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Ecosystem services assessment of Beledanga oxbow lake in the Gangetic plains: pathways to sustainable conservation

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Oxbow lakes, formed from abandoned river meanders, are unique wetlands that play a crucial role in supporting aquatic biodiversity and sustaining local communities through their ecosystem services. This study focuses on the Beledanga oxbow lake, highlighting its ecosystem services and the critical role of hydrological connectivity with the adjacent river for maintaining ecological functionality and sustainability. Using the Millennium Ecosystem Assessment framework, the study assessed provisioning, regulating, cultural, and supporting services through field surveys, stakeholder consultations, and secondary data analysis. Results show that the lake provides essential provisioning services, such as fisheries and irrigation, which support local food security and income generation. It also plays a role in regulating services like water management and carbon sequestration, while its biodiversity underpins vital ecological functions, including nutrient cycling and habitat provision. However, challenges such as seasonal water scarcity and macrophyte infestation threaten the lake's productivity and connectivity with the river. The study emphasizes the need for collaborative efforts involving local stakeholders to devise water management strategies and remove macrophytes, utilizing government initiatives like the Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) for funding. Additionally, the establishment of robust monitoring systems for sustainable fisheries management and incentive programs for conservation efforts are recommended. The research highlights the importance of hydrological connectivity in sustaining the lake's ecosystem services and enhancing biodiversity. By integrating local knowledge and stakeholder engagement, this study provides valuable insights into the sustainable management of oxbow lakes and highlights the broader significance of river-oxbow lake connectivity in wetland conservation efforts. The findings also have implications for broader wetland conservation policies in similar ecosystems.

KEYWORDS

oxbow lakes, ecosystem services, economic valuation, wetlands, Millennium Ecosystem Assessment

1 Introduction

The river system exhibits a gradual change in physical conditions from its origin to the point where it meets the ocean, and these conditions have a significant impact on ecosystem functioning (Holmlund and Hammer, 1999). The interactions among biota, biological processes, and physical and chemical factors determine how these ecosystems operate (Allan and Castillo, 2007). River channels serve as conduits for energy, nutrients, and food webs, facilitating their integration both lengthwise and laterally within river ecosystems (Allan and Castillo, 2007). Oxbow lakes, formed when a section of a river becomes isolated, remain connected either by occasional flooding or a channel unless separated by manmade or geomorphic changes over time. This connectivity is vital for supporting various ecological functions such as species diversity, carbon storage, and the production of fibers (Grabowski and Gurnell, 2016; Thorp et al., 2010). Despite covering only, a small percentage of the Earth's surface, oxbow lakes contribute significantly to maintaining ecosystem services (Barbier, 2011; Zedler and Kercher, 2005; Erwin, 2009). Oxbow lakes are frequently described as "nurseries of the floodplain" due to their calm and nutrient-rich environments, which provide ideal conditions for fish spawning and the development of juvenile aquatic organisms. These conditions contribute significantly to the sustainability of fish populations within the ecosystem (Khan et al., 2021). As "aquatic refuges," oxbow lakes offer stable habitats that protect species from extreme riverine conditions, such as floods or droughts. Their isolation from the main river flow creates an environment where species can survive and thrive even during adverse events, supporting biodiversity and ecosystem resilience (Obolewski et al., 2016).

The Gangetic plains, characterized by the formation of oxbow lakes due to the meandering of the River Ganga, exemplify the benefits and importance of floodplain oxbow lakes (Mandal et al., 2021). These oxbow lakes provide multiple ecosystem services that directly impact the livelihood strategies of neighboring communities. They offer fertile land for agriculture, irrigation opportunities, fishing and duck-rearing provisions, biodiversity conservation, aesthetic appeal, and tourism potential, creating economic opportunities and employment avenues. However, the full potential of the oxbow lake remains unrealized due to the improper assessment and underestimation of its ecosystem services.

The concept of ecosystem services, which emerged in the 1980s, aims to understand the significance of ecosystem processes for human wellbeing (Daily, 1997; Costanza et al., 1997). The Millennium Ecosystem Assessment (MEA) provides a classification of ecosystem services into provisioning, regulating, cultural, and supporting services, highlighting their economic, ecological, and socio-cultural importance (see Figure 1). While economic value is often prioritized in the consideration of ecosystem services, as it can be quantified and offers immediate benefits, it is important to recognize the broader ecological functions provided by intact floodplains surrounding oxbow lakes. These floodplains serve as critical areas for the exchange of nutrients and organic matter, promoting ecological functions and supporting diverse species assemblages. Oxbow lakes contribute to biodiversity conservation by providing habitats for various aquatic and terrestrial species, and their interconnectedness with surrounding floodplains enhances species richness and ecological diversity within these habitats. They also serve as important spawning and nursery grounds for fish, contributing to fish populations and supporting fisheries (Graff and Middleton, 2001; Schmitten, 1999; Bruton and Jackson, 1983; Newton et al., 2020). Furthermore, oxbow lakes play a role in carbon sequestration by accumulating organic matter from the surrounding lands. This process helps mitigate climate change by reducing the concentration of carbon dioxide in the atmosphere (Ribeiro et al., 2021; Farooqui et al., 2023; Petsch et al., 2023; Debanshi and Pal, 2022).

The ecological health of oxbow lake worldwide is under threat from various factors such as encroachment, habitat destruction, resource exploitation, agricultural pollution, and eutrophication (Arya et al., 2020; Sarkar et al., 2020; Aslam et al., 2021). Therefore, it is crucial to conduct a proper assessment of the ecosystem services provided by oxbow lakes, enabling their wise use, resource generation, storage, and conservation.

The objective of this assessment is to comprehensively evaluate the ecosystem services provided by oxbow lakes in the Gangetic plains of India from a stakeholder-centric perspective. This includes identifying and mapping the various ecosystem services (e.g., provisioning, regulating, cultural, and supporting services) provided by these lakes, assessing their economic, social, and ecological values, and understanding their importance to different stakeholder groups. The assessment aims to engage stakeholders throughout the process to ensure that their perspectives, needs, and priorities are considered in the development of conservation and management strategies. By achieving these objectives, the assessment seeks to contribute to the sustainable conservation and management of oxbow lakes and their ecosystem services in the Gangetic plains of India.

2 Materials and methods

Initially, the scope of ecosystem services pertaining to oxbow lakes is established based on the Millennium Ecosystem Assessment (2005), as shown in Figure 1. A comprehensive review of the literature is conducted to enhance the understanding of the contribution of oxbow lakes to human wellbeing. Both primary and secondary data sources are utilized in the study. In the present context, the primary data sources refer to information collected directly from the field or site of the study. This included firsthand observations, surveys, and interviews conducted specifically for the research project on Beledanga oxbow lake. Secondary data sources involve utilizing existing data that was not originally collected for the present study on Beledanga oxbow lake. This may include data from previous research, governmental reports, publications, or any other sources that provide relevant information for the current investigation without direct field collection. The methodology is structured into several sections, which are as follows:

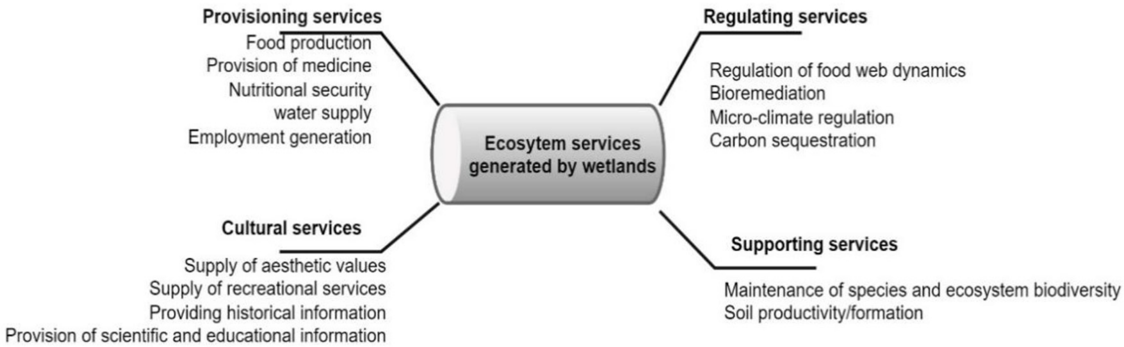

FIGURE 1
An overview of ecosystem services provided by oxbow lakes. Source: Created by the authors, modified and adapted from Millennium Ecosystem Assessment (2005).

2.1 Brief description of the study area

Beledanga, an oxbow lake situated in the lower Gangetic basin of the North 24 Parganas district in West Bengal (see Figure 2A) has geographical coordinates of Latitude: 23.0613°N and Longitude: 88.7618°E, with an altitude of 13.00 m above mean sea level. It is connected to the Ichamati River (Figure 2B). The region experiences an average annual rainfall of 1,538 mm and a mean annual temperature of 26.2°C, with a relative humidity of 59 per cent. In recent years, the area has faced natural calamities such as drought in 2017 and 2018. The oxbow lake area has experienced a substantial reduction, declining from 65.15 hectares in 1980 to 46.0 hectares in 2020, primarily due to factors such as encroachment, water stress, macrophyte infestation, and sedimentation, all exacerbated by the impacts of climate change (Karnatak et al., 2022). This reduction in area, along with habitat modification and the closure of tie channel has adversely affected fish diversity and production in the wetland. These channels play a crucial role in regulating the flow of water between the river and the oxbow lake. These channels are inherently natural in origin. The closure of these tie channel can occur through natural processes, such as sedimentation or vegetation growth, influencing the connectivity between the river and the oxbow lake (Mandal and Bhunia, 2022; Sarkar et al., 2023; Das et al., 2021; Ghosh et al., 2023).

The disconnection of the river and the oxbow lake may disrupt the production and linkages of energy and nutrient flow, which further disrupts local fish abundance (Gido et al., 2016). Floodplains with permanent, either one- or two-sided lateral connectivity to the main channel, favor total fish abundance and are essential as nursery areas for riverine fishes (Stoffers et al., 2022). Increases in fragmentation can decline the aquatic population (Crook et al., 2015; Barbarossa et al., 2020). To support the livelihoods of the local fishers, the Beledanga Fishermen Co-Operative Society (FCS), which is managed locally, practices culture-based fisheries with Indian Major Carps [IMCs refers to Catla (*Catla catla*), Rohu (*Labeo rohita*) and Mrigal (*Cirrhinus mrigala*)] and exotic species. Local fishers who fish in the Beldenga oxbow are also granted access through the nearest cooperative societies near other oxbow lakes. The three villages adjacent to Beledanga oxbow lake -Beledanga, Barrackpur, and Gopalnaga—are home to a total of 3,700 households. The FCS has 176 registered members, and fishing activities serve as the primary source of income for these families. In addition to fishing, these local fishers are involved in agriculture and other related occupations.

2.2 Data collection strategy

The data collection process is organized into three sections, with each section representing a specific strategy outlined in Table 1. These strategies encompass literature review, primary data collection, and utilization of secondary data.

2.2.1 Primary data collection

The primary method employed for obtaining information on the ecosystem involved direct means such as visual observation, photography, and limited interaction with individuals present. While these methods provided valuable insights, the scope of information was restricted to a few aspects. The beel or wetland under investigation is situated close to three villages, namely Gopal Nagar, Barrackpore, and Beledanga. To ensure a comprehensive data collection process, information was gathered from all three villages. A total of 65 individuals were randomly selected from households engaged in fishing activities within the beel-dependent community. This selection process involved the administration of a specific questionnaire tailored to capture relevant insights (for more details see Supplementary material). To complement this, we conducted detailed key informant interviews. The objective of these interviews was to collect information on crop production, nutritional, and food security aspects of ecosystem services. We engaged with a diverse group of individuals, including community leaders, professionals, and experienced individuals, all of whom had firsthand knowledge about the oxbow lake and its various uses.

Triangulation, a robust technique, was applied to enhance data validation by cross-verifying information

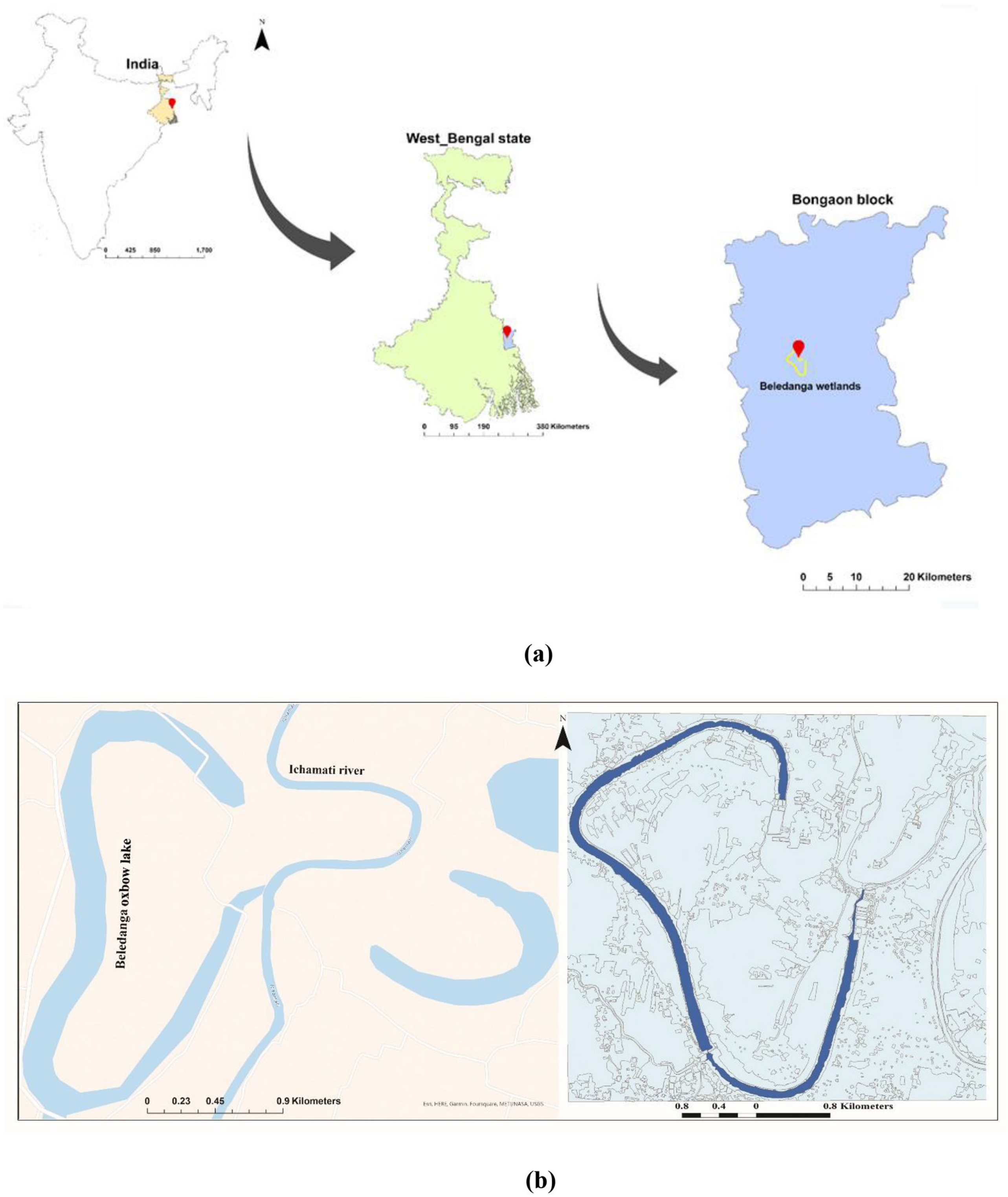

FIGURE 2
(A) An overview of the study area based on the administrative structure. **(B)** The connection of oxbow lake with the river.

from two or more sources. This technique involved verifying the collected secondary data with the State Department and other key informants to ensure authenticity and reliability.

2.2.2 Literature review and secondary data

We conducted a systematic literature review following the PRISMA method (Moher et al., 2009) to identify evidence of ecosystem services within the Gangetic Basin, including the

TABLE 1 Data collection strategy for different ecosystem services.

S.No.	Type of ecosystem services	Data collection strategy
Provisioning services		
1.	Fisheries	Secondary data
2.	Agriculture	Primary data
3.	Employment generation	Primary data
4.	Nutrition and food security	Primary data
Cultural services		
5.	Aesthetic and cultural	Primary data
Regulating services		
6.	Regulation of food-web dynamics	Literature review and primary data
7.	Bioremediation	Literature review and primary data
8.	Carbon sequestration	Literature review
Supporting services		
9.	Maintaining biodiversity	Literature review and primary data

TABLE 2 Different keyword combinations for the literature search.

ES	Keywords used with oxbow/wetland and Ganga/Gangetic/India	No. of papers	Relevant papers
Regulating services			
Regulation of food-web dynamics	Food web or Ecopath	64	25
Bioremediation	Bioremediation or Phytoremediation	78	73
Carbon sequestration	Carbon sequestration	45	35
Supporting services			
Biodiversity	Fish species richness or biodiversity	12	8
		$N = 199$	$n = 141$

Beledanda oxbow lake. Initially, we identified various regulating and supporting services associated with the oxbow lake from the literature, as depicted in Figure 1. Subsequently, we expanded our review to incorporate studies from biophysical and environmental sciences directly or indirectly related to the ecosystem functions or services of the oxbow lake.

To gather relevant information, we utilized the Scopus electronic database and employed keywords such as "oxbow lake/wetlands AND Ganga/Gangetic/India" against each ecosystem, as outlined in Table 2. Our search yielded 524 references, and after removing duplications, we selected only peer-reviewed articles written in English ($N = 199$). The title and abstract of each publication were scrutinized to align with the aim of our search, resulting in 141 references related to ecosystem services for further analysis. Within this subsample, articles were evaluated based on two criteria: (1) specific reference to ecosystem services, processes, or functions, and (2) papers specifying the role of wetlands in bioremediation, carbon sequestration, and biodiversity. For bioremediation, data collected from the literature were cross-verified in the field through visual observations.

Regarding fisheries data, we sourced information from a meticulously maintained database by the fisheries cooperative society using a proforma. This society played a crucial role in collating and organizing data related to fishery activities, ensuring the reliability and representativeness of the figures provided for the wetland area.

2.2.3 Consultation with stakeholders

Key informant interviews included a detailed exploration of institutional arrangements related to fisheries in wetlands. This involved probing into the organizational structures, regulations, and cooperative mechanisms governing fishing activities. Additionally, Focus Group Discussion (FGD) sought to uncover community perspectives on the role of institutions, their effectiveness, and their impact on the sustainable management of wetland fisheries. FDG is a qualitative research method and data collection technique in which a selected group of people discusses a given topic or issue in-depth, facilitated by a professional or external moderator. In the present study, two FGDs were conducted and 22 key informants were selected. This multifaceted approach aimed to provide a comprehensive understanding of how institutional arrangements influence and shape fisheries in wetland ecosystems.

3 Results

The results are presented based on the Millenium ecosystem assessment, 2005 classification.

3.1 Provisioning services

3.1.1 Fisheries

Oxbow lake serves as a valuable source of provisioning services, particularly in the form of fisheries. Fisheries play a significant role in supporting human wellbeing by providing livelihood opportunities. Figure 3 provides an overview of the total fish yield and the economic value associated with it. The average annual fish yield was estimated to be 37.89 lakhs ($46,799 USD).

3.1.2 Agriculture

The Beledanga oxbow lake plays a crucial role in supporting agricultural activities throughout the year, as it facilitates irrigation and provides fertile soil for crop cultivation. Approximately 30 percent of the water used for irrigation in the area is sourced from the oxbow lake. The total economic value of the crops grown in the vicinity of the lake was estimated

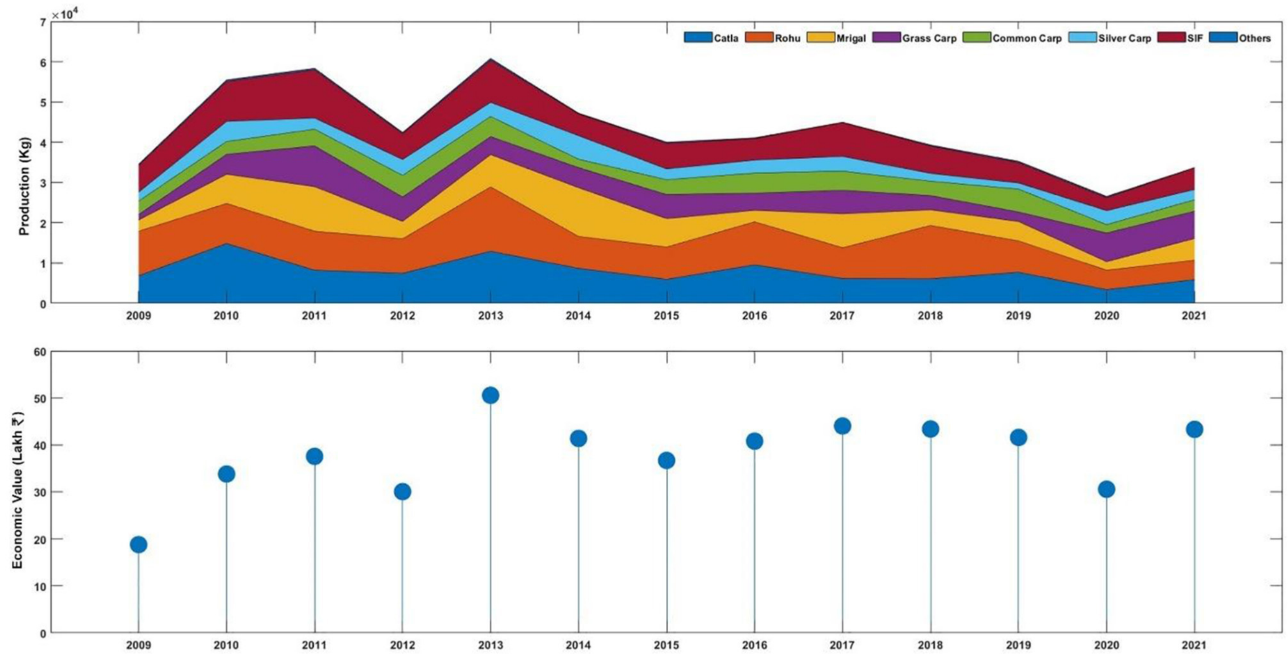

FIGURE 3
Year-wise yield and economic value of major fish species harvested from the oxbow Lake (Source: Beledanga Fisheries Cooperative Society).

to be 65.2 lakh ₹ (equivalent to 78,396.73 $ USD as of January 7, 2023) per year (Figure 4). In the context of this paper, the term "vicinity" is defined as the immediate area or surroundings adjacent to a specific location. It is utilized to emphasize spatial closeness, serving as a descriptor for the nearby geographical extent associated with the focal point under consideration in the study. Among the cultivated crops, vegetables constitute the largest portion at 33 percent of the total production, followed by oilseeds at 20 percent and rice at 10 per cent. Additionally, jute, an important fiber crop, is grown and processed in the vicinity of the lake, contributing to the local economy.

3.1.3 Employment generation (male and female)

Man-days is defined as a unit representing 1 day's worth of work conducted by an individual, irrespective of gender. In the Indian context, the standard measurement for one man's day is equivalent to 8 h of work in a day, regardless of whether the work is performed by a male or female individual. This approach ensures a standardized unit of measurement for labor, facilitating consistent and equitable assessments of productivity, effort, or resource utilization in the study area.

The Beledanga oxbow lake stands as a cornerstone for economic activities, particularly in agriculture and fisheries, shaping livelihoods for both men and women in the region. The agricultural sector thrives with the toil of ∼5,235 individuals, highlighting a substantial male and female workforce committed to cultivating the fertile lands surrounding the lake (Figure 5). Simultaneously, fisheries production involves 3,850 people, showcasing a diverse engagement of both genders in harnessing aquatic resources.

While men actively participate in agricultural and fishing pursuits, women contribute significantly to the community's sustenance and economic wellbeing through unique roles. Despite not being directly involved in fieldwork, women employ small traps known as Ghuni to collect fish intermittently, ensuring a diverse and balanced diet for households. Additionally, women play a crucial part in supplementing family incomes by harvesting wild leafy vegetables (shak) from the lake's environs. These vegetables find their way to nearby markets, not only enriching local diets but also contributing to the financial resilience of families. The Beledanga oxbow lake emerges as a vibrant ecosystem where both men and women play integral roles in agricultural and fisheries activities, reflecting a harmonious interdependence that sustains livelihoods and promotes economic diversity within the community.

3.1.4 Contribution toward nutrition and food security through fisheries

Oxbow lakes contribute to nutrition and food security by providing vital habitats for diverse fish species, supporting local fisheries that supply essential proteins and nutrients to nearby communities. These lakes offer year-round fish production, helping to stabilize food resources in rural areas. To gain a better understanding, fish consumption patterns was carried out among randomly selected households in the community relying on the beledanga oxbow lake. The investigation spanned three neighboring villages: Gopal Nagar, Barrackpur, and Beledanga village. Based on primary data collected from the study site,

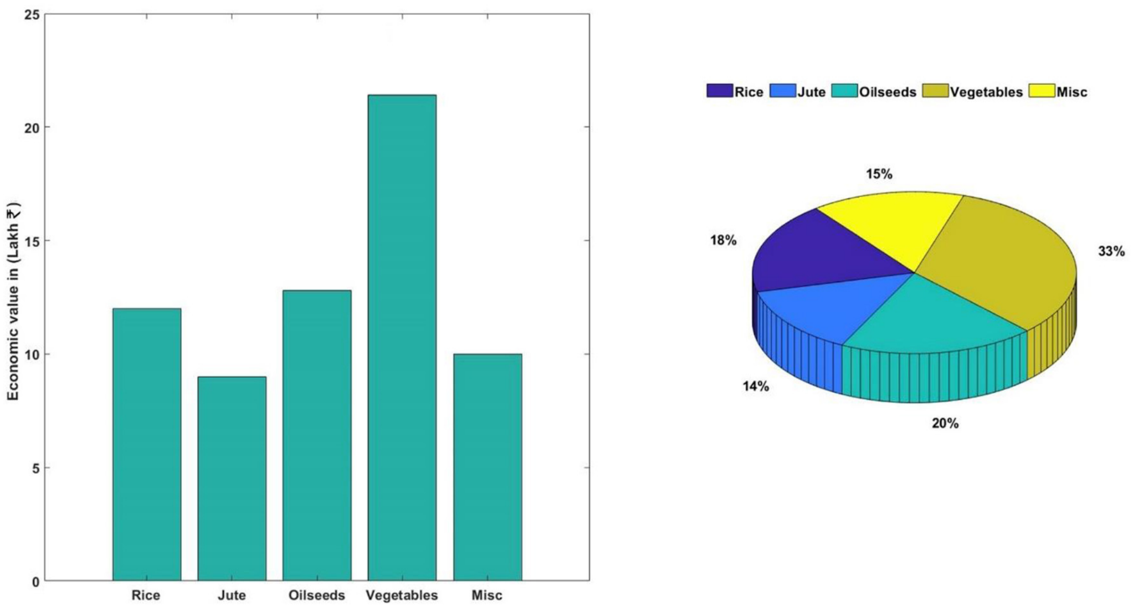

FIGURE 4
An overview of the economic value of crops produced from oxbow lake.

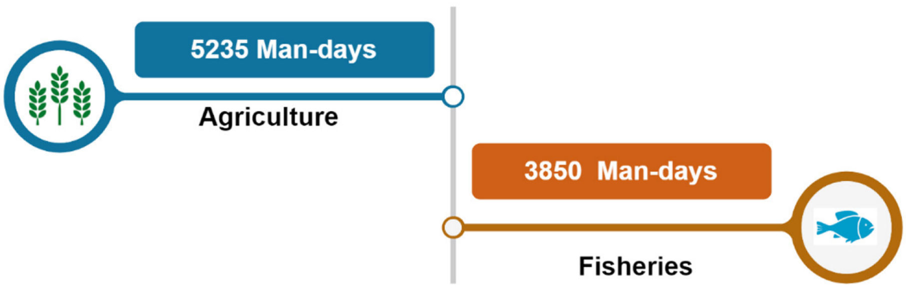

FIGURE 5
An overview of man-days generated by livelihood activities on oxbow lake.

findings indicate that only 3% of the surveyed population can afford daily fish consumption, while 89 % consume fish 3–6 days a week (Figure 6). Notably, the consumers are predominantly from the fishing community, relying on fishing for their livelihood. These individuals allocate a portion of their catch for personal consumption.

Residents in the vicinity preferred acquiring fresh fish from local vendors or markets near the lake. On average, the sampled population consumed 58 grams of fish per person per day. Considering that fish generally contains 15–23 g of protein per 100 g (Park, 2015), the Beledanga oxbow lake has the potential to contribute to the nutritional security of the lake-dependent community. The commonly consumed fish species among the sampled population included Catla (*Labeo catla*), Rohu (*Labeo rohita*) Bata (*Labeo bata*), and small indigenous fishes found in the oxbow lake. Indigenous fishes constituted a substantial portion (67%) of their regular fish diet. Given the nutritional importance of fish and the community's reliance on the lake, the findings underscore the potential role of the Beledanga oxbow lake in enhancing the overall nutritional wellbeing of the local population.

3.2 Cultural services

Freshwaters in India have long been intertwined with religious and spiritual beliefs, influencing cultural diversity, artistic expressions, and local practices, which in turn shape regional identities (Singh and Rana, 2020). Recognizing the significance of these cultural services is crucial as they contribute to the social wellbeing of communities. The surrounding areas of oxbow lake often host festivals and community programs, while religious rituals are performed near these water bodies. Such cultural practices, when integrated with wetland ecosystems, help preserve the heritage value of cultural landscapes. In the case of Beledanga oxbow lake, the lake serves as a site for cremation ceremonies, and water from the oxbow lake is utilized in various religious rituals

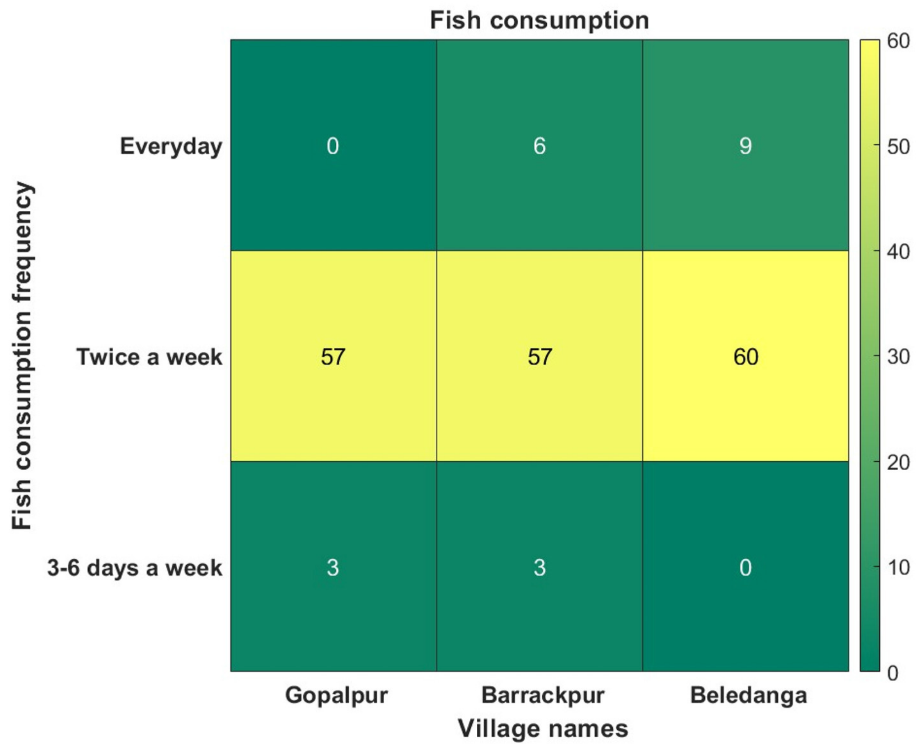

FIGURE 6
Fish consumption frequency of people living near the vicinity of oxbow lakes.

(Figure 7). Additionally, due to its proximity to urban areas, the wetland is frequently visited as a picnic spot and for bird watching, further enhancing its cultural and recreational significance.

3.3 Regulating services

3.3.1 Regulation of food-web dynamics

Oxbow lakes function as ecotones, bridging the gap between terrestrial and aquatic environments (Sturchio et al., 2022), establishing themselves as intricate and highly productive ecosystems on Earth (Singh et al., 2022). Within this ecosystem, each organism holds a distinct role and significance, contributing to different trophic levels such as primary producers (phytoplankton and aquatic weeds), primary consumers (zooplankton and certain herbivorous fishes), secondary consumers (benthos and smaller fishes), and apex predators at the top (birds or piscivorous fishes). These components are interconnected through the food web, creating a cascade of ecological services.

The literature review, however, only yielded 25 papers relevant to the Indian context, with just one paper exploring the food web dynamics of the Beledanga wetlands (Swain et al., 2023). To comprehend the food web dynamics, a mass-balanced ecopath model specific to the Beledanga wetland has been formulated (Figure 8). Considering biodiversity and fish catch data availability, the wetland's inhabitant community is categorized into 12 functional groups, including "Other piscivorous," "IMCs (IMCs refers to Indian major carps; *Labeo catla, Labeo rohita* and *Cirrhinus mrigala*)," "EMCs (EMCs referred to Exotic major carps Common carp (*Cyprinus carpio*), Silver carp (*Hypophthalmichthys molitrix*) and Grass carp (*Ctenopharyngodon idella*)," "Other carnivorous," "Omnivore fishes," "Planktivore fishes," "Benthos," "Zooplankton," "Eichhornia," "Other macrophytes," "Phytoplankton," and "Detritus." The model's inherent ecological network analysis indices offer insights into trophic status integrity, system reserve, and production cycling processes within the ecosystem. This study aims to guide fishery managers in making informed decisions for ecosystem-based fishery management and the sustainable utilization of fish resources.

3.3.2 Bioremediation

Biological treatments have gained recognition as effective and environmentally friendly methods for wastewater remediation, especially in the context of natural oxbow lakes. These lakes offer low-cost, sustainable, and easily manageable solutions for removing various organic and inorganic pollutants from contaminated water. A comprehensive literature review focusing on the Indian context revealed 73 relevant papers. Table 3 presents an overview of aquatic plants known for their role in bioremediation, addressing both organic contaminants and heavy metals. Within the Beledanga oxbow lake, as observed in Figure 9, specific phytoplankton species were identified based on the literature review, showcasing their potential for bioremediation. Phytoplankton such as *Eichhornia crassipes*, *Lemna* sp., *Spirodela oligorrhiza*, *Potamogeton crispus*, and *Elodea canadensis* were highlighted for their efficacy in pesticide

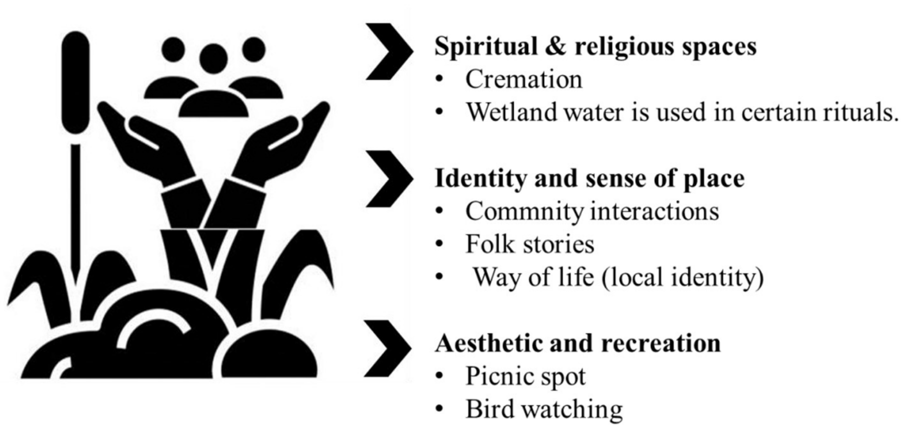

FIGURE 7
The cultural services identified for Beledanga oxbow lake.

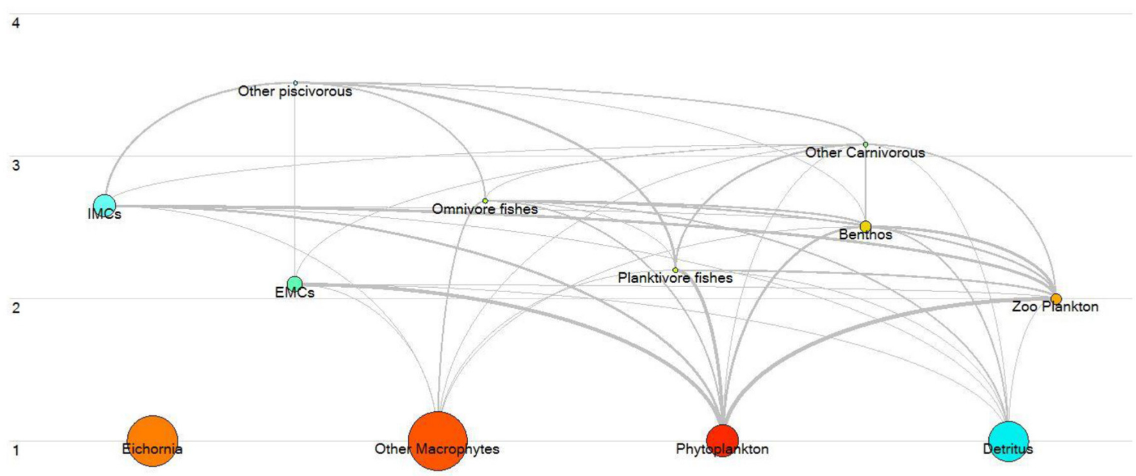

FIGURE 8
The food web structure of the Beledanga oxbow lake. Sizes of the circle denote the size of biomass, numbers (1, 2, 3, 4) on the left side represent the Trophic Level (TL), the arch lines in the pictures identify the flow pattern.

bioremediation. Additionally, species like *Cyperus rotundus, Ipomoea aquatica, Hydrilla verticillata*, and *Azolla pinnata* were identified for their role in heavy metal bioremediation.

The utilization of these diverse plant species emphasizes the versatility of oxbow lakes as natural systems for mitigating various water pollutants. The findings from the literature review contribute to a growing body of knowledge on the potential of biological treatments, particularly within the Indian context, and provide valuable insights for sustainable and cost-effective water remediation strategies.

3.3.3 Carbon sequestration

Oxbow lakes, though relatively small in spatial extent, contribute to carbon sequestration within wetland ecosystems. They capture organic matter in sediments, making them effective carbon sinks, albeit on a more localized scale compared to larger wetland types. Research has shown that oxbow lakes, as part of freshwater wetlands, play a role in soil carbon accumulation, but they do not comprise a large share of the global soil carbon stock.

Globally, wetlands store ∼20%−30% of soil organic carbon, even though they cover only about 5%−8% of the Earth's surface (Mitsch and Gosselink, 2015). Oxbow lakes fall within this category but contribute modestly due to their limited global presence. Their importance lies in their role in localized carbon sequestration and the biodiversity they support, especially within riverine ecosystems (Kayranli et al., 2010).

In terms of annual carbon sequestration, terrestrial ecosystems, including all types of wetlands, have a potential sequestration rate of 5–10 gigatons of carbon per year, although current rates are closer to two gigatons per year (Pant et al., 2003a,b). While oxbow lakes contribute to this total, their individual share is small compared to larger wetland systems like peatlands, which are the most significant wetland carbon sinks (Lehner and Döll, 2004).

TABLE 3 An overview of aquatic plants useful in pesticides and heavy metal bioremediation.

Plant species	Contaminant	References
Eichhornia crassipes	Ethion, dicofol, cyhalothrin, Fe pentachlorophenol	Roy and Hänninen, 1994; Singh and Rai, 2016; Xia et al., 2002
Lemna gibba	Phenol, 2,4,5-trichlorophenol (TCP)	Sharma et al., 1997; Tront and Saunders, 2002
Lemna minor	2,4,5-trichlorophenol (TCP), halogenated phenols	Biswas et al., 2010; Singh and Rai, 2016; Tront et al., 2007
Spirodela oligorrhiza	Organophosphorus and organochlorine compounds (o,p′-DDT, p,p′-DDT), chlorobenzenes	Gobas et al., 1991
Myriophyllum aquaticum	Simazine, o,p-2 DDT, p,p-2 DDT, hexachloroethane (HCA), perchlorate	Knuteson et al., 2002
Potamogeton crispus	Phenol	Hafez et al., 1998
Ceratophyllum demersum	Organophosphorus and organochlorine compounds, chlorobenzenes	Gobas et al., 1991
Elodea canadensis	Phenanthracene, organophosphorus and organochlorine compounds, Hexachloroethane (HCA), DDT	Gobas et al., 1991; Sehrawat et al., 2021; Parween et al., 2018
Pontederia cordata	Oryzalin (herbicide)	Fernandez et al., 1999
Scirpus lacustris	Phenanthracene	Machate et al., 1997
Salvinia cucullata	Iron (Fe)	Singh and Rai, 2016; Rai and Singh, 2020
Pistia stratiotes	Calcium (Ca), chromium (Cr), Copper (Cu), Lead (Pb), Zinc (Zn), Magnesium (Mn) and Iron (Fe)	Singh and Rai, 2016; Rai and Singh, 2020
Cynodon dactylon	Zinc (Zn)	Chatterjee et al., 2011
Alternanthera philoxeroides	copper (Cu), zinc (Zn), chromium (Cr), lead (Pb), nickel (Ni)	Ramachandra et al., 2020
Cyperus rotundus	Calcium (Ca), chromium (Cr), Copper (Cu), Lead (Pb), Zinc (Zn), Magnesium (Mn) and Iron (Fe)	Mazumdar and Das, 2015; Chatterjee et al., 2011
Ipomea aquatica	Calcium (Ca), chromium (Cr), Copper (Cu), Lead (Pb), Zinc (Zn), Magnesium (Mn) and Iron (Fe)	Mazumdar and Das, 2015; Chatterjee et al., 2011
Hydrilla verticillata	Copper (Cu), Arsenic (As)	Mazumdar and Das, 2015
Azolla pinnata	Mercury (Hg), Cadmium (Cd)	Mazumdar and Das, 2015

Only eight relevant studies were documented in India, and none specifically focused on the Beledanga oxbow lake. Consequently, a similar oxbow lake with the same geographical characteristics was found that could serve as a model for understanding the carbon storage potential of Beledanga oxbow lake.

A study conducted in Bhomra and Mathura oxbow lakes, similar to the Beledanga oxbow lake in the Gangetic plains, revealed that these oxbow lakes are productive ecosystems based on the physicochemical parameters of water and soil. The carbon accumulation in the oxbow lakes, up to a depth of 0.3 m, ranged from 144 to 166 Mg/ha, which was 3.43 to 4.78 times higher than the corresponding reference upland sites. In the case of Bhomra wetland, the reference upland sites were agricultural lands where crops are grown in different seasons, while for Mathura wetland, the corresponding reference upland site was a grassland area used for animal grazing (Nag et al., 2023). In a sewage-fed wetland, the estimated carbon accumulation was 50 Mg/ha, which was 1.27 times higher than the corresponding upland site. These findings highlight the high efficiency of wetland ecosystems, particularly floodplains, in sequestering carbon in their soils and offsetting greenhouse gas emissions.

3.4 Supporting services

3.4.1 Maintaining biodiversity

Oxbow lakes play a crucial role in supporting freshwater fish biodiversity by providing essential functions such as shelter, food, breeding grounds, and nurseries (Sarkar et al., 2021a). The oxbow lakes in India exhibit high species richness, with over 90 fish species documented (Suresh and Chitranshi, 2011; Sandhya et al., 2015; Sarkar et al., 2021b). These lakes offer suitable habitats that are rich in nutrients, making them ideal feeding and breeding grounds for various small indigenous fishes found in nearby rivers. Additionally, the inundated floodplains serve as productive nursery habitats for the larval development of many freshwater fish species.

Among the fish populations in floodplain oxbow lake, Small Indigenous Fishes (SIFs) are abundant. These SIFs typically do not exceed 30 cm in size during their adult stage (Lakra et al., 2010). The complex habitat of the oxbow lake supports a diverse community of SIFs, with minnows and barbs being the dominant groups in the Ganga River basin and associated floodplains (Sarkar and Lakra, 2010). SIFs are small in size but provide a valuable source of micronutrients, vitamins, and other essential nutrients, contributing to good nutrition (Kongsbak et al., 2008). Local fishing communities often consume SIFs themselves rather than selling them in the market. In the case of Beledanga wetland, a survey identified 36 fish species, out of which 19 were SIFs (Figure 10). All these species are considered food fishes and are either consumed or sold in the fish market.

4 Discussion

As per Grooten and Almond (2018), the Living Planet Index for freshwater vertebrate populations has decreased to only one-third of its 1970 levels. One of the primary factors contributing to the loss of freshwater biodiversity is the alteration of river hydrological patterns by human activities (Nilsson et al., 2005; Ekka et al., 2020, 2022). The paper adopts an ecosystem services perspective to examine the significance of

FIGURE 9
A field observation of plants used for bioremediation in Beledanga wetlands.

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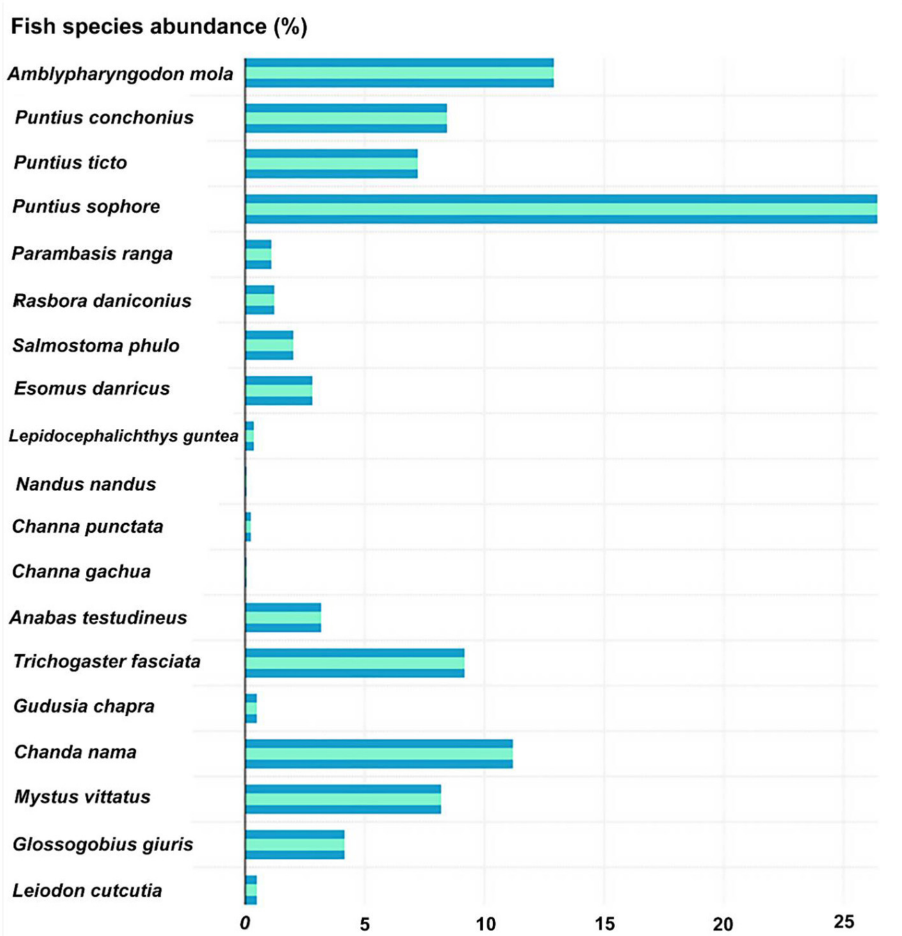

FIGURE 10
Small Indigenous fishes (SIF) recorded from Beledanga oxbow lake (Total record over all seasons) *x* axis-nos.

oxbow lakes in wetland management and to pinpoint existing gaps and challenges.

4.1 The socio-economic and cultural perspective

The Beledanga oxbow lake has been identified as essential for provisioning services, particularly in terms of fisheries and agriculture. These services play a crucial role in ensuring nutritional security and income for farmers and fishermen. In India, specifically in Assam, West Bengal, and Bihar, small-scale wetland fisheries directly support the livelihoods and nutritional security of ∼2 million people (Roy and Das, 2022). Moreover, in a rural Bengal fish is even taken twice with rice (lunch and dinner). The same type of finding has been supported by Shyam et al. (2021), in Purba Medinipur District (West Bengal) where the average monthly household consumption is 7.65 kg (with an average family size of 4). Studies have shown that fisheries contribute over 60% of household income for people dependent on oxbow lakes (Pandit et al., 2023). More than 68% of households depended on oxbow lake in West Bengal obtained animal proteins through fish caught in the beel (Pandit et al., 2023). The cultural and aesthetic value of fisheries is also widely recognized. Moreover, there is a growing demand for green spaces, and oxbow lake offers a low-maintenance solution while contributing to various ecosystem services such as water purification, biodiversity conservation, and carbon sequestration. Oxbow lake also enhances human wellbeing by providing a pleasant environment and improving overall living standards (Das et al., 2022).

Consequently, the oxbow lakes have significant implications for livelihood generation and poverty reduction, aligning with the Sustainable Development Goals (SDGs) set by the United Nations (Basu et al., 2024). The conservation and sustainable management of wetlands and fisheries are critical components of achieving various SDGs, ranging from poverty reduction to environmental sustainability and food security. Integrating these aspects into broader development strategies is essential for making progress toward sustainable development.

4.2 The ecological perspective

Wetlands, from an ecological perspective, represent dynamic and diverse ecosystems that bridge the gap between terrestrial and aquatic environments. In the present study, the value of regulating and supporting services of oxbow lake has been underestimated. Without proper quantification, there is a potential risk to the sustainability and conservation efforts (Costanza and Daly, 1992). The intricate web of trophic interactions within wetland ecosystems, involving primary producers, consumers, and decomposers, results in complex food webs. This biodiversity not only sustains the wetland ecosystem but also provides essential resources for surrounding terrestrial and aquatic environments. Therefore, it is crucial to adopt ecosystem-based approaches by constructing food web models like Ecopath. These models are based on trophic interactions among organisms, taking into account their density or biomass within the ecosystem. Ecopath models, often referred to as mass-balanced models, provide a snapshot of an ecosystem by illustrating the food web and flow of energy between different nodes (Behera et al., 2020; Christensen and Walters, 2004; Pauly et al., 2000). They also quantify the amount of matter or energy circulating within the wetland ecosystem (Deng et al., 2015). Such assessments can provide valuable information and insights that can be used by environmental managers and land use planners to make informed decisions about natural resource management, conservation, and sustainable development.

There have been only a few reported cases of oxbow lakes acting as bioremediation agents in the Gangetic plains (Sonkamble et al., 2019; Rana and Maiti, 2018a,b; Mahato et al., 2022). While some studies on bioremediation have been conducted in Indian environmental conditions, focusing on factors like geo-stability, biochemical interactions, and hydrogeological attributes of oxbow lake, there is a need for further research to replicate and standardize these processes in different oxbow lakes. Additional studies should explore phytoremediation and the interaction of microorganisms to address heavy metal contamination in municipal wastewater. This will contribute to identifying and implementing biological treatments suitable for oxbow lake and their specific conditions. Wetland ecosystems provide habitats for diverse types of microbes, including aerobic, anaerobic, anoxic, and facultative species. Understanding the composition and function of these microbial communities in Oxbow Lake is crucial for monitoring restoration efforts and wastewater treatment processes. Additionally, microbes play a vital role in the growth and functioning of plant communities and contribute to the overall sustainability of wetland ecosystems (Borgulat et al., 2022).

Other essential regulating services, such as carbon sequestration, have also received only limited attention. Oxbow lake serve as a crucial carbon sinks, playing a vital role in the global carbon balance and climate change mitigation (Salimi et al., 2021). Many studies on the importance of mangroves as carbon stocks have been documented (Bal and Banerjee, 2019; Vinod et al., 2019; ShyleshChandran et al., 2020; Vinod et al., 2018). However, Only two studies were documented in the Gangetic basin (Nag et al., 2023; Jana et al., 2020). Therefore, more studies are required to highlight the importance of carbon sequestration of the oxbow lake. Research should also focus on linking carbon sequestration with clean development mechanisms to design policy and payment for ecosystem services (Ekka et al., 2016; Villa and Bernal, 2018).

4.3 Limitations of the study

The study on the Beledanga oxbow lake provides valuable insights into the ecosystem services offered by these unique aquatic ecosystems, yet several limitations should be acknowledged. One notable limitation is the potential sampling bias due to poor road conditions that restricted access to certain areas. This might have led to the exclusion of some households or community members who could have contributed to a more comprehensive understanding of wetland dynamics. Additionally, the focus group discussions were primarily centered around fisheries and agriculture, leaving out other community members who might have provided insights into cultural and regulating services, such as water filtration and biodiversity conservation. Also, the study highlighted the contribution of biodiversity to the health of the entire ecosystem, benefiting a variety of living organisms beyond fish. However, studies documenting the specific contributions of other organisms in these ecosystems are limited. More comprehensive research could help illuminate the interconnected benefits that fish diversity provides to other species within these habitats. The study also underrepresented certain critical regulating services like soil formation and carbon sequestration, which are vital for understanding the full ecological contributions of the wetlands (Costanza et al., 1997). Furthermore, vital services such as the conservation of genetic materials were not explored, limiting the scope of the ecosystem services assessment (Millennium Ecosystem Assessment, 2005).

Another key limitation of the study is its narrow geographical focus, which restricts the generalizability of the findings to other regions or ecosystems. While the study offers in-depth insights into the socio-ecological dynamics of the Beledanga oxbow lake, its findings may not be applicable to other oxbow lakes in the Gangetic Plains or similar ecosystems elsewhere (Bennett et al., 2016). This localized focus also limits the study's potential to inform broader wetland conservation policies. The exclusion of a detailed discussion on the impacts of climate change, such as increased sedimentation and water scarcity, further reduces the relevance of the findings for long-term sustainability strategies (Adger et al., 2003; IPCC, 2014). Lastly, the scale of the analysis is limited to the local context, which, while beneficial for understanding site-specific issues, does not provide insights at the regional or national level, where multi-scalar approaches are crucial for comprehensive wetland management and policy-making (Cash et al., 2006).

4.4 Implications for river-oxbow lake connectivity in ecosystem functionality and conservation

Ecosystem service research, particularly focusing on the connectivity between rivers and oxbow lakes, has significant implications for wetland conservation and sustainable management. Maintaining the hydrological link between oxbow lakes and their rivers is critical for preserving the flow of nutrients, supporting biodiversity, and ensuring the continued provision of essential ecosystem services such as fisheries, agriculture, and water purification (Thorp et al., 2010; Gido et al., 2016). Understanding these dynamics through localized studies provides valuable data that informs tailored conservation strategies, addressing specific challenges such as water scarcity and habitat degradation.

For instance, the study identifies agriculture, fisheries, and employment generation as critical ecosystem services that are closely tied to the hydrological connection between the Beledanga oxbow lake and its river. However, challenges such as water scarcity during the summer months and the presence of macrophytes threaten the lake's connectivity and productivity. To address these issues, it is crucial to involve local stakeholders in devising water budgeting strategies and explore financial mechanisms, such as utilizing Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) funds for macrophyte removal. Ensuring that the lake remains connected to the river will enhance the flow of nutrients and support fish populations, thereby sustaining fisheries as a vital service. Monitoring systems should also be established to ensure compliance with sustainable fishing practices, and incentive programs should be implemented to encourage conservation efforts. Understanding and addressing these localized challenges is key to sustaining the broader ecosystem functionality of oxbow lakes.

From a policy perspective, recognizing the importance of river-lake connectivity can shape water management and conservation efforts. By engaging local stakeholders in decision-making processes and communicating the economic, ecological, and cultural value of maintaining these connections, policymakers can foster greater public awareness and support for wetland protection. Furthermore, integrating the monetary and non-monetary values of these ecosystems ensures that conservation efforts are holistic and sustainable, balancing short-term economic interests with long-term ecological health and community livelihoods. The involvement of local communities in managing oxbow lakes and their rivers is essential for effective, context-specific conservation that promotes resilience and sustainability.

5 Conclusion

The concept of ecosystem services plays a vital role and directly impacts the conservation of freshwater biodiversity. Urgent attention is required to conduct studies on the significance of wetland populations in managing regulatory and supportive services. It is crucial to study and practically integrate the importance of trophic structure and food web dynamics into wetland management plans. The future increase in water demand will further strain river water resources, thereby affecting floodplain oxbow lake. India faces the challenge of meeting developmental needs while ensuring the socio-ecological resilience of oxbow lake.

The study emphasizes the importance of customizing management strategies to suit the unique characteristics of each wetland. Although oxbow lake share commonalities in terms of the ecosystem services they offer, each wetland possesses distinct ecological, social, and cultural attributes. Hence, it is essential to tailor management strategies to the specific context of individual oxbow lakes to maximize their effectiveness. Collaboration among fishermen, water managers, scientists, and policy planners would facilitate a better understanding of wetland impacts and the development of adaptation and mitigation measures (Lakra and Gopalakrishnan, 2021).

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AE: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. BD: Conceptualization, Funding acquisition, Project administration, Supervision, Validation, Visualization, Writing – review & editing. AR: Investigation, Methodology, Writing – original draft. AP: Methodology, Writing – original draft, Writing – review & editing. PS: Investigation, Methodology, Writing – original draft. LL: Methodology, Writing – original draft. TC: Methodology, Writing – original draft. PP: Methodology, Project administration, Writing – original draft. PD: Methodology, Writing – original draft, Writing – review & editing. SB: Methodology, Visualization, Writing – original draft. SC: Investigation, Writing – original draft. KM: Data curation, Investigation, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffwsc.2024.1491720/full#supplementary-material

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