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TOPICAL REVIEW

Spatial heterogeneity of ecosystem services and their valuation across himalayas: a systematic literature review and meta-analysis

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Abstract

The Mountain Ecosystems, such as the Himalayan region, not only provide numerous Ecosystem Services (ESs) to millions of people living in mountainous areas but also provide essential ES to those living downstream. However, there is often an uneven distribution of ES availability and its value across different regions. Therefore, a better understanding of the spatial heterogeneity of ES is required for efficient and sustainable management of ES. This study thoroughly reviews literary data to examine ES's spatial distribution and economic values across the Western, Central, and Eastern Himalayas. The literature was searched in the Scopus online database using the Boolean method from specific keywords such as 'Ecosystem Services' AND 'Himalayas'. A systematic review of 76 of the most relevant literature sources yielded 31 unique ES divided into three categories: Provisioning (PES), Regulating (RES), and Cultural (CES). The distribution of reviewed literature is relatively balanced across the Himalayas (Western: 30.26%, Central: 32.89%, Eastern: 36.84%); however, the analysis identified a bias towards PES (43.54%), highlighting a need for increased research focus on RES (36.48%) and CES (19.98%). Notably, water-related services such as PES9 (Surface water used as a material (non-drinking purposes)) and PES8 (Surface water for drinking) have been ranked highest in all regions of the Himalayas yet have not been comprehensively studied in terms of their quantification and valuation. Furthermore, while most literature focused on the identification of ES (73.68%), there is a significant lack of attention to quantification (39.47%) and valuation (23.68%) of ES in the region. The average economic values for PES, RES, and CES were 446.75 USD/ha/year, 1128.81 USD/ha/year, and 457.51 USD/ha/year, respectively, indicating higher valuation for RES. This underlines the need for a more balanced research approach that includes identifying and thoroughly quantifying and valuing all types of ES in the Himalayas.

1. Introduction

The concept of Ecosystem Services (ESs) has received much attention as a framework for understanding the relationship between humans and the environment. Daily (1997) points out that the biosphere operates through complex natural cycles that generate ES. These services include diverse components and processes of the natural environment, which offer several benefits to meet human needs (Mauerhofer 2018). ES contributes significantly to human well-being by preserving cultures, boosting the economy, and enhancing the quality of life (Millennium Ecosystem Assessment 2005). Furthermore, these services are important for biodiversity protection since ecosystems provide habitat for many species. The Millennium Ecosystem Assessment (Millennium Ecosystem Assessment 2005) was the first to use a comprehensive framework to classify ESs into four primary categories: provisioning (PES), regulating (RES), cultural (CES), and supporting (SES). PES are the direct benefits of ecosystems, such as timber, firewood, and non-timber forest products (NTFPs). Furthermore, freshwater ecosystems provide drinking water and irrigation, which is essential in supporting the region's water demand (Meraj *et al* 2022, Saeed *et al* 2022, Yadav *et al* 2022). RES are critical for mitigating the effects of natural disasters, preserving ecological balance, and providing key benefits through processes like water flow regulation, soil conservation, and erosion control (Millennium Ecosystem Assessment 2005). CES, which are the indirect benefits, such as recreational activities, spiritual and CES experiences, and aesthetic delight, are critical for generating revenue and providing a source of income for local communities (Elwell *et al* 2020). SES are intermediate services such as nutrient cycling, soil formation, and primary production, essential for providing other ES in the region, such as PES, RES, and CES.

The Alpine or Mountain Ecosystem not only provides numerous ES to millions of people living in mountainous areas, but it also provides essential ES to the people living downstream (Huber *et al* 2013, Wester *et al* 2019, Grêt-Regamey and Weibel 2020). Viviroli *et al* (2020) predicts that more than 24% of the world's lowland population will be heavily dependent on runoff from mountainous areas by 2050. However, the sustainability of mountain ecosystems is under threat due to effects of climate change and rapid urbanization (Suberi *et al* 2018, Hoy and Katel 2019, Ebner *et al* 2022, Amoako Johnson and Hutton 2014, Singh *et al* 2022, Zam *et al* 2021). These threats present significant challenges and implications for the environment and human well-being. The potential loss of mountain ES could disrupt critical water supply chains, affect agriculture and food security downstream, and exacerbate natural disasters (IPCC 2022).

The Himalayas are the youngest and one of the most dynamic mountain ranges in the world and are home to numerous species of flora and fauna, with over 35 000+ plant species and 30 000+ animal species (Apollo 2017, Chandra Sekar *et al* 2017). The Himalayas play a significant role in the lives of more than 300 million people who rely on them (Schild 2008). They sustain the lives and livelihoods of 52.8 million people in several countries, including India, Bhutan, Nepal, and China (Apollo 2017). Notably, the unique topography of the Himalayan region influences the weather of the Indian subcontinent and the Central Asian highlands (Momblanch *et al* 2020, Ghosh 2021). Furthermore, by storing greenhouse gases such as carbon dioxide, the Himalayas play a key role in climate regulation (Singh 2007). Furthermore, the region's ecosystems offer a wide range of CES, making it a popular destination for tourism, spirituality, and religion. The Himalayas, home to numerous sacred sites and pilgrimage locations, attract millions of tourists yearly, making it an important ecotourism destination (Nepal *et al* 2018, Ncube *et al* 2021). Hence, managing and conserving these ecosystems and ensuring their sustainability becomes critical.

The Himalayan region has the highest human population of any mountain range on the planet, underscoring the necessity of studying ES in this area (Grêt-Regamey and Weibel 2020). Over the past 50–60 years, the rise in population in the Himalayas has been around three times the global average, potentially burdening natural resources and impacting ES availability (Apollo 2017). Therefore, gaining a deeper understanding of the Himalayan ES becomes critical for developing sustainable practices for conserving and using ES in the world's alpine ecosystems. As a result, this comprehensive review aims to address critical knowledge gaps in the context of ES in the Himalayan region. The work examines and assesses the contributions of ES to human well-being, identifies the important ES in the Himalayan region, and studies their spatial distribution across the Himalayas. The specific objectives of this review are: (1) to conduct a thorough literature review to gain a better understanding of ES in the Himalayan region; (2) to analyze the spatial distribution of these services across the Himalayas; and (3) to identify the challenges and knowledge gaps in the existing literature and provide recommendations for future research directions.

2. Material and methods

2.1. Study area

The study area spans the vast Himalayan Mountain chain, from the Indus River's big bend in the northwest to the Brahmaputra River's bend in the east (figure 1). Its geographical features include towering mountain peaks, glaciers, deep valleys, tranquil lakes, and meandering rivers and streams. The Himalayan region includes several Indian states, including Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Sikkim, and parts of Arunachal Pradesh, as well as the northwest corner of West Bengal. Furthermore, the Sub-Himalayas are primarily found in Nepal, with a smaller portion extending into Sikkim, India, and a small portion in the southern half of Bhutan. Notably, the Himalayan Mountain range extends from South Asia into Central Asia, encompassing countries such as China and Afghanistan. This work focuses on the Himalayas within three developing South Asian countries: India, Bhutan, and Nepal.

The study divides the Himalayas into three regions: the Eastern Himalayan Region (EHR), the Central Himalayan Region (CHR), and the Western Himalayan Region (WHR) (figure 1). The WHR stretches from the Indus to the Sharda, covering the Indian states- Himachal Pradesh, Jammu and Kashmir, and Uttarakhand. The CHR spans Nepal, from the Kali River in the west to the Teesta River in

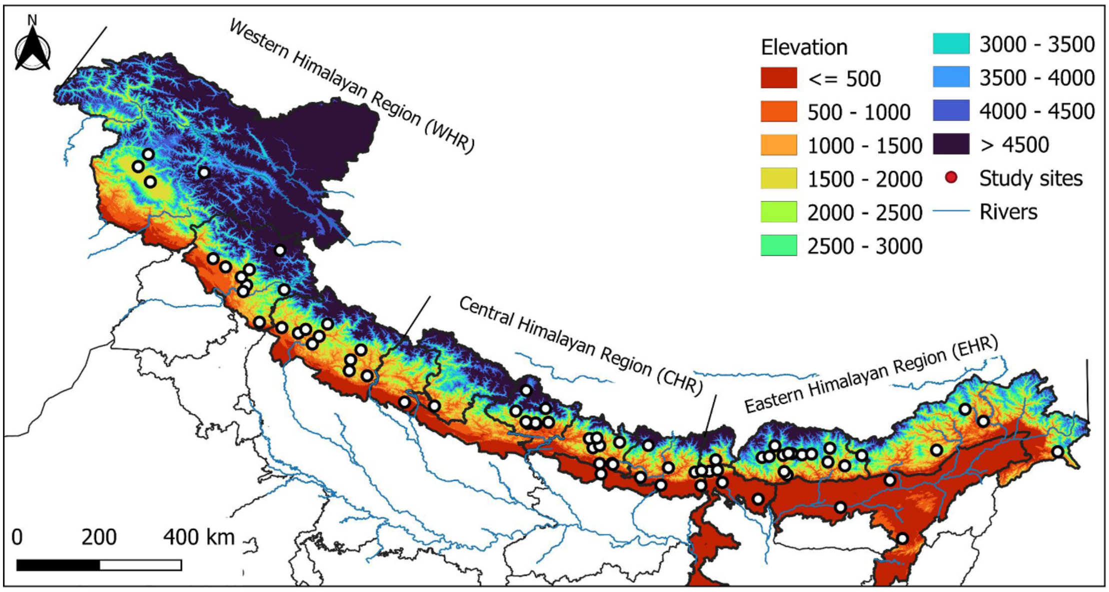

Figure 1. Study area map showing the literature study sites across the Himalayan region. The region is divided into three sub-regions: Western, Central and Eastern. The river network and DEM are taken from HydroSHEDS.

the east. This region also has some of the highest peaks in the world, such as Mt. Everest, Kanchenjunga, Makalu, Annapurna, Gosainthan, and Dhaulagiri. Bhutan, Assam, and Arunachal Pradesh comprise most of the EHR. It spans around 720 km and is between the Teesta River in the west and the Brahmaputra River in the east.

From June to September, the Himalayan region's climate gets influenced by South Asian monsoon. The Himalayas have a distinct climatic divide, with tropical and subtropical temperatures prevailing from the foothills to a polar climate with snow-covered summits at higher altitudes. In the WHR, subtropical westerly winds and low-pressure monsoon systems contribute to heavy rainfall during the summer. Winter precipitation over the Karakoram and Hindu Kush Mountain ranges accounts for approximately half of the annual precipitation. The Eastern Himalayas have a more diverse geomorphic history and widespread topographic features than the Central and WHRs.

2.2. Data collection

A systematic literature review approach was used to gather relevant publications on ES in the Himalayan region for this research. The search was conducted using the Scopus online academic database, focusing on articles published up to 2023. Two sets of specific keywords were initially searched using the Boolean approach (figure 2). The first set of keywords focused on the Himalayas as the geographic extent and included the terms ('Ecosystem services,' OR 'Environmental services,' OR 'Ecological services,') AND ('Himalayan,' OR 'Himalayas,' OR 'Himalayan region,' OR 'Himalaya') resulting in 398 articles. The second set of keywords focused on specific regions within the Himalayas. It included the terms ('Ecosystem Services') AND ('Nepal,' OR 'Bhutan,' OR 'Sikkim,' OR 'Himachal Pradesh,' OR 'Uttarakhand,' OR 'Jammu and Kashmir,' OR 'Arunachal Pradesh,') resulting in 338 articles. The articles were then filtered to include only research articles, reducing the numbers to 279 for the first and 266 for the second set. Duplicate articles appearing in both sets were removed, resulting in 430 unique articles (list provided in supplementary material section S1). Subsequently, the articles with study sites/locations/regions outside the defined study area of this review were removed, reducing the total number of articles to 191. Furthermore, only the articles specifically focusing on the study, identification, quantification, or valuation of the ESs were selected. This selection resulted in 68 articles, and finally, relevant reports were added, resulting in 76 articles deemed relevant for a comprehensive review. A list of these selected literature is provided in supplementary material section S2.

2.2.1. Temporal and spatial distribution of ES studies

Based on a Scopus search, research on ES in the Himalayan region began in 2002, with the period of this study covering publications up to 2023. The year-wise distribution of the number of publications related to ESs in the Himalayan region from 2002 to 2023 is shown in figure 3. A significant increase can be seen in publications over the years. In the initial years (2002–2008), publications were almost negligible. The publications show an overall consistent increase from 2008 until 2021, except for 2015, which experienced a sudden rise in publications from

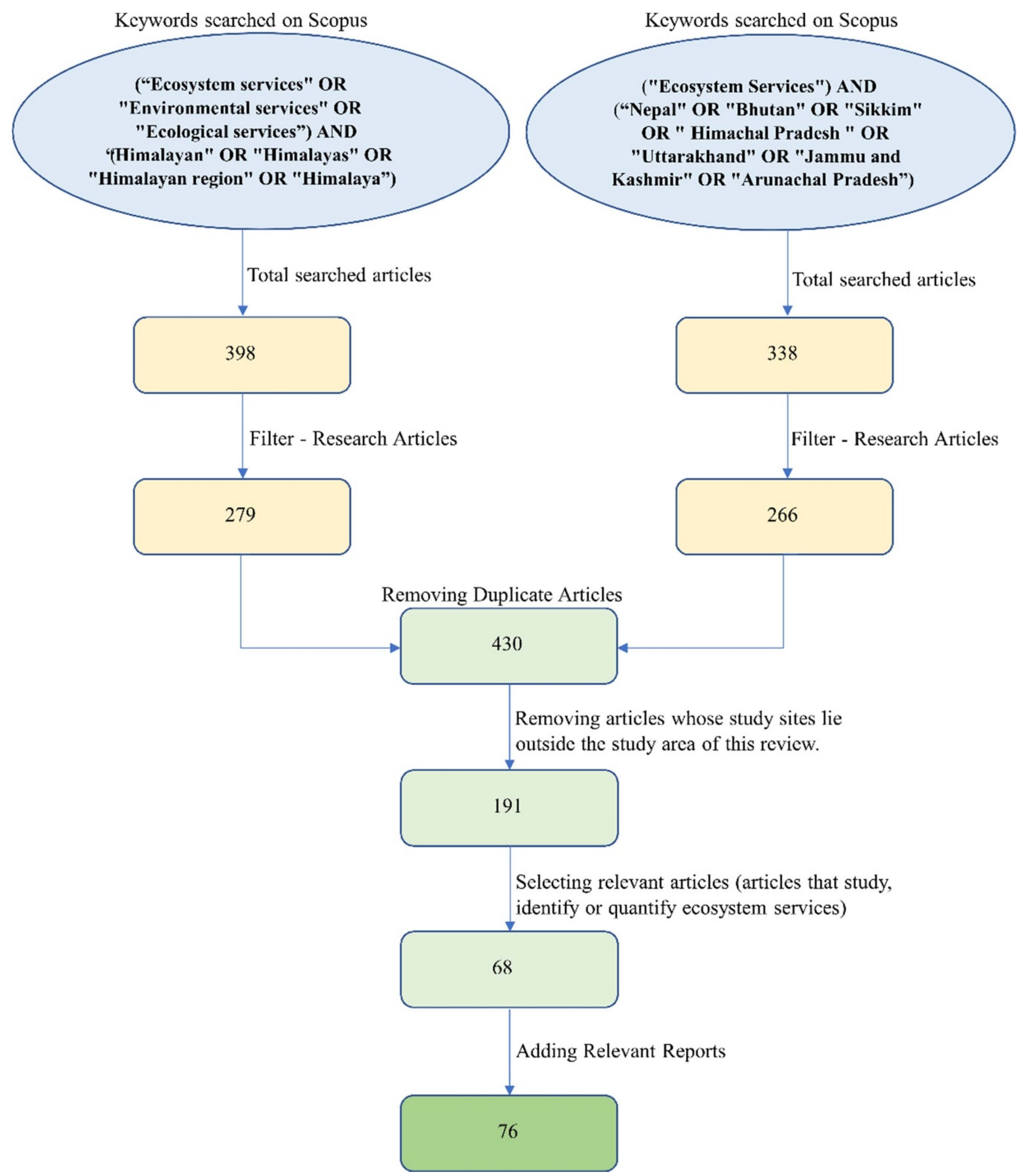

Figure 2. Flowchart depicting the method used for selecting the literature for the review.

14 to 28. This rise in publications may be attributed to a growing global awareness of the importance of ES. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, established in 2012, and its early work program (2014–2018) produced several thematic and regional assessments emphasizing the links between biodiversity, ESs, and human well-being. Moreover, adopting the Sustainable Development Goals (2015), which highlight the crucial role of ecosystems in human well-being and sustainable development, likely further contributed to this trend. This increasing trend reflects growing academic and research interest in the ESs of the Himalayan region.

There is a variation in the spatial distribution of ES study sites. This variation of study sites is dependent on various factors such as accessibility, population density and institutional presence. Accessibility plays an important role in ES research, as some parts of the Himalayas are remote and not easily accessible. This may limit the research that can be conducted there; for example, there are relatively fewer studies in WHR, especially in the high-elevation zones. The variation in the spatial distribution of ES studies could also be due to population density. It can be observed that regions of low population density, like the Jammu & Kashmir region of WHR and the Arunachal Pradesh region of EHR, have fewer study

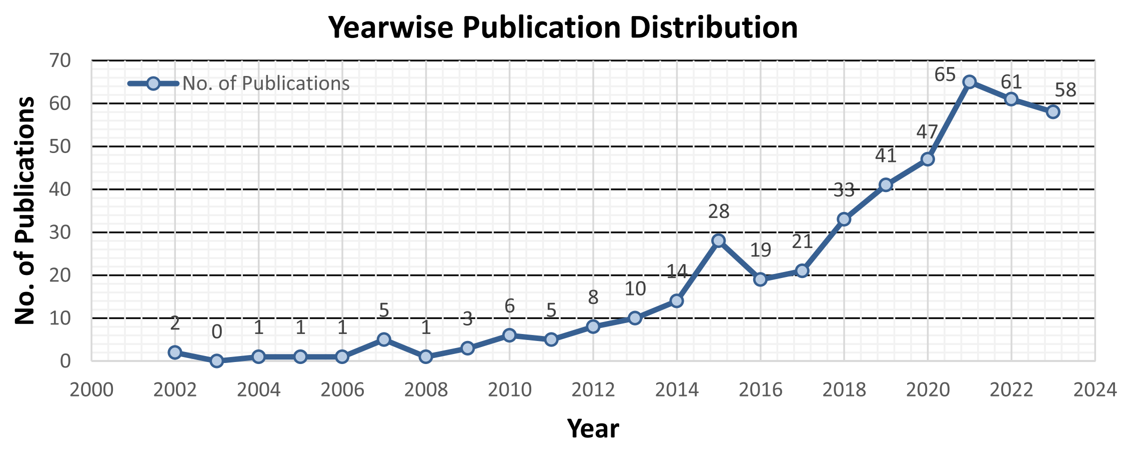

Figure 3. Year-wise distribution of literature found on Scopus for the period 2002–2023.

ES sites than the CHR region, which has a higher population density. The institutional presence may also be a factor in the spatial variation of the ES study site. Regions with established institutions may be more likely to have more ES studies. A map of study sites, institutional presence and population is provided in the supplementary material section S3.

2.3. Mapping and ranking of ES

The studied ES were manually examined from the identified literature, and the study site locations were mapped in the GIS platform. The locations of study sites were analyzed to understand the spatial distribution of ES across the Himalayas. Further, to understand the role of altitude in defining the relative importance and relevance of different ES, the spatial distribution map of ES was overlaid with the elevation map of the region. The elevation map of the region was derived from a digital elevation model of HydroSheds at 90 m resolution. Furthermore, we examined the dominant ecosystem type for each study site location to examine the role of ecosystem type and the land cover on ES diversity.

Different research studies identify, quantify or value ES based on classification systems such as MEA, The Economics of Ecosystem and Biodiversity, etc. Different ES are classified according to the Common International Classification of Ecosystem Services (CICES) for standardization (Haines-Young and Potschin-Young 2018). CICES is a reference and can easily translate the ES from different classifications. While classifications like MEA classify the ES into four categories, CICES classifies them into three, i.e. PES, RES and CES. CICES does not classify the ES into SES as these are the intermediate services that support other services, while CICES focuses on the final ES, which are the outputs from the ecosystem that directly impact human well-being. The ES were tallied for each subregion, i.e. WHR, CHR, EHR, and the entire Himalayan region. The ES with higher occurrences in the literature were given higher ranks, with the ES having the highest occurrences in each region assigned rank 1. A higher rank indicates that the ES has been more frequently studied in the region.

2.4. Valuation of ES

To compare the economic values of ES, only the studies that provided valuations for individual ES were included. In contrast, the studies that did not provide the economic valuation of individual ES were excluded. Since the economic valuations of ES were conducted across different countries, different currency units were used, such as Indian Rupees, Nepali Rupees, Bhutanese Ngultrum and US Dollars (USD/US$). Moreover, some literature reported values per hectare, while others reported the values per person or household. To standardize these data, all the currency values were converted to a common unit (US$), and the values reported per household or person were first multiplied by the total number of households or population and then divided by the area of the study region (in hectares) to obtain comparable per-hectare values. The standard unit of US$/ha/year was used for the final comparison of the economic values of different ES in the Himalayas.

2.5. Bibliometric analysis

Bibliometric analysis is a quantitative technique for assessing and interpreting scientific literature data, which helps identify patterns, trends and the evolution of research areas over time. This approach assesses the volume of publications and helps map the collaborative networks within a research topic. In this study, the following analysis will be done: identification of the most influential countries, organizations, and journals and network analysis of different research topics based on co-occurring keywords.

2.5.1. Performance analysis

In this study, the performance analysis of the literature focuses on identifying the countries, institutions, and journals contributing to ES research in the Himalayan region. The literature was analyzed based on the number of publications in various journals and the volume of publications from different institutions across different countries.

2.5.2. Co-word analysis

Co-word analysis is a well-known method for analyzing bibliometric data and identifying patterns in various fields (Kulakli and Arikan 2023, Paul and Roy 2023). This technique allows for effective text mining and thematic content analysis. A high frequency of co-occurring keywords, in particular, indicates a stronger association between related articles (Paul and Roy 2023). A network map of co-occurring keywords was drawn using VOSviewer software.

3. Results

3.1. Bibliometric analysis

3.1.1. Performance analysis

A total of 55 countries around the world have contributed to the research on ES in the Himalayan region. Figure 4(a) visualizes the global distribution of research publications on Himalayan ES. It can be observed that the Himalayan countries, such as India, Nepal, China, etc., have contributed most to the Himalayan ES research. India has contributed the most to the Research, with 24.2% of the total world contribution (figure 4(a)). Nepal has the second most contributions, with 15.4% of the world's contributions to publications. Additionally, countries from other continents that are geographically distant, such as Australia (9.7%), the United States (9.6%), and the United Kingdom (5.7%), have also contributed significantly to world research on Himalayan ES. Although contributions from continents like Asia, Australia, North America, and Europe are high, South America and Africa have had very few contributions to the research.

The research on ES in the Himalayan region (based on the searched articles) was published in 160 journals from 2002 to 2023. Out of these 160 journals, more than half (51.25%) published only a single paper, and 91.25% of journals published five or fewer publications on Himalayan ES. The distribution of publications across various journals is compared in figure 4(b). A review of various journals publishing articles on Himalayan ESs revealed a diversified and vibrant research field. 'Ecosystem Services' published 24 articles demonstrating its importance in sharing research in this sector. Sustainability, with 14 articles, and Land Use Policy, with 13 articles, are also major contributors towards Himalayan ES publications.

Across the globe, 158 research institutions or organizations from 55 countries have contributed to Himalayan ES research. Figure 4(c) shows the different institutions researching Himalayan ES. Nepalese institutions are well represented; the International Centre for Integrated Mountain Development (Nepal) leads with 39 publications, demonstrating its important contribution to enhancing knowledge in this field. Tribhuvan University also appears strongly with 38 publications. The Chinese Academy of Sciences (35 articles) and the University of Chinese Academy of Sciences (13 publications) demonstrate China's scientific presence in this area. Institutions such as the G.B. Pant National Institute of Himalayan Environment (24 publications), the University of Kashmir (17 publications) and H.N.B. Garhwal University (17 publications) highlight India's strong contributions in the field of Himalayan ES. Non-Himalayan countries, such as Australia—represented by the University of Southern Queensland (23 publications) and the University of Melbourne (14 publications)—and Indonesia, through the Center for International Forestry Research (17 publications), have also made significant contributions to the assessment of ESs in the Himalayan region.

3.1.2. Co-word analysis

A network of co-occurring keywords across all 441 publications, highlighting the interrelationships between various research topics, is shown in figure 5. From figure 5, a network of six different colored clusters can be seen in which keywords with a high correlation with one another are clustered together. The most co-occurring keywords are biodiversity, ecosystem, climate change, forestry, and land use, which indicates that most studies on ES in the Himalayan region have focused on these topics. It can be observed that forest and forest-related keywords seen in the red cluster are very prominent, and it can be inferred that many studies have focused on forest ES. However, comparatively less attention is paid to freshwater and other water-related services, as seen from the smaller keywords 'water quality' and 'water yield' in the light blue and purple clusters. Figure 6 depicts the co-occurrence of keywords specifically within the selected 76 works of literature to gain deeper insights. According to the analysis, the most frequently used keywords in conjunction with ES are 'Climate change,' 'Economic valuation,' and 'Provisioning ES,' indicating extensive research in these areas.

3.2. Standardization of ES

Different studies used different classification systems, and a total of forty-five different ES were identified. These forty-five ES were then classified into 31 unique CICES classes, and unique codes were given to each ES. The unique ES codes assigned to each service will

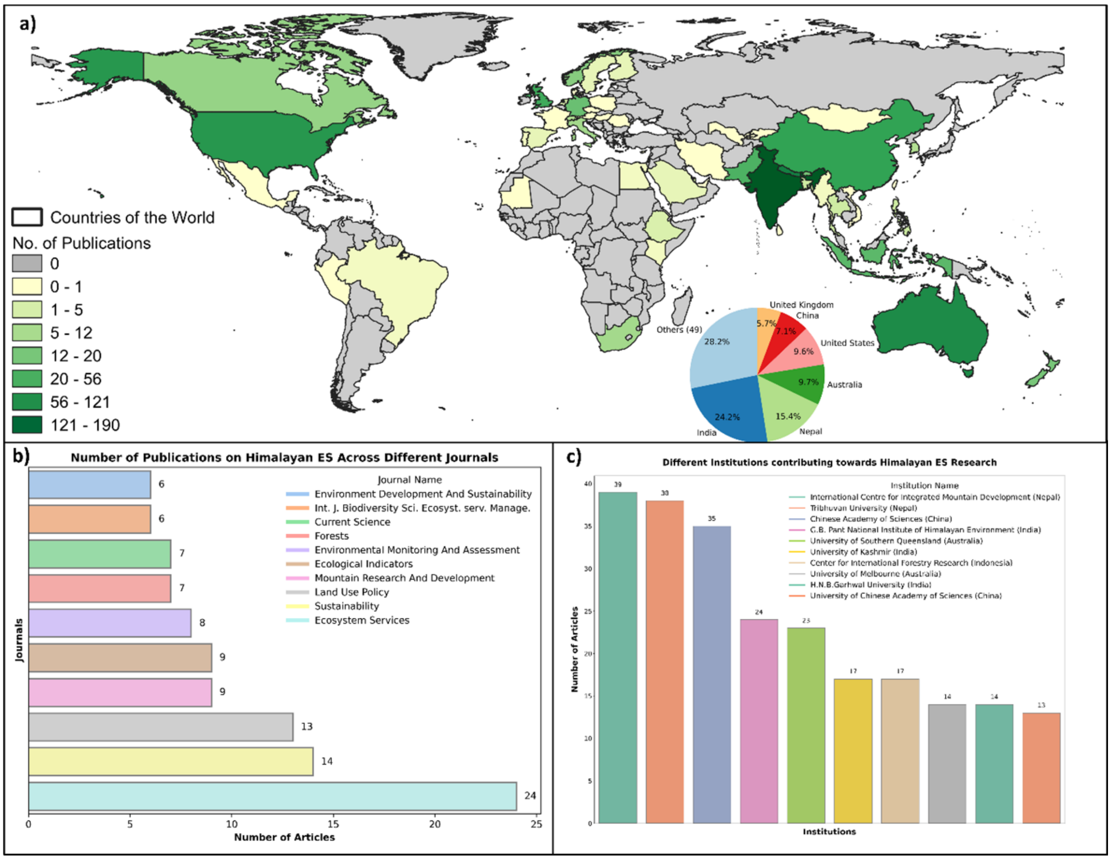

Figure 4. (a) Global distribution of research publications on Himalayan ES; (b) number of publications on Himalayan ES across different journals; (c) different institutions contributing towards Himalayan ES research.

be used to refer to the respective ES throughout the remainder of this paper. The CICES classification of the ES is shown in table 1.

3.3. Mapping of ES in the Himalayan region

Our analysis revealed a total of thirty-one unique ES, with RES being the most prevalent (38.71%), followed by PES (35.48%) and CES (25.81). Figure 7 depicts the spatial variation of the number of ES studied across the study sites across the Himalayan region, while figure 8 depicts the distribution in the number of ES identified in the literature.

3.3.1. PES in the Himalayas

PES were the most extensively studied, with 73 literature sources identifying 11 distinct types of PES. We discovered that 39.6% of the literature sources studying the PES were in EHR, 34.5% in CHR, and 25.9% in WHR (figure 7). PES9 and PES8 were the most frequently identified PES across the Himalayan region, which was studied in 79.45% and 76.71% of the total literature for PES, respectively (Momblanch *et al* 2020, Shakya *et al* 2021, Wangchuk *et al* 2021, Aryal *et al* 2023). This indicates that water-related services are critical for the region's population and economy. Forest ES, such as PES11, PES10, etc., are also prevalent, indicating their importance in the region. On the other hand, PES2 (2.74%) and PES5 (2.74%) have received the least attention in the literature (figure 8) (Murali *et al* 2017, Saeed *et al* 2022, Pradhan and Khaling 2023).

It can be observed from figure 7 that the literature identifying PES are well distributed across the Himalayan region. There is also a cluster of larger blue circles in CHR and EHR compared to WHR, indicating a higher number of PES studied per each research article. Since most papers identified the ES based on surveys and questionnaires capturing people's perceptions of the ES, it can be inferred that the people in CHR and EHR could identify more PES or have more knowledge of different PES that the ecosystems can provide compared to people in WHR.

3.3.2. RES in the Himalayas

Sixty-five literature sources identified the twelve RES provided by the Himalayan region. Most of the studies on RES were conducted in the EHR (38.46%), followed by the CHR (35.38%) and the WHR (26.15%) out of 65 sources, as seen in figure 7. The distribution of these services across the Himalayan region indicates that 40.33% of RES were identified in CHR and EHR each, and 19.34% were identified in WHR. Notably, RES5 and RES2 (Bajracharya *et al* 2018, Everard *et al* 2019, Ghosh 2021, Pradhan and

Table 1. Thirty-one unique ES according to CICES Classification identified through literature.

S. No.	ES Identified	CICES ES Class	ES Codes
1	Fish	Animals reared by *in-situ* aquaculture for nutritional purposes	PES1
2	Animal-based Energy	Animals reared to provide energy (including mechanical)	PES2
3	Food Production/Crops	Cultivated terrestrial plants (including fungi algae) grown for nutritional purposes	PES3
4	Fruits and Vegetables		
5	Ornamental	Fibers and other materials from cultivated plants, fungi, algae for direct use or processing	PES4
6	Fodder		
7	Animal-based Resources	Fibers and other materials from reared animals for direct use or processing (excluding genetic materials)	PES5
8	Leaf Litter/Organic Matter	Fibers and other materials from wild plants for direct use or processing	PES6
9	Resin		
10	Timber		
11	Hydropower	Freshwater surface water used as an energy source	PES7
12	Freshwater (drinking)	Surface water for drinking	PES8
13	Freshwater (Irrigation)	Surface water used as a material (non-drinking purposes)	PES9
14	Photosynthesis	Wild plants (terrestrial and aquatic, including fungi, algae) used as a source of energy	PES10
15	Primary production		
16	Fuelwood		
17	Medicines	Wild plants (terrestrial and aquatic, including fungi, algae) used for nutrition	PES11
18	NTFP		
19	Wild edibles		
20	Natural hazard prevention	Buffering and attenuation of mass movement	RES1
21	Soil erosion prevention	Control of erosion rates	RES2
22	Soil protection		
23	Nutrient cycling	Decomposition and fixing processes and their effect on soil quality	RES3
24	Organic matter decomposition		
25	Carbon Sequestration	Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals	RES4
26	Water/Flood regulation	Hydrological cycle and water flow regulation (Including flood control and coastal protection)	RES5
27	Local water cycling		
28	Habitat regulation	Maintaining nursery populations and habitats (Including gene pool protection)	RES6
29	Ecosystem resilience		
30	Pest and disease control	Pest control (including invasive species)	RES7
31	Pollination	Pollination (or 'gamete' dispersal in a marine context)	RES8
32	Air purification	Regulation of chemical composition of atmosphere and oceans	RES9
33	Climate regulation	Regulation of temperature and humidity, including ventilation and transpiration	RES10
34	Water purification	Regulation of the chemical condition of freshwaters by living processes	RES11
35	Soil moisture retention	Weathering processes and their effect on soil quality	RES12
36	Soil formation		
37	Cultural heritage	Characteristics of living systems that are resonant in terms of culture or heritage	CES1
38	Recreation	Characteristics of living systems that enable activities promoting health, recuperation, or enjoyment through active or immersive interactions	CES2
39	Ecotourism	Characteristics of living systems that enable activities promoting health, recuperation, or enjoyment through passive or observational interactions	CES3
40	Satisfaction for pure environment		
41	Aesthetics	Characteristics of living systems that enable aesthetic experiences	CES4
42	Ecological education	Characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge	CES5
43	Bequest	Characteristics or features of living systems that have an option or bequest value	CES6
44	Spiritual and religious values	Elements of living systems that have sacred or religious meaning	CES7
45	Sense of place	Elements of living systems that have symbolic meaning	CES8

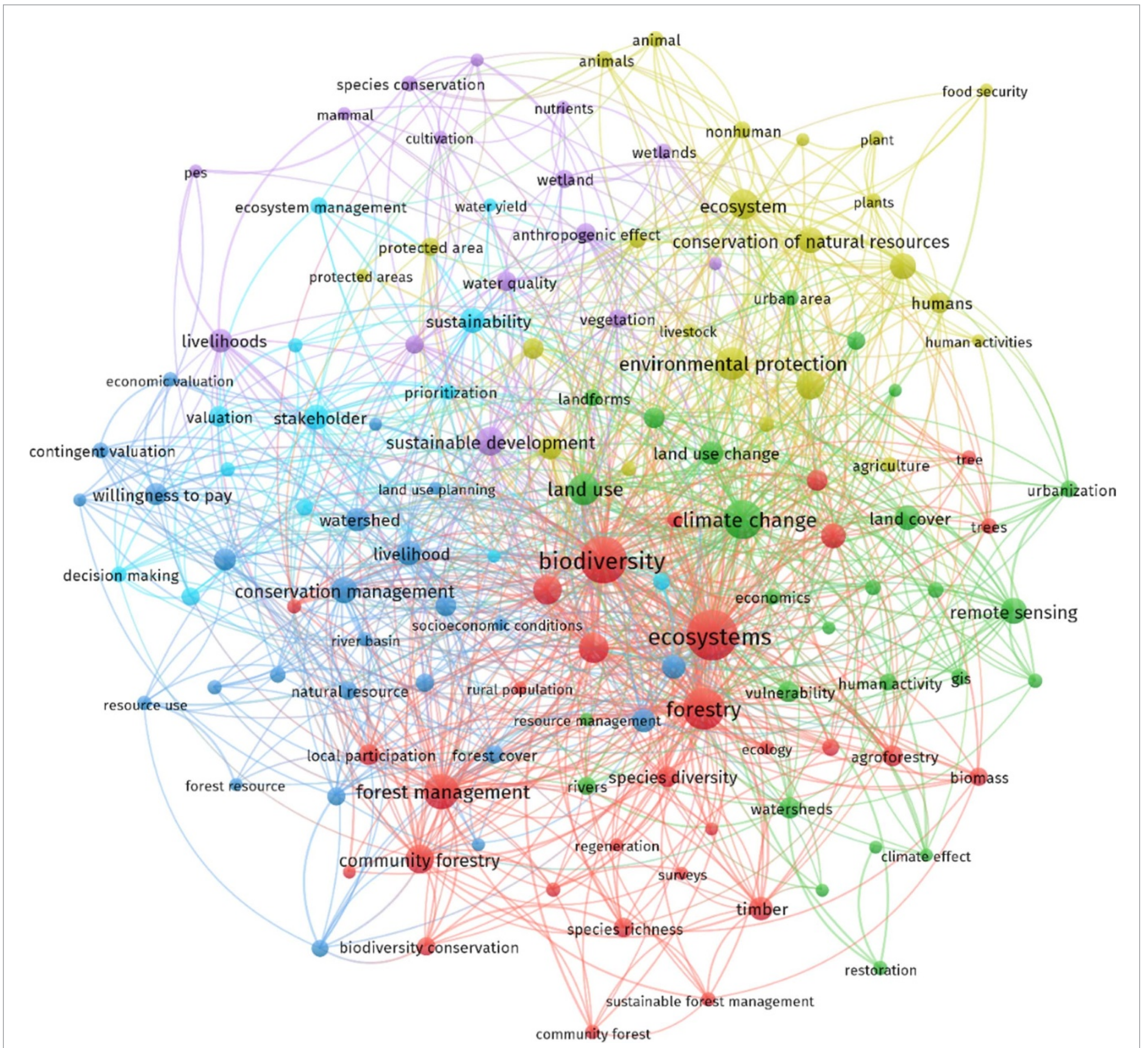

Figure 5. Network of co-occurring keywords in the searched publications.

Khaling 2023) were the most studied RES across the Himalayan region, while RES12 (Singh *et al* 2018, Acharya *et al* 2019, Uniyal *et al* 2020, Naudiyal and Schmerbeck 2021, Wang *et al* 2022) was the least studied as shown in figure 8. In figure 7, the larger green circles representing the number of RES identified by the literature show a pattern similar to that of PES. Therefore, similar inferences can be made that people in CHR and EHR identified more RES than people in WHR.

3.3.3. CES in the Himalayas

Forty-eight literature sources studied CES in the Himalayan region. The EHR had the highest number of literature sources studying CES (41.67%), followed by the CHR (39.58%) and the WHR (18.75%) (figure 7). These literature sources identified and studied 8 different CES. Six out of Eight CES were mentioned in the literature sources for all three regions, with CES6 and CES8 not being identified in EHR and WHR, respectively (figure 8). The distribution of CES across the Himalayan region showed that 44.91% of CES were identified in CHR, 40.72% in EHR, and only 14.37% in WHR. The most mentioned CES in the region was CES2 (Peh *et al* 2016, Adhikari *et al* 2018, Shrestha and Acharya 2021, Thapa *et al* 2022, Das *et al* 2023, Devkota *et al* 2023), while CES6 (Murali *et al* 2017, Acharya *et al* 2019, Aryal *et al* 2021, Thapa *et al* 2022) was the least mentioned (figure 8). The literature identifying CES is more in CHR and EHR than WHR. However, by observing the bigger orange circles in figure 7, the size distribution is almost constant across the Himalayas. It can be interpreted that people could identify the CES in all regions of the Himalayas. However, the total literature on CES was less than those that studied PES and RES. Overall, in most of the papers reviewed, most CES were listed as essential to the communities of the Himalayan regions since most economic benefits are obtained through services like CES3.

3.4. Ranking of ES

The thirty-one unique ES identified across the different Himalayan regions through literature were ranked based on the frequency with which each service was studied (figure 9).

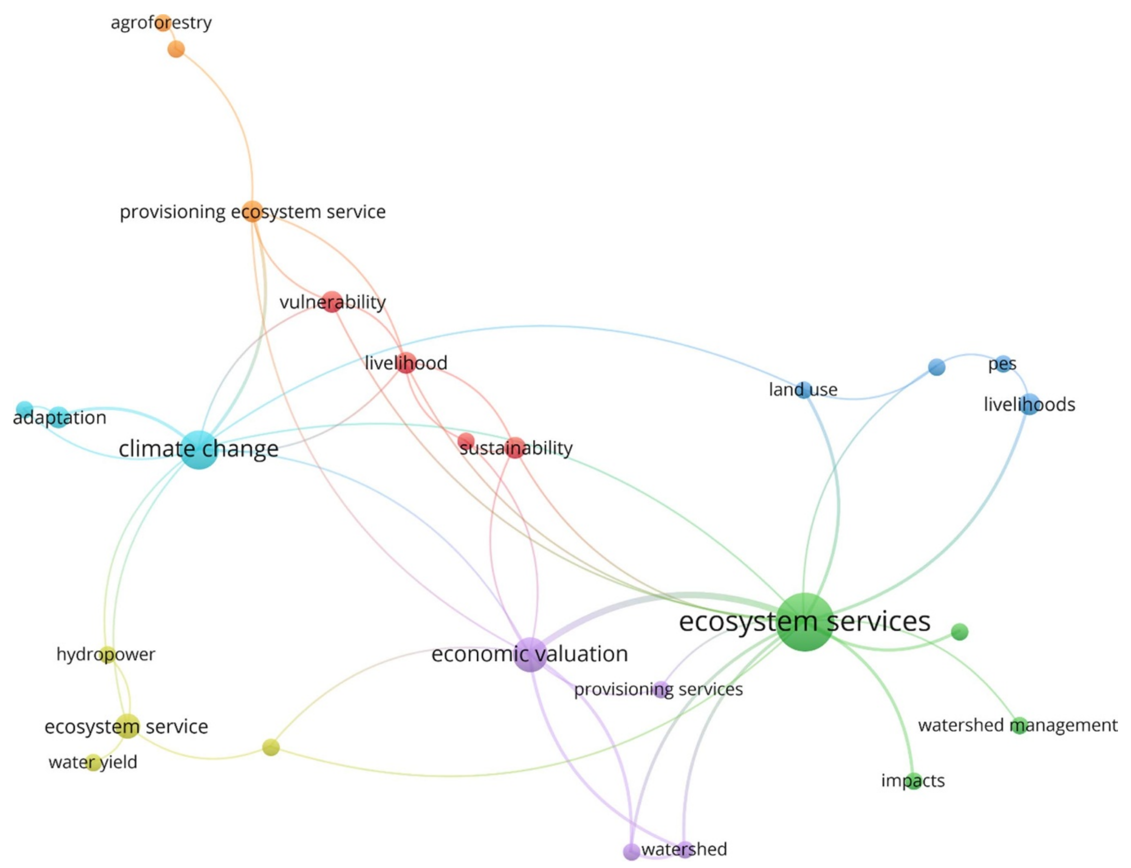

Figure 6. Co-word analysis network chart of keywords from 76 selected literature.

It can be observed that water-related PES, such as PES9 and PES8, were ranked higher than the terrestrial PES, such as PES11, PES10, PES4 and PES6 for the entire Himalayan region and CHR and EHR. This suggests a greater reliance on freshwater resources for basic human needs and agriculture throughout the Himalayas, potentially due to population density or aridity in certain areas. However, PES4 and PES10 were ranked higher than the water-related PES for WHR. This could be linked to the high dependence on terrestrial services WHR. In the case of RES, RES2 and RES5 were ranked the highest for the entire Himalayan region. In WHR and CHR, RES2 was ranked the highest, while in EHR, RES5 was ranked the highest. This highlights the importance of erosion control and flood regulation throughout the Himalayas due to frequent floods and landslides in the mountainous terrain. Furthermore, RES6 consistently ranked higher across the Himalayas and its subregions. This signifies the critical role played by these services in maintaining ecological health across the Himalayas. CES2 emerged as the highest-ranked CES for CHR, EHR, and the Himalayan region. This implies that recreational activities are a significant aspect of the CES values of Himalayan communities. Meanwhile, CES3 was ranked highest for WHR and is linked to more regional tourism.

3.5. Identification, quantification, and valuation of ES

The assessment of ES involves three critical steps: identification, quantification, and valuation. In this review, the majority of the literature (73.68%) focused on identifying ES, while 39.47% quantified ES and only 23.68% presented the valuation of ES in the Himalayan region. Among the studies that identified ES, 83.93% utilized questionnaires, surveys, and focus group discussions (FGDs), reflecting the public's perception of the identification process. The remaining 16.07% of the literature relied on secondary and field data for ES identification in the region. Three main methods were used to quantify ES: survey and questionnaire-based approaches, ES modeling, and secondary data. ES modeling was the most commonly used method (53.33%), followed by surveys and questionnaires (36.67%) and secondary data (10%) for quantification of ES.

In the case of regional distribution, the literature that identified ES, 23.21% of the literature identified ES in WHR, 30.36% in CHR and 46.43% in EHR. The distribution indicates more recognition of ES in EHR than in CHR and WHR and can be attributed to the increased awareness of ES in EHR compared to other regions. From the literature quantifying ES, 50% quantified ES in WHR, 33.33% in CHR

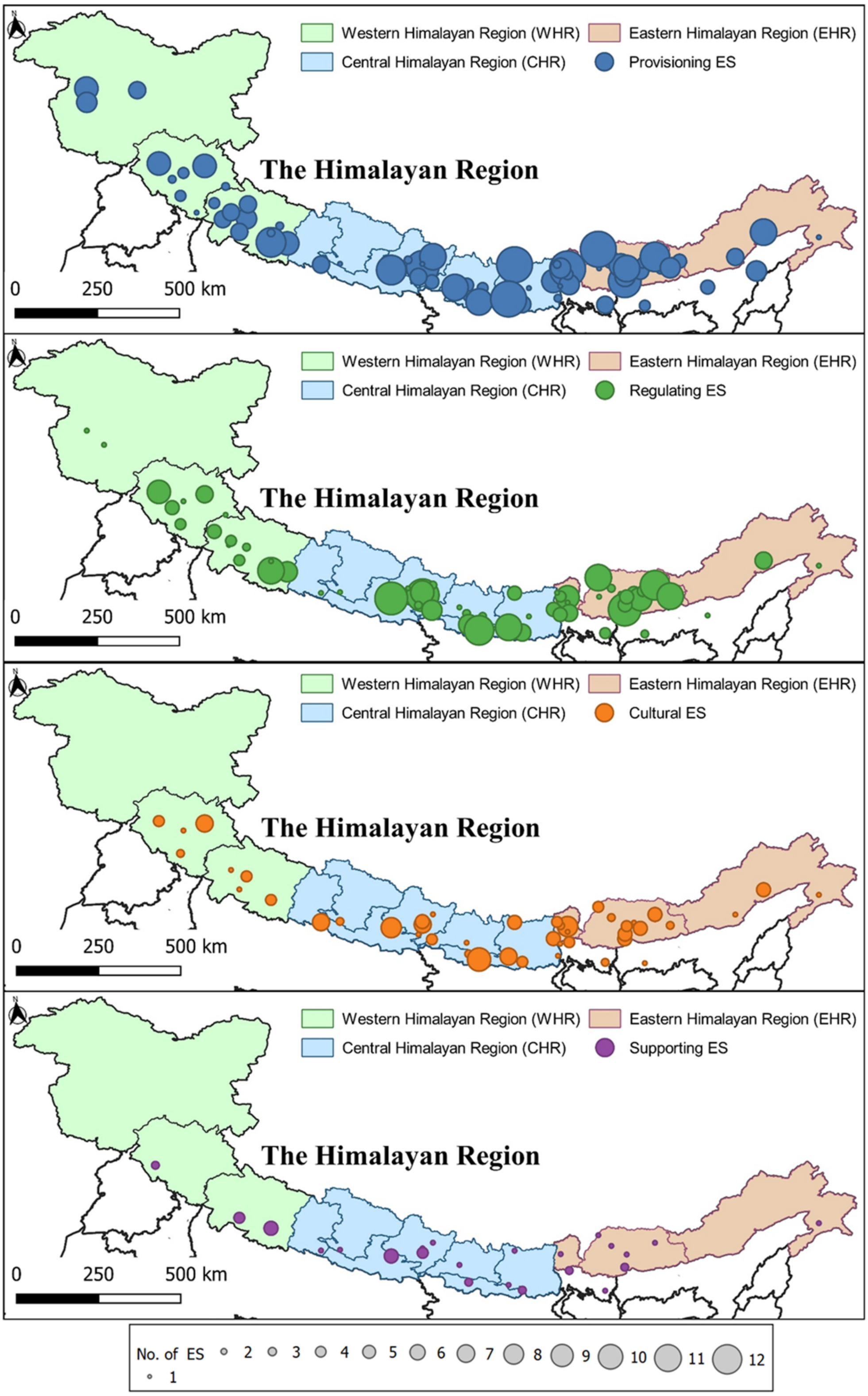

Figure 7. Spatial variation of the number of ES studied in each literature across the Himalayas.

and 16.67% in EHR. Finally, from the literature that evaluated ES, 33.33% gave a valuation of ES in WHR, 38.89% in CHR and 27.78% in EHR. It can be inferred that the literature on the valuation of ES was more evenly distributed through the regions than the literature identifying and quantifying ES.

It can be observed from figure 10 that most ES in the Himalayan are concentrated at lower elevation levels, specifically between 500–2000 m. Conversely, very few studies on ES have been conducted at higher elevations (above 4000 m). Considering the different subregions, it can be seen that in WHR, most ES

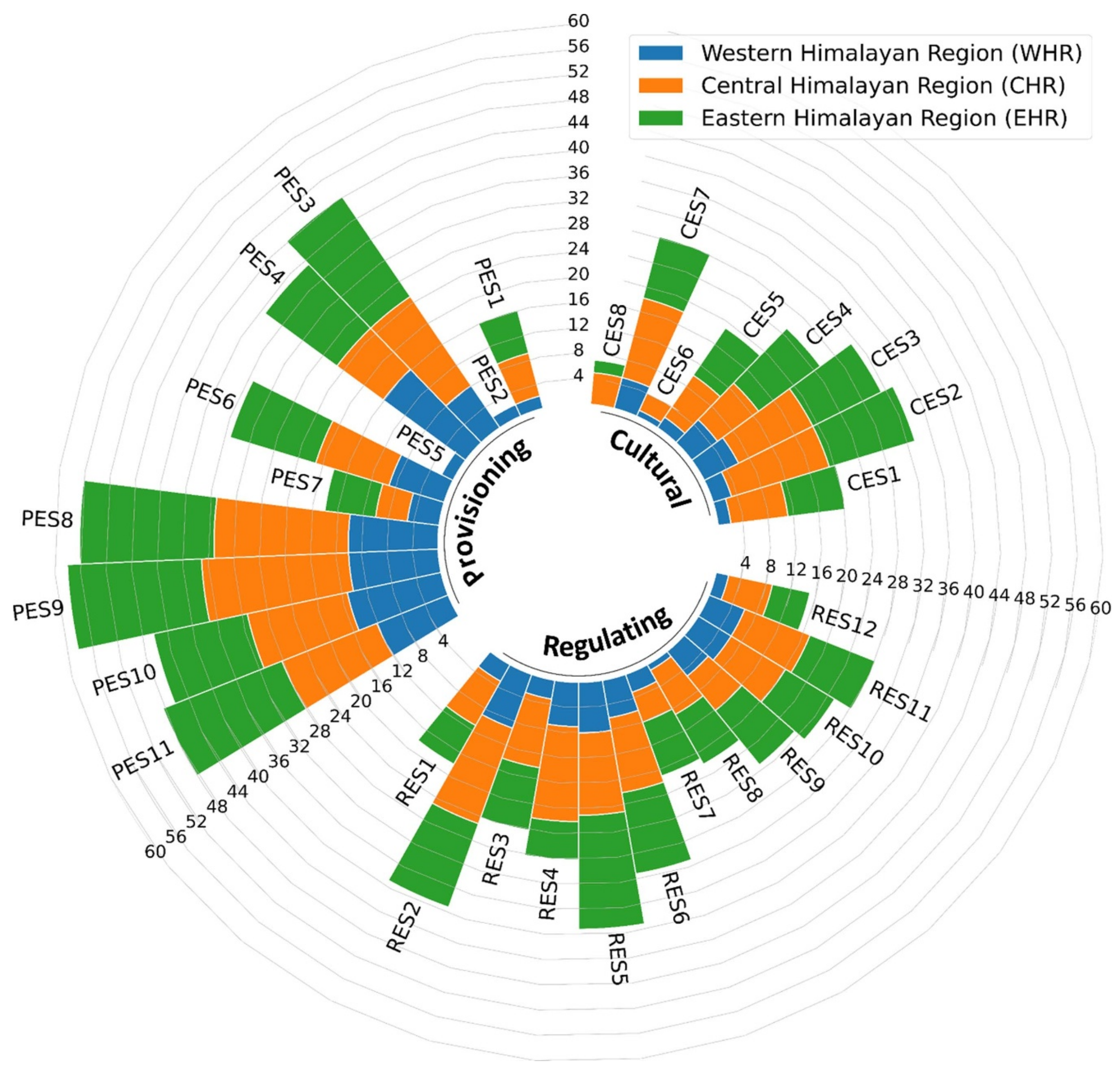

Figure 8. The Circular Stacked column chart represents the number of ES identified in each region.

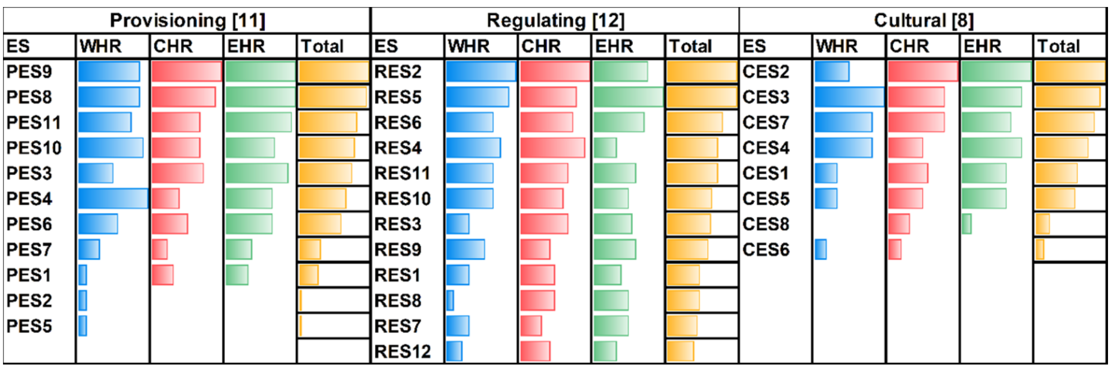

Figure 9. Ranking of ES in each region of the Himalayas. (The length of the bars represents the rank, i.e. the longest bar represents Rank 1, and size decreases with increasing rank. The service not identified is left blank).

studies were conducted between 500 and 2000 m, and the ES studied were well identified at these elevations. However, the number of studies on ES decreased with increasing elevation, particularly for RES and CES, which are notably sparse at higher elevations. Most ES were identified for CHR at lower elevations of 0–1500 m. While the number of ES identified decreased with elevation, the decline was less pronounced than in the WHR. A few ES, such as PES8, PES9, and PES3, were identified across all elevations.

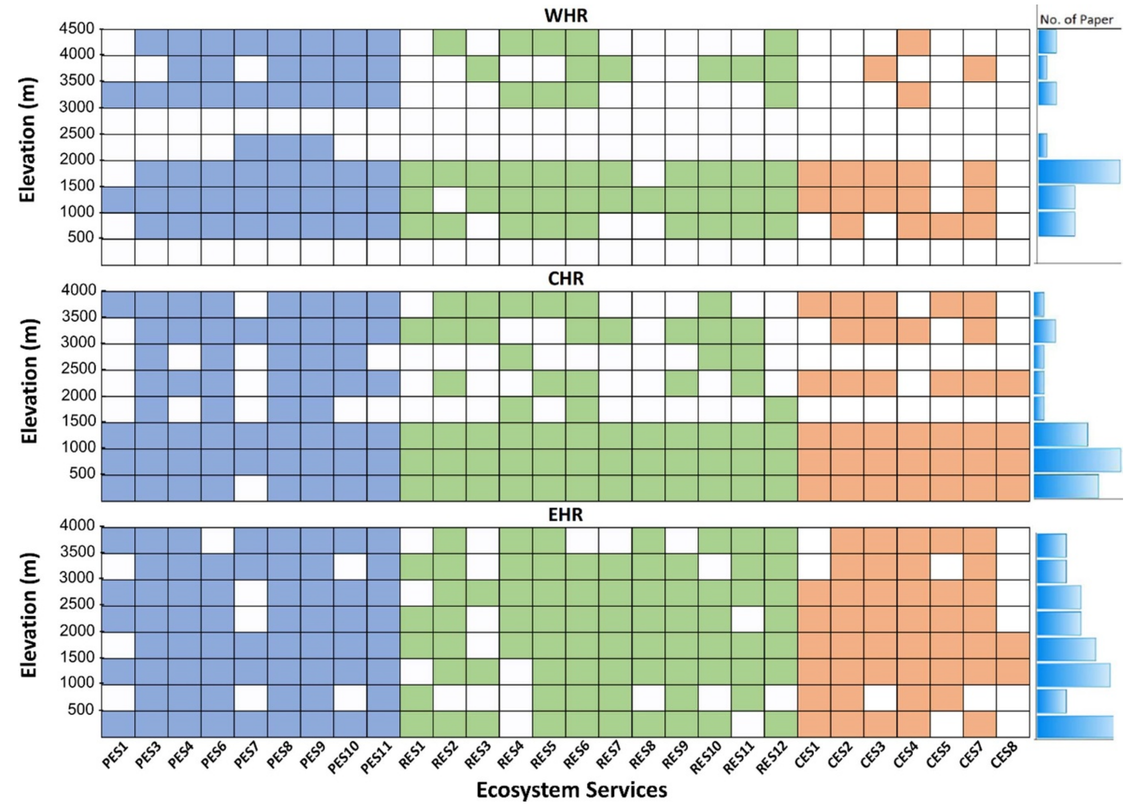

Figure 10. Distribution of ES based on different elevation bands across different regions of the Himalayas.

In the EHR, the distribution of ES studies was well spread across all elevations. ES, such as PES3, PES4, PES8, PES9, PES11, RES5, CES2 and CES4 were found at all elevations. Overall, there is a significant concentration of ES studies at lower elevations, with a noticeable gap at higher elevations, especially for RES and CES in the WHR. In contrast, the CHR and EHR exhibit a more balanced distribution of ES studies across different elevations.

3.6. Valuation of ES

Out of the thirty-one ES, the economic values of twenty-eight ES were gathered from the literature. The ES's minimum, maximum and mean values are shown in figure 11.

It can be observed from figure 11 that PES have been the most researched, followed by RES and CES. The economic valuation of PES ranges between 0.13 USD/ha/year (PES9) to 2633.92 USD/ha/year (PES7), with an average value of all PES as 446.75 USD/ha/year. All eleven PES have been valued in the Himalayan region. The PES with the high average economic values are PES7, PES8 and PES3, with average values of 2633.92 USD/ha/year, 1215.65 USD/ha/year, and 587.27 USD/ha/year, respectively. Among the PES, PES9, PES5 and PES2 have the lowest average economic valuations of 0.13, 5.41 and 14.91 USD/ha/year, respectively, according to the literature. Out of twelve RES, the economic valuation of eleven RES was provided in the literature, but the valuation of RES7 was not provided. The average economic valuation of RES is 1128.81 USD/ha/year, the highest among all the ES. The RES with the highest average values are RES1, RES6, and RES11, which have values of 3070, 2589.86, and 2256 USD/ha/year. The RES with lower average values are RES3, RES2, and RES8, which have values of 118.78, 213.01, and 247.50 USD/ha/year. The literature provided economic valuations for six of the eight CES but not for CES1 or CES8. The economic value of CES in the Himalayan region ranges from 6.73 USD/ha/year (CES6) to 1668.79 USD/ha/year (CES3), with an overall average value of 457.51 USD/ha/year. CES3, CES2, and CES7 have the highest economic value of the CES. The CES with the lowest average value are CES6, CES4 and CES5, with values of 6.73, 34.0, and 124.0 USD/ha/year, respectively.

4. Discussions

In this work, we conducted a literature review to identify and analyze the ES in the Himalayas, classified as PES, RES, and CES. The findings provide insights into the distribution and prevalence of ES in the region, and the research focuses on different ESs. These findings reveal significant variability in the distribution of literature and the ES these literatures have studied. PES are typically more extensively studied

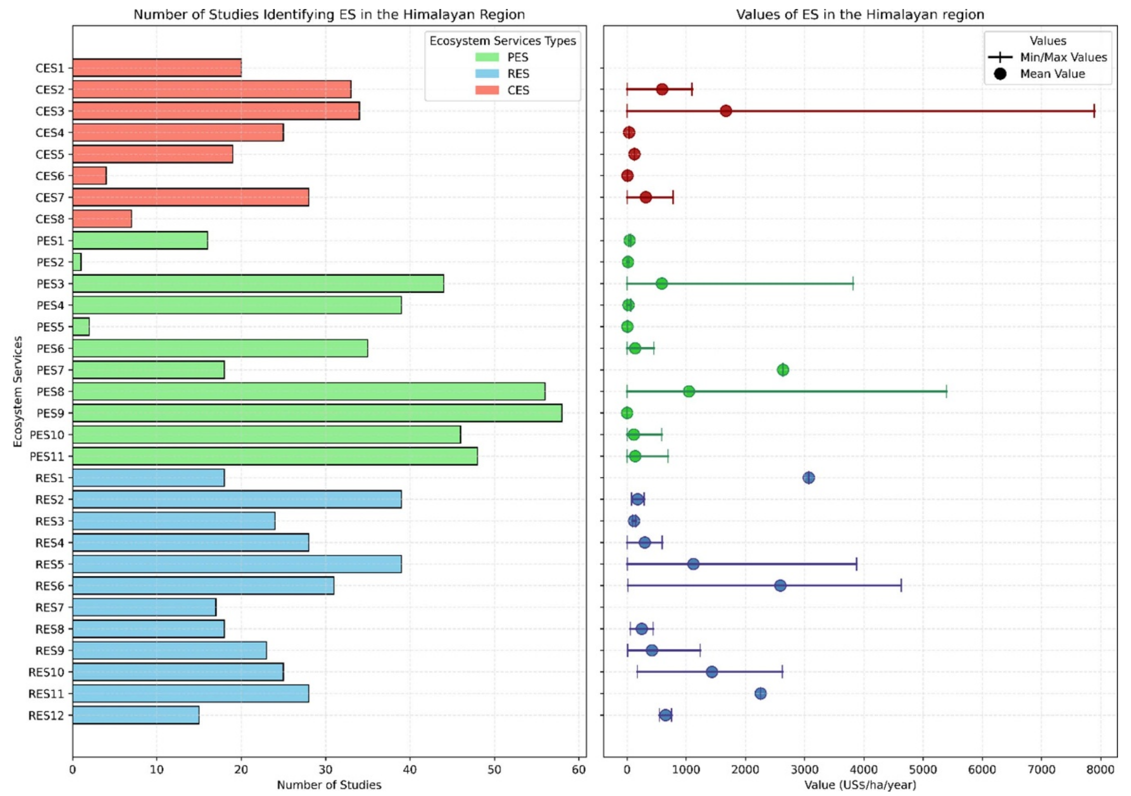

Figure 11. Comparative analysis of ecosystem services studies and valuation in the Himalayan region.

because they provide direct and tangible benefits (Johnson and Hutton 2014, Wang *et al* 2022). The literature review also noticed a similar pattern throughout the Himalayan region. The PES has been studied less in WHR (27.20%) than in CHR (34.62%) and EHR (38.19%). The most identified PES in the Himalayan region are PES9 and PES8, underscoring the importance of freshwater ecosystems. Additionally, significant attention is given to plant and tree services, including PES11, PES10, PES3, PES4 and PES6, highlighting the importance of terrestrial ecosystems in the Himalayan region. This result is consistent with other global research where mountain ecosystems have provided essential ES such as food and water for residents (Biber *et al* 2015, Melnykovych *et al* 2018, Cuni-Sanchez *et al* 2019, Orsi *et al* 2020). Furthermore, it can also be observed that among various PES, PES5 and PES2 have gotten the least attention in Himalayan literature (Murali *et al* 2017, Rai *et al* 2020, Saeed *et al* 2022, Pradhan and Khaling 2023). This may be because locals lack awareness and knowledge about animal resources being ES.

The RES are critical for RES the ecological processes in the Himalayan region. However, being indirect, these are challenging to identify, quantify, and value (De Groot *et al* 2002, Small *et al* 2017). Nevertheless, these services provide essential benefits for humans and the environment. The RES has been less identified in the WHR (19.34%) as compared to CHR (40.33%) and EHR (40.33%). The most identified CES in the Himalayan region are CES2, CES3, CES7 and CES4. The CES are important in the Himalayan region as they provide benefits that support the local population's well-being and livelihood. The distribution of CES across the Himalayas is like those of PES and RES i.e. they are also less identified in WHR (14.37%) as compared to CHR (44.91%) and EHR (40.72%). From the literature, the ES identified in the Himalayan region has been from two ecosystems, i.e. Terrestrial and Freshwater. Although both ecosystems provide about the same number of ES, more literature focuses on terrestrial ES than Freshwater ES.

4.1. Terrestrial ES

The forests of the Himalayas play a significant role in providing several benefits, such as Fodder, Fuelwood, Timber, etc., to the people. PES11, PES10, PES3, PES4 and PES6 are important PES and have been identified more frequently throughout the literature. Out of 11 PES identified in the Himalayan region, the majority were forest-based, reflecting the importance of forest ecosystems in providing direct benefits to local communities. In addition, forests also provide many RES and regulate the eco-hydrological processes and hydrological cycle by obstructing rainwater and increasing groundwater recharge (Bhuju 2018, Everard et al 2019). The forests also help slow the surface runoff, which helps control floods and erosion (Joshi and Negi 2011). The dense root network of the forest binds the soil together while the forest cover intercepts and obstructs the rainwater, which significantly reduces erosion (Wiśniewski and Märker 2019, Flores et al 2020, López-Vicente et al 2021). RES2 and RES5 have been identified as the most important RES in the Himalayan region.

Forests also sequester and store carbon dioxide from the atmosphere through photosynthesis, reducing atmospheric CO_2 concentrations (Kumar et al 2021). RES4 has been identified as one of the most frequent in WHR and CHR, whereas it is less identified in EHR. Additionally, forests transpire water vapor and provide shade, which humidifies and lowers the temperature of the surrounding air (Pandey et al 2017). RES10 is an important RES that is well-identified in CHR and EHR while less identified in WHR. The region's forest also provides food and shelter for millions of plant and animal species (Elsen et al 2017, Måren and Sharma 2018). These forests support biodiversity and maintain the ecological balance of the region (Seymour and Kanowski 2016, Björklund et al 2020, Piczak et al 2023). RES6 is well-studied in CHR and EHR but less studied in WHR.

The forests offer a variety of CES, including CES2, CES3, CES7, CES4, etc. The CES were identified more frequently in CHR and EHR but less frequently in WHR. The Himalayan region's lush green forests offer a variety of recreational opportunities for tourists, including hiking and camping. Forests also serve as locations for yoga and meditation, bringing millions of pilgrims to the region every year. The Himalayan Forest ecosystems are spiritually significant and full of scenic beauty. From clear lakes to snow-capped peaks to lush green forests, the Himalayan region's aesthetics inspire and attract many hikers, nature lovers, and others.

4.2. Freshwater ES

Another major ecosystem in the Himalayas is the freshwater ecosystem, which supplies freshwater to millions of people downstream (Bastola et al 2019, Hill et al 2020, Jana et al 2021, Zam et al 2021). It is observed that water is frequently identified as a PES in all regions (79.45% of the total literature reviewed) (Goyal and Khan 2017, Bastola et al 2019, Hill et al 2020, Singh et al 2018, Zam et al 2021, Shrestha and Nepal 2022, Singh et al 2022). Additionally, the most important freshwater RES in the Himalayas is the RES5. Himalayan freshwater sources, particularly subsurface ones, help regulate and maintain water by retaining it during monsoons and releasing it during dry seasons. This retention of water and release as baseflow is essential for the millions of downstream residents relying on these sources for their daily water needs (Sarkar et al 2019, Thapa et al 2020, Aryal et al 2021, Ghosh 2021, Zam et al 2021). Another important freshwater source, the wetlands, provides us with two important RES: RES5 and RES11. Wetlands act as sponges and absorb flood water, which helps regulate floods (Kadykalo and Findlay 2016, Tang et al 2020). With increasing flood frequencies in the Himalayan region due to climate change, RES5 is essential (Swarnkar and Mujumdar 2023). These wetlands also function as natural filters, removing contaminants from the water (Sileshi et al 2020). This is especially important in the Himalayan region because of the growing population (primarily dynamic—tourists), which may contribute to water pollution and contamination.

Freshwater ecosystems also provide important CES across the Himalayan region. According to the literature review, the most important CES in the Himalayan region were CES2, CES3, and CES7. The recreational options for locals and tourists, including boating, rafting, fishing, and other activities, enhance physical and mental well-being. Freshwater ecosystems also play an important religious and spiritual role in the Himalayas. Rivers such as the Ganges, Yamuna, and Saraswati are considered sacred and attract millions of devotees (Visvanathan 2013, Agoramoorthy 2015). The Himalayan region is a popular ecotourism destination due to the numerous recreational activities it provides and the religious and spiritual values it offers. Millions of tourists visit the region for these services, which provide a source of livelihood for locals and thus contribute to the region's economy.

4.3. Role of climate change and human disturbances

Climate in the Himalayas is highly variable, with a tropical climate at the foot of the Himalayas, while at the higher elevations, there is a polar climate. Due to the region's susceptibility to climate change, the temperature in this region is rising faster than the rest of the globe which has resulted in shrinking of glaciers (Sabin et al 2020). According to Tse-ring et al (2010), minor variations in temperature and precipitation in mountain ecosystems can affect water availability and other crucial ES, increasing the risk of natural disasters, including droughts, floods, and landslides. The flow of ES is significantly affected by climate change as it alters the hydrological cycle and its components (Jha et al 2022). Watershed processes and freshwater ES, such as flood regulation, erosion control, water supply, etc., will likely be affected by future climate change (Momblanch et al 2020).

Despite their apparent inaccessibility and remoteness, the Himalayas have not been spared from human-induced biodiversity loss. The socioeconomic transformation of mountain landscapes, such as alterations in biogeochemical cycles, catchment processes, etc., owing to climate change impacts the ES

(Xu *et al* 2008). According to the factsheets published by Grooten and Almond 2016, the biodiversity of ecosystems, especially of global freshwaters, is being threatened by overexploitation, water pollution, flow modification, habitat destruction or degradation, alien species invasion, and climate change. Among these, habitat degradation was the most significant threat to the declining freshwater biodiversity.

Human well-being, dependent on access to ES, is impacted by regional and global climate change. Climate change, such as rising temperatures, can cause shifts in tree lines and alter the phenology, which significantly impacts ES and, thus, human well-being (Jha *et al* 2022). Several studies have found an agreement between people's perception of climate change and actual climate records in the Himalayan region. In all three regions of the Himalayas i.e. WHR, CHR, and EHR, people have observed reduced precipitation, erratic rainfall, and increased diseases and pests, which affects crop production in the region (Bhatta *et al* 2015, Macchi *et al* 2015, Negi *et al* 2017, Nand *et al* 2022). Studies have shown that agroforestry can be used as a sustainable land use practice to mitigate the effects of climate change on food security in the mountain regions (Pandey *et al* 2017).

4.4. Valuation of ES in the Himalayan region

PES8—Freshwater/surface water used as an energy source has the highest economic value, according to the literature. This is especially significant in climate-sensitive regions like the Himalayas. Hydropower is a renewable energy source that reduces reliance on fossil fuels while mitigating greenhouse gas emissions. Additionally, hydropower projects benefit national economies by providing a stable source of revenue. Furthermore, countries can export surplus electricity from hydropower to neighboring countries, generating additional revenue and improving regional energy cooperation. PES8—Surface water for drinking has an average value of 1215.65 USD/ha/year. PES8 is highly valuable in the Himalayan region because surface water is the primary source of drinking water for both rural and urban areas. The region faces challenges as freshwater availability declines, particularly due to climate and anthropogenic changes, which leads to diminishing springs and less discharge in rivers during the lean season. Increased local awareness of the value of clean water may have led to the increased economic value of PES8, as they may have realized that a lack of clean drinking water can impact their livelihoods and overall well-being. The average value of PES3—Cultivated terrestrial plants (including fungi and algae) grown for nutritional purposes is 587.27 USD/ha/year. Agriculture is the primary source of livelihood in the Himalayan region, and the supply of cultivated crops in the local markets contributes to a stable local economy. The availability of agriculture throughout the year plays an important role in maintaining food security in the Himalayan region. PES9—Surface water used as a material (for non-drinking purposes) has the lowest average economic value among the PES, even though it has been the most identified PES in the Himalayan region. This may be because even though irrigation is well recognized as the service from surface water in the Himalayan region since most of the agriculture in the region is rainfed, the economic value of irrigation is low. PES5 and PES2 are the least identified services in the Himalayas; hence, not much value has been given to them in the region.

RES1—Buffering and attenuation of mass flows have the highest average value at 3070 USD/ha/year. Natural hazards such as landslides and floods have been increasing in the Himalayan region, and RES these hazards, as well as their frequency and magnitude, has become critical; thus, the literature has provided high value. The literature also provided a high value to RES6—Maintaining nursery populations and habitats (including gene pool protection). The Himalayan region, known for its rich biodiversity, relies on this service to protect habitats for various species, which has a high economic value. According to the literature, the average value for RES11—Regulation of the chemical condition of freshwaters by living processes is 2256 USD/ha/year. Water pollution may increase due to increased tourism, construction, and other factors, making natural water purification processes essential for clean water availability. Although RES3—Decomposition and fixing processes and their effect on soil quality are important for maintaining soil fertility, the economic contribution of these processes, such as nutrient cycling and organic matter decomposition, is difficult to quantify and thus undervalued. RES2—The control of erosion rates is another important service in the Himalayan region. The Himalayan region's steep gradient makes it susceptible to soil erosion, so controlling it is critical. Despite this, RES2 has been assigned a lower value. Similarly, RES8—Pollination has been given a lower value, although pollination is critical to biodiversity conservation in the Himalayan region.

CES3—Characteristics of living systems that enable passive or observational interactions—has an average annual value of 1668.79 USD/ha. The Himalayan region's unique landscape and biodiversity attract tourists worldwide, helping boost the local and national economies. With an average value of 593.50 USD/ha/year, CES2- Characteristics of living systems that enable active or immersive interactions also have a high economic value. The natural setting of the Himalayan region provides a wealth of opportunities for pursuits like hiking, camping, and meditation that are highly regarded for their ability to improve both physical and mental health. Another important CES in the Himalayan region is

CES7- Elements of living systems with sacred or religious meaning, valued at 316.07 USD/ha/year and representing the region's spiritual or religious significance. The Himalayan region is home to numerous sacred sites such as temples, pilgrimage sites, monasteries, etc. Even the rivers and springs in the Himalayan region are considered sacred, attracting millions of tourists. The CES with the lowest average value are CES6—Characteristics or features of living systems that have an option or bequest value; CES4—Characteristics of living systems that enable aesthetic experiences; and CES5—Characteristics of living systems that enable scientific investigation or traditional ecological knowledge creation, with values of 6.73, 34.0, and 124.0 USD/ha/year, respectively. These CES, while important, are difficult to quantify and thus cannot be easily monetized.

4.5. Challenges in ES research across the Himalayas

ES research aims to improve ecosystem management by studying the interactions between natural and social systems (Daily *et al* 2009). Although important for understanding environmental management and decision-making, researchers face various problems when conducting ESs research in this region. As the mountainous regions such as the Himalayas are sensitive to developments that are on local and global scales, such as land use or climate changes, Schröter *et al* (2005) suggest that these changes might also have an impact on the ecosystem as well as the services provided by them. Some of the major challenges faced by researchers are identified and discussed below.

4.5.1. Availability and quality of data

ES research, being interdisciplinary, requires multiple data sources, such as hydrological, meteorological, ecological, economic, and thematic data. However, in the current scenario, there is a data limitation regarding its availability and quality in almost all the disciplines across the Himalayas, which limits the accurate assessment of ES. The Himalayan region covers several developing countries, where ES data are often unavailable (Suich *et al* 2015). High-resolution and long-term hydro-meteorological data such as discharge, precipitation, temperature, snowmelt, etc., are crucial for estimating ES, such as freshwater availability, hydropower, regulation of water/floods, etc. For example, long-term discharge data is fundamental for accurate model configuration, calibration, and validation but is often unavailable in the Himalayan region due to limited gauging sites (Yadav *et al* 2021, Dhote *et al* 2023). Additionally, remote and high-elevation regions of the Himalayas face a scarcity of meteorological data. One of the reasons for this paucity of data is the unavailability of a network of field observation sites in the region because of its complex terrain, setup costs, and inaccessibility (Uprety *et al* 2019, Kumar and Sen 2023a). In their study, Yadav *et al* (2021) observed significantly more field observation sites in the WHR, followed by CHR, and finally, almost negligible in EHR. Furthermore, there is a lack of *in-situ* snow data in the glaciated regions of the Himalayas. The measurement sites of snow data are often restricted to lower elevation regions, which are more accessible, but even these are not uniformly distributed (Sinha *et al* 2023).

In addition to hydro-meteorological data, ecological data such as forest and biodiversity data is also essential for assessing ES such as timber, fuelwood, carbon sequestration, climate regulation, etc. The spatial distribution of biodiversity is uneven and poses a challenge to assessing ecosystems and their services (Grattarola *et al* 2020). Although there is an abundance of Long-Term Ecological Research and Long-Term Ecological Monitoring (LTEM) in various parts of the globe, long-term data collection and monitoring remains limited in the Himalayan region (Negi *et al* 2019). Even for quantification of ES, accuracy and LTEM are required for ES modeling.

To overcome the problem of unavailability of scarce field-based observations, Remote Sensing (RS) products are often utilized in the studies. However, even these RS products are not always available at high spatial and temporal resolution with reasonable accuracy as often there are significant uncertainties. Other solutions, such as using ensemble models for better accuracy in assessing ES, are suggested by Willcock *et al* (2023). Kumar and Sen (2023b) have suggested using rating curves for catchments where discharge data is unavailable or scarce. Some studies have also suggested using big data sources like crowdsourced data for better assessment of social aspects of ES, which helps assess CES (Manley *et al* 2022, Zapata-Caldas *et al* 2022). Regional cooperation and international collaboration can also solve the problem of data unavailability in the Himalayan region (Chauhan *et al* 2023).

4.5.2. Challenges of interdisciplinarity

ES research is interdisciplinary and requires integrated efforts of ecologists, hydrologists, agriculturists, economists, environmentalists, anthropologists, and social scientists. According to the search conducted in Scopus using the keyword 'ecosystem services', it was found that most sources (36 490 documents) were from the subject area of environmental sciences (figure 12). Other areas where ES has been mentioned in the literature are social sciences, engineering, and economics. Even though numerous publications are available in various fields, not all services are being equally studied and addressed. It can be observed that although the valuation of ES is important for the more holistic assessment of ES and for policy making, there is less literature in Economics and Finance (figure 12). Another challenge of interdisciplinarity is that different disciplines use diverse methodologies to

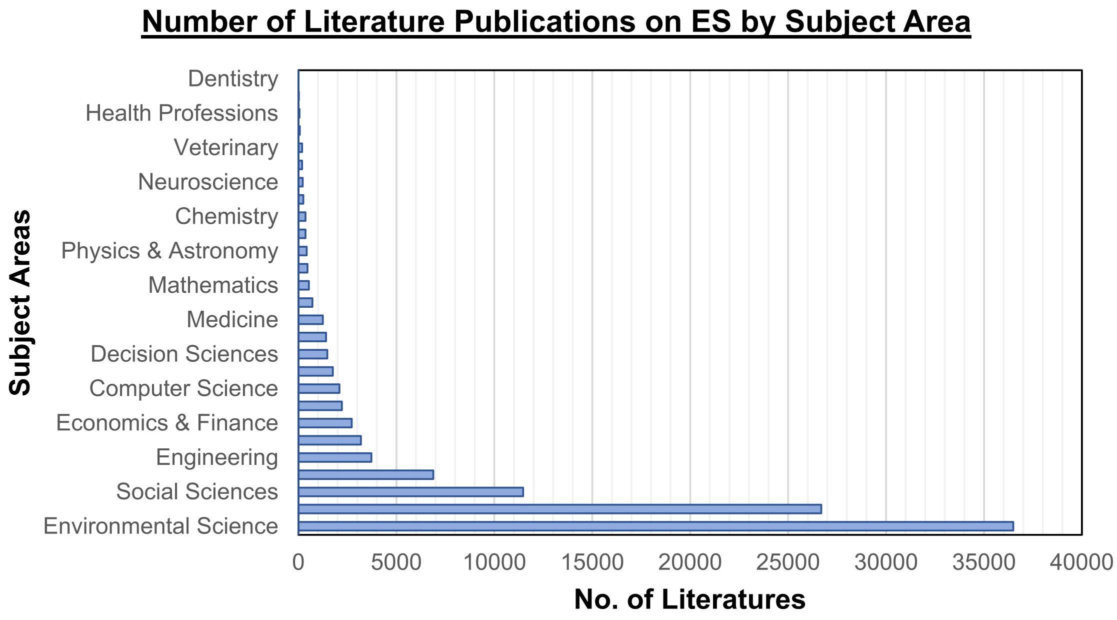

Figure 12. Graph showing the number of literature on ES by Subject Area.

assess ES, e.g. social scientists rely on community surveys, questionnaires, etc. In contrast, engineers and hydrologists use ES modeling techniques to assess ES, and economists focus on the valuation of ES. However, for a more holistic assessment of ES, it is critical to integrate the different methodologies of various disciplines. Moreover, there is an issue of different scales in integrating different data, e.g. ecological data, such as photosynthesis, are measured at the plant level while hydrological data, such as discharge, are measured at the watershed level. Hence, upscaling or downscaling techniques are utilized for data integration, which often introduces uncertainties in the data.

The literature on ES is usually fragmented rather than integrated, making it difficult to aggregate ideas from different disciplines for a better understanding of ES to make conservation strategies and policies for the sustainable use of ES (Bennett 2017). Furthermore, integrating findings from diverse disciplines into a cohesive framework necessitates the effort of all researchers involved. (Katz and Martin 1997).

5. Conclusion

The Himalayan region plays a crucial role in providing numerous ESs that support the livelihoods and well-being of millions of people. A literature review was conducted to understand better ES's prevalence, distribution, and research focus in the region. Thirty-one unique ES in the Himalayan region were identified and classified. While the distribution of reviewed literature is even across the Himalayas (Western: 30.26%, Central: 32.89%, Eastern: 36.84%), the analysis revealed a 43.54% bias toward PES. This highlights the need for more research into RES (36.48) and CES (19.98%), which play significant but less quantifiable roles. Furthermore, terrestrial and freshwater ecosystems have been identified as the major providers of ES in the Himalayan region. Terrestrial ES, such as PES11, PES10, PES3, PES4 and PES6, are recognized as important PES that directly benefit local communities. Similarly, PES9 and PES8 have been identified as the region's most important PES. Other ES, such as RES2, RES5, RES6, CES2, CES3 and CES7, are provided by both forests and freshwater ecosystems. Even though the ES provided by both terrestrial and freshwater ecosystems are almost the same, there have been more studies on the terrestrial than on the freshwater ecosystem. Additionally, the flow of ES in the Himalayan region is affected by climate change. It has been found that both freshwater and terrestrial ES will be impacted by future climate change, resulting in the depletion of ES in the region and increased natural disasters. It was observed from the literature that while most studies focused on identifying ES across the Himalayas, less attention was paid to the quantification and valuation of these services. Furthermore, despite being the most frequently identified, PES had a lower average economic value per hectare per year than RES and CES. Because of their ease of quantification and valuation, there was an imbalance in favor of PES, although RES and CES play important roles in supporting human well-being and the environment and are valued higher than PES. Future research should focus on a more holistic and sustainable approach to the assessment of ES for better decision-making and conservation of the Himalayan ecosystems.

Table 2. Number of articles found in Scopus database on freshwater, ecosystem services, and the Himalayan region (as of November 2024).

Keywords searched in Scopus database (up to November 2024)	No. of Articles found
1. Considering Freshwater and Ecosystem Services (('water' OR 'freshwater' OR 'wetland' OR 'wetlands' OR 'rivers' OR 'river' OR 'lakes' OR 'lake') AND ('Ecosystem services' OR 'Environmental services' OR 'Ecological services'))	25 498
2. Considering Freshwater and Himalayan region (('water' OR 'freshwater' OR 'wetland' OR 'wetlands' OR 'rivers' OR 'river' OR 'lakes' OR 'lake') AND ('Himalayan,' OR 'Himalayas,' OR 'Himalayan region,' OR 'Himalaya'))	11 336
3. Considering Freshwater, Himalayan region and Ecosystem Services (('water' OR 'freshwater' OR 'wetland' OR 'wetlands' OR 'rivers' OR 'river' OR 'lakes' OR 'lake') AND ('Himalayan,' OR 'Himalayas,' OR 'Himalayan region,' OR 'Himalaya') AND ('Ecosystem services' OR 'Environmental services' OR 'Ecological services'))	211

5.1. Knowledge gaps and future research directions

This literature review has identified a few areas where more research is required. The following research directions and knowledge gaps have been identified as key for future studies:

5.1.1. Less attention to freshwater ES

The Scopus search reveals that there are 25 498 articles related to freshwater and ES, indicating a strong focus on this topic globally. In the Himalayan region, studies related to freshwater are also substantial, with 11 336 articles. However, when focusing on freshwater ES, specifically within the Himalayan region, the number of articles decreases sharply to 211. This indicates that while extensive research has been conducted on freshwater ES globally and on freshwater-related studies in the Himalayan region, there remains a significant gap in the assessment of freshwater ES, specifically within the Himalayan region, as shown in table 2.

The reviewed literature highlights freshwater ES's critical significance in supporting the Himalayas' local population despite receiving comparatively less attention (particularly regarding their quantification and valuation). This limited attention to freshwater ES can be caused by prioritizing research for other ecosystems, such as forest ecosystems (Faghihinia *et al* 2021, Vári *et al* 2021). Nevertheless, the importance of water as an ES in the Himalayas is widely acknowledged, even if it has not been extensively researched. Future research should concentrate on comprehensive assessments of freshwater ecosystems, such as quantifying their services, understanding their vulnerability to climate change, and investigating the effects of human activities on their health and functioning.

5.1.2. Quantification and valuation of ES

It was observed that while there is a strong emphasis on identifying ES in the Himalayan region, primarily through participatory methods such as surveys, questionnaires, and FGDs, there is a noticeable lack of quantification and valuation of ES. In the reviewed literature, 39.47% of the total literature focused on quantification and only 23.68% on valuation of ES. Additionally, out of the literature focused on quantification, 53.33% of them quantified the ES using a well-established method of ES modeling. Furthermore, there has been limited focus on quantifying indirect services i.e. RES and CES. Future research should focus not only on the identification of ES but also on the quantification and valuation of ES, especially RES and CES (indirect services).

Overall, it can be observed that although RES and CES have higher average economic values per hectare than PES, PES are the most frequently identified services in the Himalayan region. This represents a significant knowledge gap in the region. RES and CES provide critical yet intangible or indirect benefits, such as climate regulation, water regulation, spiritual values, and recreation, often governed by complex processes. As a result, they are difficult to identify, quantify, and value. Most research focuses on PES that provide tangible benefits such as food, water, and timber, making them easier to identify, quantify, and value. The economic valuation of PES is straightforward as it directly correlates with market prices. RES and CES are difficult to accurately value due to their complexity and lack of clear market prices. The ease of quantifying and valuing PES has led to an imbalance in research focus, leaving crucial services like RES and CES under-researched despite their importance in ensuring ecosystem sustainability.

5.1.3. Integrated conservation approach

Understanding different ES's interdependence and reliance on healthy ecosystems is essential for effective conservation. (Tucker *et al* 2023) addressed the need for additional research on the interconnection and feedback between various dimensions of ES and common pool resources. Ecosystems have a feedback mechanism in which changes in one component, or ES, can cascade effects on others. For example, deforestation may alter the water balance of a river basin, which may impact other ES such as water provision, soil retention, flood regulation, etc. (Lima *et al* 2014). Future research should take an integrated approach to design comprehensive conservation and management plans considering the interdependence of PES, RES, CES, SES, and ecosystem components.

5.1.4. Long-term monitoring and data collection

The Himalayan region's ecosystems are complex and dynamic, demanding regular monitoring to understand temporal changes and acquire insights into how ecosystems adapt to various drivers such as climate change and anthropogenic activity. It is critical to develop monitoring criteria or ecological markers that will aid us in evaluating ecosystems across time (Negi *et al* 2019). ES data and accurate measurements are often unavailable but are especially required in the Himalayan region, which covers several developing countries such as India, Nepal, Bhutan, etc. (Suich *et al* 2015). Long-term monitoring and accurate estimates of ES data can provide essential data for decision-making to sustain these mountainous ecosystems.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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