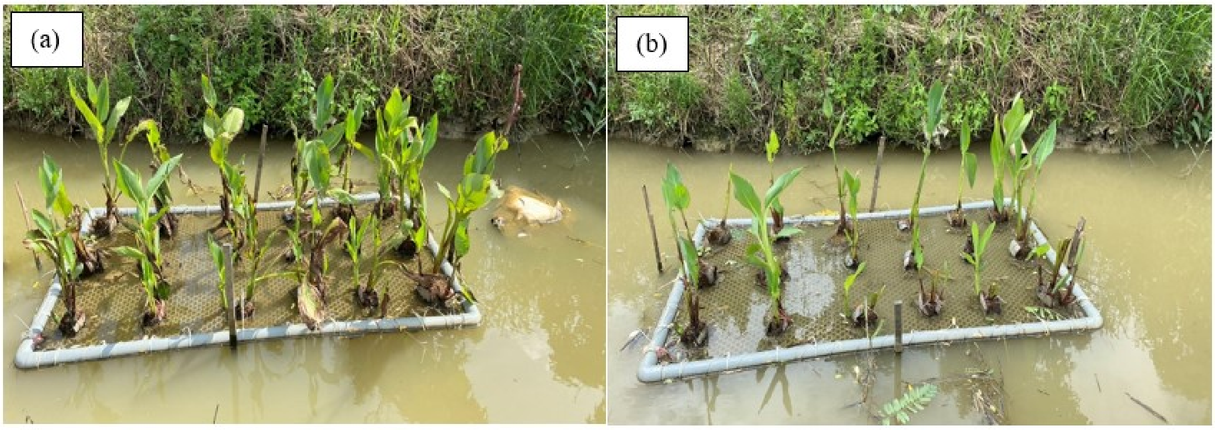

FIGURE 11. Infested plants by insects (a) and after pruning infested parts (b).

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-

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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.

6. ACKNOWLEDGEMENTS

The authors would like to thank the Asia Pacific Network for Global Change Research (APN) for funding this project with grant number CRRP2021-06MY-Jegatheesan. The authors would also like to acknowledge the following:

- Mr. Nguyen Tien Anh at Rice Seed Centre, Agricultural Seed Centre, Vinh Long province, Vietnam, for trialling (CFWs) in the canal adjacent to the Agricultural Seed Centre.
- The 40 Students from Can Tho University for their contributions to constructing and installing (CFWs).
- Ho Chi Minh City University of Technology and Vietnam National University Ho Chi Minh for their contribution to the green roof trials at Ho Chi Minh City.
- Local government unit (LGU) of Bayawan City, Engineer Antonio Aguilar, LGU of Pangil, Laguna, and Panguil Eco Park management for data gathering and for co-hosting APN activities.
- LP4Y team at Green Village, Calauan Laguna, particularly Sonny Author, Paul Dizon, and Pierre Delaporte, for their contributions in the retrofitting of their constructed wetlands.
- Architect Ma. Cheryl F. Prudente (Executive Director/Vice-President for Green STEPS, Inc., Green Simple Technologies for the Environment, People and the Society, Inc.) for sharing her CW designs.
- The Sri Lanka team would like to extend their appreciation to the following: Mr. A.C.M. Nafeel (Additional Secretary, Ministry of Water Supply), Dr. (Eng.) N.S. Wijeratne (Deputy General Manager, Sri Lanka Land Reclamation and Development Corporation), Dr. Shamen Vidanage (Country Representative, IUCN), Eng. Mrs. K.A.D.K. Dheera (Director, Central Province, Irrigation Department, Kandy), Eng. Mr. D.N.D.S. Gunatileke (Additional General Manager, Water Reclamation, National Water Supply and Drainage Board), Mr. Anura Bandara (Additional Secretary, Sri Dalada Maligawa, Kandy) Mr. P. Massumaarachchi (Deputy Commissioner, Kandy Municipal Council), Eng. Mr. Gayan Jayasekara (Chief Engineer, Kandy Municipal Council), Mr. M.A.B.C. Alokabandara (Commissioner, Kurunegala Municipal Council), Eng. Mrs. H.G.D. Amarasinghe (Chief Engineer, Kurunegala Municipal Council), Eng. Mr. D.M.B Dissanayake (Engineer, Kurunegala Municipal Council), Mr. Harshana Jatasiri (Deputy Commissioner, Kurunegala Municipal Council), Eng. Mr. D.S.N. Jayanayaka (Chief Engineer, Irrigation Department, Kurunegala), Eng. Mr. I.R. Gamage (Manager, Kurunegala Water Reclamation Section, National Water Supply and Drainage Board), Eng. Mr. D.M.B.T.B. Dissanayaka (Senior Engineer, Kurunegala Water Reclamation Section, NWSDB), and Mr. E.M.S.B. Ekanayaka (Director, Urban Development Authority, Kurunegala).
- The project team would like to thank the following for serving as guest speakers during the project quarterly meetings: Engr. Asoka Ajantha, Engr. Dhanesh Gunathilake, Mr. Albert A. Magalang, Prof. John Robert Kemmel Argue, Dr. Christopher Walker, Prof. Magdalena Gayewska, Brigadier, K.M.S. Kumara, Ms. Yolanda Gomez, Jeremy Rudd, Fany Wedahuditama, Mr. A.C.M. Nafeel, Dr. Anuradha Jayaweera, Engr. Donny Rey Camus, Nuria Moncada, Doug Warner, Anh Tuấn Nguyễn, Assoc. Prof. Casper Boongaling Agaton, Patricia Marie Caparas Guila, Prof. Ignasi Rodriguez-Roda Layret, Dissanayake D.M.B.T.B., Rey J. Casas, and Anne Dominique Hitape Rodriguez.
- Renzo Mori Junior at RMIT University, for assisting in creating the project webpage on the RMIT website.
- APN staff, Dr. Linda Anne Stevenson, Dr. Nafesa Ismail, Ms. Aiko Seki, and Ms. Naomi Young, thank you for your great support and timely responses to our requests.

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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