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RESEARCH ARTICLE

Adaptive Co-Management and Future Resilience of Coastal Winter Migratory Bag Net Fisheries in Indian Sundarbans: Ensuring Livelihood Sustainability Amidst Climate Change

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ABSTRACT

Winter Migratory Bagnet fishery (WBNF) in Indian Sundarbans contributes significantly to local food security and livelihoods, yet they are increasingly threatened by rising sea levels, declining fish stocks, and recurring cyclones. The main objective of the study is assessing its vulnerabilities and focusing on the adaptive response strategies employed by stakeholders to mitigate the challenges to sustain fisheries and fisher livelihoods. Baseline data were collected from 2019 to 2024 to assess species diversity and fishery dynamics. The findings reveal that WBNF not only provides a steady source of fish protein and income for thousands of households but also serves as a governance model for similar ecosystems, showcasing how community-based practices, traditional knowledge, and adaptive management can sustain fisheries under ecological and socio-economic pressures. Research further evaluates the vulnerability of Bagnet fisheries in response to current cyclonic events and climate change, which impacts reduced catches and also the damage to fishing crafts and gears. The Livelihood Vulnerability Score for winter bagnet fisheries in the Sundarbans ranged from 0.253 at Kalisthan to 0.402 at Fraserganj, indicating an overall high-risk situation faced by fishing communities. Several environmental and socio-economic drivers such as sea level rise, dependence on middlemen, decrease in species richness, decrease in Catch Per Unit Effort, shift in fish spawning season, changes in rainfall patterns, different adaptation strategies, and so on. influencing the sustainability of these fisheries were also identified and documented for the first time. To address these challenges, the study highlights adaptive management approaches, including stronger community participation, livelihood diversification, and institutional support.

1 | Introduction

The Sundarbans, the largest mangrove forest in the world, is located at the estuary of the River Ganga in Bangladesh and India (Sharma 2024). In India, it spans large portions of the South 24 Parganas and North 24 Parganas districts, supporting nearly 4.4 million inhabitants according to the 2011 Census of India. Despite being an ecologically sensitive and fragile zone, it is a densely populated region (Jamal et al. 2022). Among the diverse fishing practices of the Sundarbans, the offshore winter migratory bag net fishery (WBNF) stands out as a distinctive and seasonally intensive activity. This fishing practice is mainly operated during the winter season from November to January with the set bagnets locally known as *Been Jaal* or *Behundi Jaal*, which account for around 74.7% of the total catch in the area (Pillay 1960; Talwar et al. 2013; Ahsan 2015). Fish availability in bag nets is estimated to be 15–30 times higher during these coastal locations compared to the other parts and seasons (Paul et al. 1997). Favorable climatic conditions and reduced fishing operations in the sea region result in this higher abundance (Ghosh 2008). Several groups of fishermen migrate from different estuarine zones toward the sea mouth on the delta from late October to establish temporary fishing camps, locally known as *Khunties* (Dutta et al. 1973).

The higher percentage of finfish diversity in the Bag net could be due to the reduction in low bycatch and limited fishing pressure from Trawlers in the Hooghly Matlah Estuary at this time (Roshith et al. 2018; Biswas and Talwar 2018). The fisheries aspect of the aforementioned fishery has been thoroughly studied and documented by numerous researchers in the past decade (Dutta et al. 1975; Saigal et al. 1987; Mitra et al. 1997). The fishery targets dense congregations of fish and shellfish near the estuarine mouth. At the same time, most of the catch obtained during this season is sun-dried, except for the more commercially valuable species consisting of *Tenualosa ilisha*, *Polynemus paradiseus, Eleutheronema tetradactylum, Pampus argenteus*, and *Parastromateus* spp. The demand for dried fish products is enormous both domestically and internationally (Saha, Nazmun Naher, et al. 2022).

Women play a crucial yet frequently overlooked role in this fishery (Biswas and Rao 2022). In this region and other parts of Southeastern Asia, women's employment outside the home has been severely restricted; however, they are predominantly involved in the fish-drying industry, especially in winter (Pramanik 1996; Roy et al. 2017). Women's control over fish drying provides them with income that can be used for future fishing investments and to supplement family livelihood (Mazumder et al. 2018).

The degree of social and natural pressure on fishermen's livelihoods is referred to as exposure of vulnerabilities by the Intergovernmental Panel on Climate Change (IPCC) (Turner et al. 2020). The sustainability of WBNF is increasingly challenged by climate change and environmental stressors. Recurring cyclones such as Amphan, Foni, and Yaas have damaged fishing infrastructure, altered fish migration patterns, and reduced catch stability, while rising sea levels and erratic rainfall patterns threaten long-term species diversity (Islam et al. 2023). Typically, income, housing, and employment dependency are used to calculate the sensitivity index (Su et al. 2019). The possible long-term impacts of stressors are represented by exposure and sensitivity, which depend on the ability of adaptation (Thiault et al. 2018). The IPCC (2007) defines adaptive capacity as a community's ability to respond to risks and losses. Many factors, including income, access to infrastructure, skills, education, information, and management abilities, influence adaptive capability (Kais and Islam 2019; McCarthy et al. 2001). In this context, adaptive co-management has emerged as a promising governance approach, combining community participation with institutional support to enhance resilience (Marschke and Nong 2003; Olsson et al. 2004; Plummer and Armitage 2007).

WBNF in the Sundarbans holds significance far beyond its immediate context, serving both regional and global roles. Regionally, it provides a reliable source of affordable fish protein while also sustaining thousands of livelihoods through fishing, drying, and trade activities. Globally, this activity stands as a model of small-scale fisheries in mangrove ecosystems, illustrating how community-based practices, traditional knowledge, and adaptive strategies can sustain resources in the face of climate change and ecological pressures. The strong involvement of women in processing and marketing further underscores their importance in advancing gender-inclusive fisheries governance. As such, Sundarbans bag net fisheries demonstrate how small-scale fisheries can simultaneously enhance food security, preserve cultural heritage, and provide a governance model for managing vulnerable coastal ecosystems.

The present study aims to document (i) the species diversity in the winter Bag net fishery of the Indian Sundarbans, (ii) evaluate the multifaceted vulnerabilities, including environmental and socioeconomic factors, that impact winter Bag net fisheries, (iii) assess coping mechanisms and adaptive response strategies employed by stakeholders to mitigate the challenges posed by these vulnerabilities. By linking vulnerability assessment with adaptive co-management approaches, this research contributes to the sustainable management of WBNF in the climate-sensitive coastal ecosystems and offers insights applicable to similar small-scale fisheries worldwide.

While this study provides critical baseline insights about WBNF, some major limitations include: reliance on self-reporting data by fishers or camp owners, which may be biased; sometimes remote or informal camps were underrepresented; reliance on manual catch counts; middlemen-controlled markets sometimes limit transparency of price and income data; multiple interacting stressors (salinity intrusion, sedimentation, pollution), making it difficult to isolate climate change impacts from other drivers; and sensitive issues like indebtedness, women's labor roles, or income distribution are often underreported. The findings of the study are fully site-specific, and it does not represent the whole Sundarbans or other mangrove fisheries globally. These limitations highlight the need for future research focusing on long-term monitoring, broader spatial coverage, integration of participatory methods, and interdisciplinary approaches combining ecology, economics, and social parameters.

2 | Materials and Methods

2.1 | Study Area

In the present study, a survey was conducted in the lower zone of the Hooghly-Matlah estuarine system, on the western edge of the Sundarbans, primarily in Fraserganj (FRJ), Bakkhali (BAK), Kalisthan (KHS), and Lalganj (LAL) of the Namkhana Block, under the South 24 Parganas, West Bengal (Figure 1). The lower estuarine Sundarbans experiences an increase in fishing activity throughout the winter. Numerous temporary landing sites are established at two main clusters, including the Fraserganj complex, which comprises Fraserganj, Jambudwip, Bakkhali, Lothian Island, Lalganj, and Kalisthan, accounting for 92% of the WBNF catch, and the Sagar Island complex, which contributes only 8%. Due to the threat to the mangrove forests on Jambudwip and also to national security, the Government banned fishing since 2002 and evicted fishermen from this island.

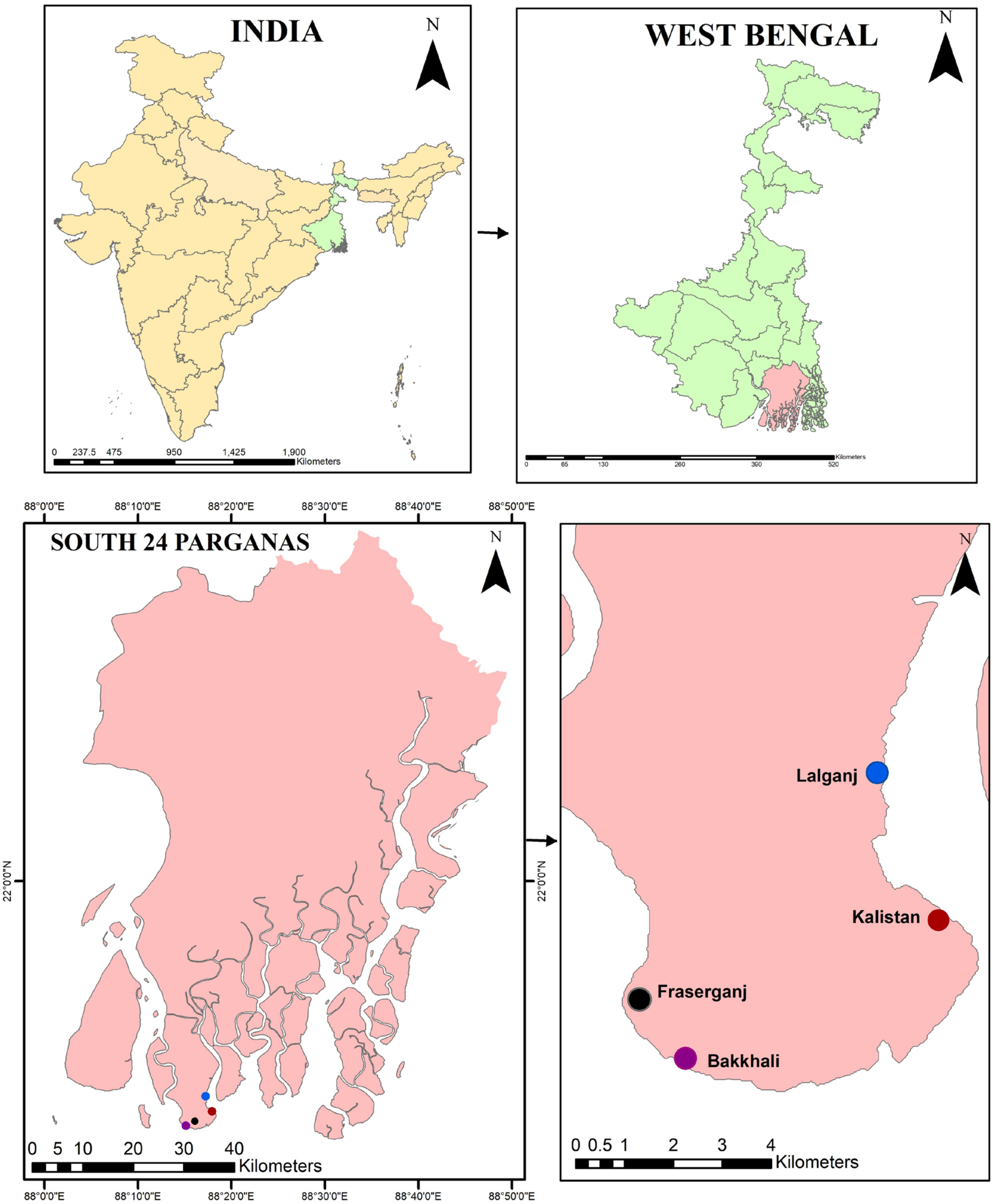

FIGURE 1 | Study area map of WBNF in Indian Sundarbans identifying Fraserganj, Bakkhali, Kalisthan, and Lalganj.

2.2 | Collection of Data

The study was conducted from 2019 to 2024, spanning a period of 5 years, and lasted 7–10 days each month, from the waxing gibbous to the full moon, from November to February in each study area. The WBNF specifically operated between the 11th or 12th day of the waxing lunar cycle in Autumn (November) and the 5th or 6th day of the waxing lunar cycle in Spring (February). The timeframe for the study was selected based on traditional fishing practices and ecological considerations. The data were collected from secondary and primary sources (Figure 2). The primary data encompass various aspects of river fisheries, while the secondary data comprise production, essential river and fisheries information, and climatic variables (temperature and rainfall) prior to 2019. Every year, approximately 235 fishing camps, including small, medium, and large camps, are established in these four landing sites. The camps' transactions above 1 crore are generally classified as large camps, transactions over 60 lakhs are known as medium camps, and below 60 lakhs are small camps. In this study, primary data were collected through interviews with 30 fishing camp owners (8 large camps, 10 medium camps, and 12 small camps), 80 fishers, 120 post-harvest workers, and 12 traders of dry and fresh fish. The camps were selected randomly depending on their size and transaction amount. Two large camps from each study area, three medium-sized camps from each Fraserganj and Lalganj, two medium

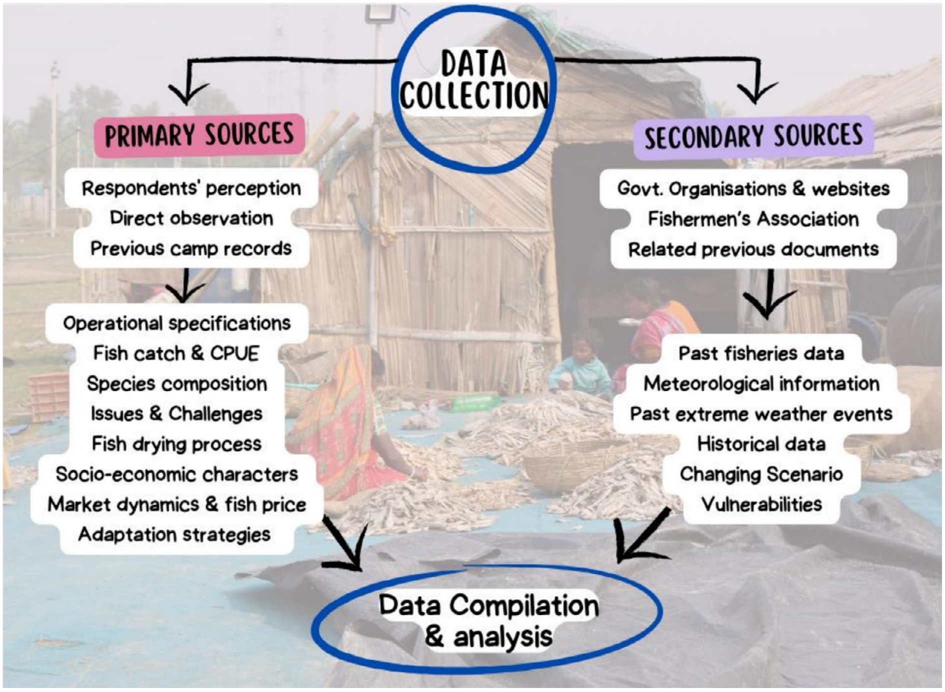

FIGURE 2 | Data collection procedure and key information about socio-economic condition, fisheries, and ecological condition.

camps from each Bakkhali and Kalisthan, and three small camps from each study area were selected for data collection. The specifications of camps, numbers of gears, along with manpower details of the camps were collected from camp owners. ANOVA was then applied to determine the differences among the camps. Fishers were selected using purposive sampling method (20 from each study area) to ensure participants had at least 15–20 years of experience in bag net fisheries. Traders are selected (three from each study area) based on their long-term experiences and local as well as export market linkage in the fisheries sector. Traders also give information about fish pricing, market dynamics, and demand for the species. Male and female post-harvest workers were selected (10 males and 20 females from each study area) for detailed data. The gender-related data were also collected from the interviewed womenfolk. Fishers also provide their perspectives on climate change, variability, and its impacts on species diversity, production, and fishing patterns. The secondary information was collected from available research articles, documents, and records of local authorities. The climate change and weather data were collected from the Indian Meteorological Department (IMD).

Semi-structured personal interviews (SSIs) and focused group discussions (FGDs), these two group-based and individual techniques of the participatory rural appraisal (PRA), were used for data collection. The questions asked in the SSIs surveyed the following themes: insights into fishing activities, species composition, socio-economic conditions, their learning from past experiences, how this knowledge had helped them cope and adapt, and factors that influenced them to translate their knowledge into action. Six FGDs aimed to document the collective views of fishing camp owners, fishers, and workers regarding their understanding of the evolving patterns of market dynamics, coping strategies, and learning processes. Each focus group discussion (FGD) lasted 50–60 min and consisted of 8–10 participants. Ten key informant interviews (KIIs) were organized with local organizations for community welfare. Each interview continued from 30 to 45 min and explored the following questions: lessons had been learned from past natural disasters, institutional changes and the main focus of the learning. The direct observation catch data and species diversity data were gathered from different WBNF campsites and fish landing centers.

2.3 | Fisheries Data Analysis

To assess ichthyofaunal diversity, fish samples were collected from the main channel of the river during both new moon and full moon phases of the lunar cycle, periods known for higher species availability. Specimens were either identified on-site or preserved in 7% formalin and transported to the laboratory for detailed examination. Taxonomic identification was performed using morphometric and meristic characters, following the guidelines provided by Talwar and Jhingran (1991). For updated taxonomic nomenclature and classification, Eschmeyer's Catalog of Fishes (2020) was consulted, while the global conservation status of the recorded species was determined using the IUCN Red List (2025). For crabs, the identification was done following Ng et al. (2008) while for cephalopods and crustaceans, the identification manual of FAO Carpenter and Niem (1998) was employed. Paleontological Statistics (PAST) version 3.0 was used for evaluating the Hierarchical Cluster Analysis. For species composition assessment and catch estimation, we examined random samples from fishing camp catches using the formula by Saigal et al. (1987). The monthly total catch of each landing center is estimated by using the formula:

$$\hat{Y} = \frac{N}{n} \sum_{j} \sum_{i-1}^{n} Y_{ij}$$

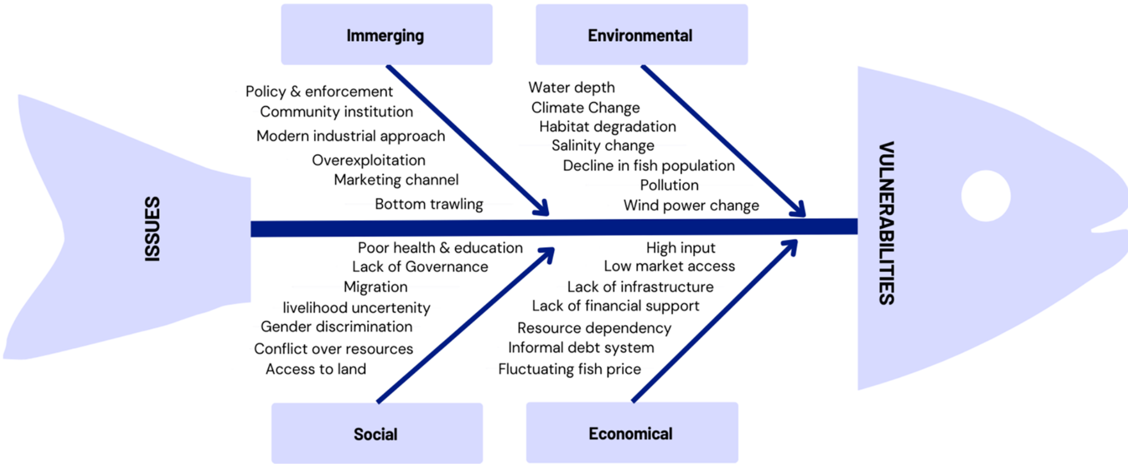

FIGURE 3 | Issues and vulnerabilities of WBNF in Indian Sundarbans.

where Y_{ij} is the total catch on the ith day of the jth fishing camp; N represents the number of fishing days in a month; n represents the number of sampling days selected.

The average CPUE of a landing center is estimated as,

$$\text{CPUE} = \frac{\widehat{Y}}{\widehat{X}}$$

The percentage group of fish is estimated as per Benitez et al. (2022).

$$\text{Percentage of group} = \frac{\text{Weight of individual fish group}}{\text{Total catch}} \times 100$$

2.4 | Livelihood Vulnerability Index (LVI)-IPCC Assessment

According to the 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007), vulnerability is the function of exposure (E), adaptive capacity (A), and sensitivity (S). The different domains of stressors or exposure in WBNF can be categorized into four main areas: environmental, economic, social, and emerging issues, which are the primary factors contributing to vulnerability (Figure 3).

Vulnerability is assessed using the driver-filtered approach, based on the fishermen's perceptions and the availability of previous data. The associated indicator is given a positive monotonic link if the value increases, indicating greater vulnerability. If not, the indicator is given a negative connection. Natural capital, financial capital, human capital, physical capital, and social capital are the five categories into which fishermen's adaptive capacity can be separated according to their means of subsistence (Chen et al. 2020). The Socio-Demographic Profile, Social Networks, Livelihood Strategies, Food, Water, Health, Natural Disasters, and Climate Variability are the seven main parts of the LVI. Each of these elements comprises several sub-components. There are two methods used in the LVI method: (1) computing LVI as a composite index of principal components and (2) presenting the IPCC's primary component (Sutanto et al. 2022). The LVI formula is a modification of the Human Development Index's formula, which is the ratio of the difference between the specified maximum and minimum value range and actual life value (UNDP 2007).

$$index_{Sd} = \frac{S_d - S_{min}}{S_{max} - S_{min}}$$

where Index S_d is the actual sub-component for d area, and S_{min} and S_{max} indicate the minimum and maximum values of each sub-component from all study areas. After that, the value of major components is calculated by the average of sub-components.

$$M_d = \frac{\sum_{i=1}^{n} index_{Sdi}}{n}$$

M_d represents the major components for d area (Socio-Demographic Profile [SDP], Livelihood Strategies [LS], Health [H], Social Networks [SN], Water [W], Food [F], and Natural Disasters and Climate Variability [NDCV]), $index_{sdi}$ denotes the sub-components, which are indexed by i, that make up every major component, and n denotes the total number of sub-components in each major component.

Once the values of each major component for each study area were calculated, they were averaged to obtain the LVI of each area.

$$LVI_d = \frac{\sum_{i=1}^{7} W_{M_i} M_{di}}{n \sum_{i=1}^{7} W_{M_i}}$$

where LVI_d, the LVI for area d, weighted average of seven major components. W_{Mi}, the weights of every major component, are determined by the number of total sub-components that make up individual major components and are included to ensure that all sub-components contribute equally to the overall LVI

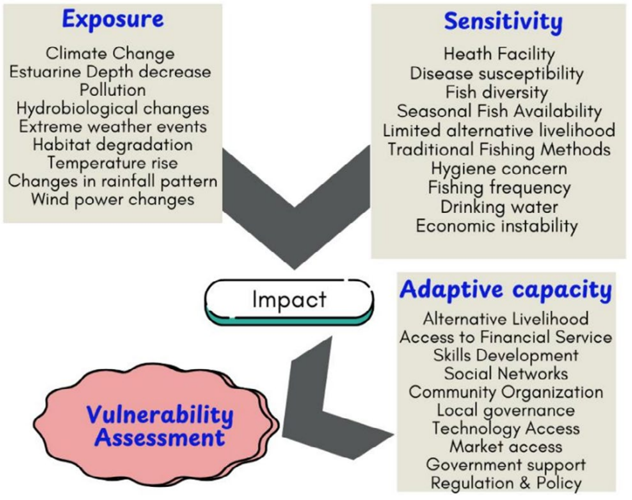

FIGURE 4 | WBNF vulnerability index assessment framework.

(Sullivan et al. 2002). In the present study, LVI is ranged from 0 (least vulnerable) to 0.5 (most vulnerable).

A technique for determining the Livelihood Vulnerability Index, as incorporated in the IPCC, is employed in the present study (Hahn et al. 2009). In this method, Natural Disasters and Climate Variability are calculated for exposure. The Health, Food, and Water statuses of fishers measure sensitivity. Socio-demographic profile, Livelihood Strategies, and Social Networks determine adaptive capacity. The indicators of exposure, sensitivity, and adaptive capacity, along with their relationship to vulnerability, are described in Figure 4. According to the IPCC (2007), sensitivity refers to the degree to which a system is positively or negatively affected by exposure.

In this method, instead of combining all the major components of LVI, all indexes are categorically merged using the formula:

$$CF_d = \frac{\sum_{i=1}^{n} W_{M_i} M_{di}}{n \sum_{i=1}^{n} W_{M_i}}$$

where CF_d is a contributing factor (exposure, sensitivity, or adaptive capacity) for area d as defined by the IPCC, M_{di} are the major components of area d indexed by i, W_{Mi} denote the weight of every major component, and n denote major components number for each contributing factor. Following formula used combining three contributing factors, exposure, sensitivity, and adaptive capacity:

$$LVI - IPCC_d = (e_d - a_d) * S_d$$

where $LVI–IPCC_d$ is the LVI for study area d expressed by using IPCC framework, e denotes the calculated exposure score for area d, a is the calculated adaptive capacity score for area d, and s is the calculated sensitivity score for area d. In this study LVI–IPCC scaled from −1 (least vulnerable) to 1 (most vulnerable).

2.5 | Community Learning Experience for Adaptive Strategies

The experiences of community members impacted by management techniques may be reflected in the fisheries' governance system (Hamelin et al. 2024). Strengthening sustainable fishing practices by enhancing community participation in collaboration with local governments, NGOs, policymakers, and research organizations is an important aspect. The community learning approach is described in Figure 5.

All data analysis, graphical depiction, and modeling in this paper were performed using Microsoft Excel 2013, PAST 4.22, OriginPro 2025, SPSS 22, and Canva software.

3 | Results

3.1 | Operational Details

In the early 1960s, fishermen from the Chittagong and Noakhali areas of Bangladesh, utilizing their traditional skills and aptitude, established WBNF. They chose this area because of its proximity to the fishing grounds, the presence of a natural creek for harboring their boats, and the availability of drinking water. These people started to settle down near the Ganga River basin, that is, Kakdwip, Namkhana, or even Triveni in Hooghly, West Bengal, so that they can easily fish in the river throughout the year and migrate to the coastal area in winter for bagnet fishing. The local fishermen of these areas also started to learn the techniques within a certain time. However, local fishers of the coastal areas have also recently become involved in these fishing activities. The bag net is made of high-density polyethylene (HDPE) and is typically conical in shape, with a wide mouth tapering into a cod-end, the narrow portion of the nets where fish are collected. The cod-end mesh size ranges from 12 mm in larger nets to as low as 6 mm in smaller nets (Ramesan et al. 2009). The overall size of a bag net is usually determined by the number of meshes at the mouth opening, with small, medium, and large nets comprising approximately 800–1000, above 1000, and around 1200 mesh counts, respectively. The size of the

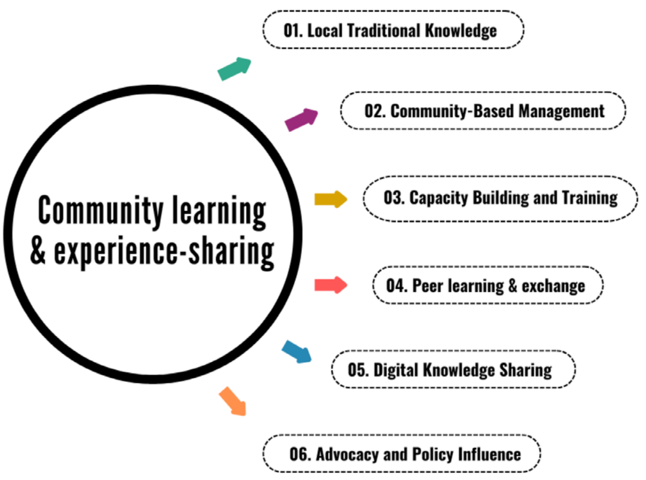

FIGURE 5 | Community learning and lesson-sharing approaches for small-scale fisheries sustainability.

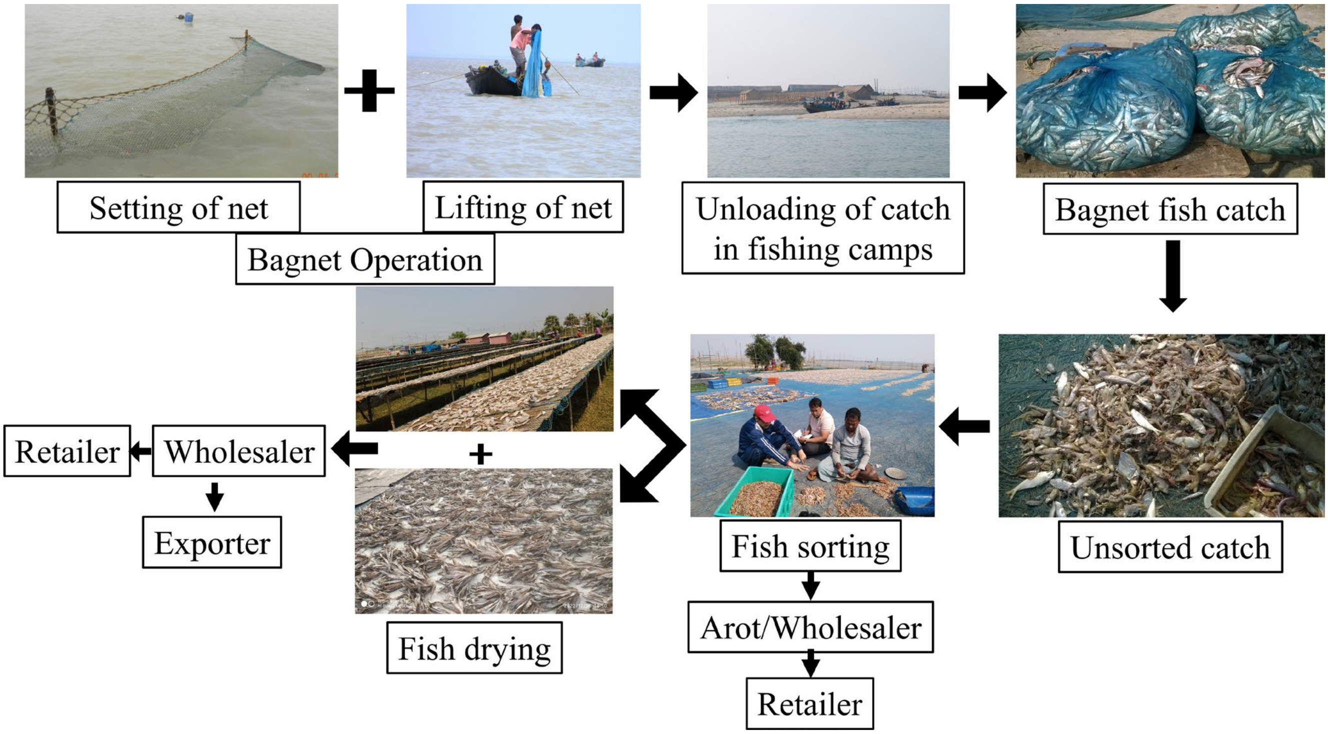

FIGURE 6 | Process of WBNF operation from Bagnet setting to final marketing.

bag net largely determines the volume of catch obtained per fishing trial. The WBNF targets a mixed assemblage of finfish and shellfish, but studies consistently flag high juvenile bycatch due to small mesh size (Rashed-Un-Nabi and Ullah 2012). Although fisheries regulations in India recommend a minimum mesh size of 37 mm in marine waters to reduce juvenile capture, enforcement in the Sundarbans remains weak, thereby undermining sustainable management of the fishery. Consequently, the indiscriminate use of small-meshed bag nets in estuarine areas has had severe impacts on fish stocks by capturing juveniles (fry and fingerlings) that inhabit these regions (Islam et al. 2015; Krishnan 2017; Remesan 2019).

In winter, the tranquil weather in the lower estuary's extreme stretches by the sea provides the ideal conditions for operating stationary bag nets. At this time, the north wind creates favorable conditions for fish abundance, and this condition persists until the onset of the south wind, which causes rough seas and makes the operation of these nets difficult. In recent years, repeated cyclonic events disrupted the seasonal cycle of the bagnet fisheries. Rising cyclone frequency, shifting wind patterns, unpredictable rainfall, and other weather events shorten the fishing periods and reduce catch stability. Damage to fishing gear and camps, resulting in economic losses for fishermen, is a frequent consequence of extreme events. These changes highlight how climate variability directly affects the operational feasibility and long-term sustainability of winter bag net fisheries in the Sundarbans.

Bagnets generally operate from 8 to 30 nautical miles from shore at depths of 20 m, where the water current is strong enough to set the net (Krishnan and Talwar 2021). The fishers at FRJ, KHS, and LAL operate bagnets in estuarine coastal waters approximately 12–15 km away from the mouth where deeper waters and stronger tidal currents facilitate the availability of pelagic and migratory species. The species diversity in this region was significantly greater than that of the BAK fishers who operate bagnets near the estuarine mouth (within 10 km from shore) due to the predominance of marine juvenile species. These environmental and operational variations explain the observed differences in species diversity, with offshore operations targeting more migratory and larger fish, while nearshore operations yield higher proportions of estuarine and juvenile species. A complete bagnets fishing operation usually takes place within the duration of one full tide (approximately 6 h). The fishing trips were conducted using large motorized trawlers, while smaller boats fitted with outboard motors, locally known as "Chot boats," were used to transport the catch to shore (Krishnan and Talwar 2021). The entire process of WBNF in the Sundarbans is described in Figure 6. The fishing operation contributes to a significant number of community livelihoods, not only for fishermen but also for the laborers engaged in post-harvest work on land. In this area, approximately 2000 daily post-harvest workers are employed, of whom nearly 70%–80% are women. The findings indicated significant differences ($p < 0.05$) through one-way ANOVA between the three different parameters (large, medium, and small camps) in terms of the number of boats and bagnets in operation. The number of fishers and laborers in the camps is directly proportional to the size of the camps (Table 1).

3.2 | Fisheries Details

The number of fish species captured varies greatly depending upon the fishing intensity and prevalent hydrometeorological conditions; a total of 65 species of finfish belonging to 25 families and 13 orders were recorded during 2019–2024 in the WBNF catches. Among these, the Engraulidae family (*Setipinna* spp.)

contributed the maximum abundance in WBNF. Hierarchical clustering of fish species abundance, based on family taxonomic profiles, resulted in the clustering of samples by fish sampling sites (Figure 7). The color scale reflects availability values, that is, −1.5 to +1.5. BAK and KHS appear to cluster together, indicating similar species compositions, whereas the species composition of FRJ and LAL is slightly different from that of BAK and KHS. The hierarchical clustering of finfish species based on taxonomic profiles at the family level across four sampling locations BAK, FRJ, LAL, and KHS used Bray–Curtis similarity and UPGMA linkage. The leftmost cluster groups species families with greater abundance in BAK, reflecting the distinct community structure of this site. BAK's stronger marine influence, high tidal action, and relatively open habitat may favor pelagic and semi-demersal taxa from families such as Engraulidae and Trichiuridae. The low similarity index (40%–50%) between BAK and the other sites supports this ecological distinctiveness. The central cluster, which includes families more dominant in FRJ and LAL (highlighted in red), indicates a moderately high similarity (70%–80%) between these two sites. This could be attributed to shared environmental characteristics, moderate salinity regimes, productive estuarine creeks, and soft-bottom

TABLE 1 | Specification of three different fishing clusters and their associated workforce.

Size of camp	No. of boat, Avg ± SD (range)	No. of bagnet, Avg ± SD (range)	Head fisher	Fishing labor, Avg ± SD (range)	Post-harvest labor, Avg ± SD (range)
Large	$7^{b,c} \pm 0.75$ (6–8)	$26.27^{b,c} \pm 1.65$ (25–30)	2	21.81 ± 1.99 (20–25)	14.27 ± 1.13 (13–16)
Medium	$4.4^{a,c} \pm 0.48$ (4–5)	$18.4^{a,c} \pm 1.49$ (16–20)	1	17.5 ± 1.68 (15–18)	8.8 ± 2.89 (8–10)
Small	$2.5^{a,b} \pm 0.5$ (2–3)	$9.5^{a,b} \pm 1.44$ (8–12)	1	10.58 ± 2.09 (8–14)	5.5 ± 0.5 (5–6)

Note: Superscript (a, b, c) indicates the significant difference ($p < 0.05$) between columns.

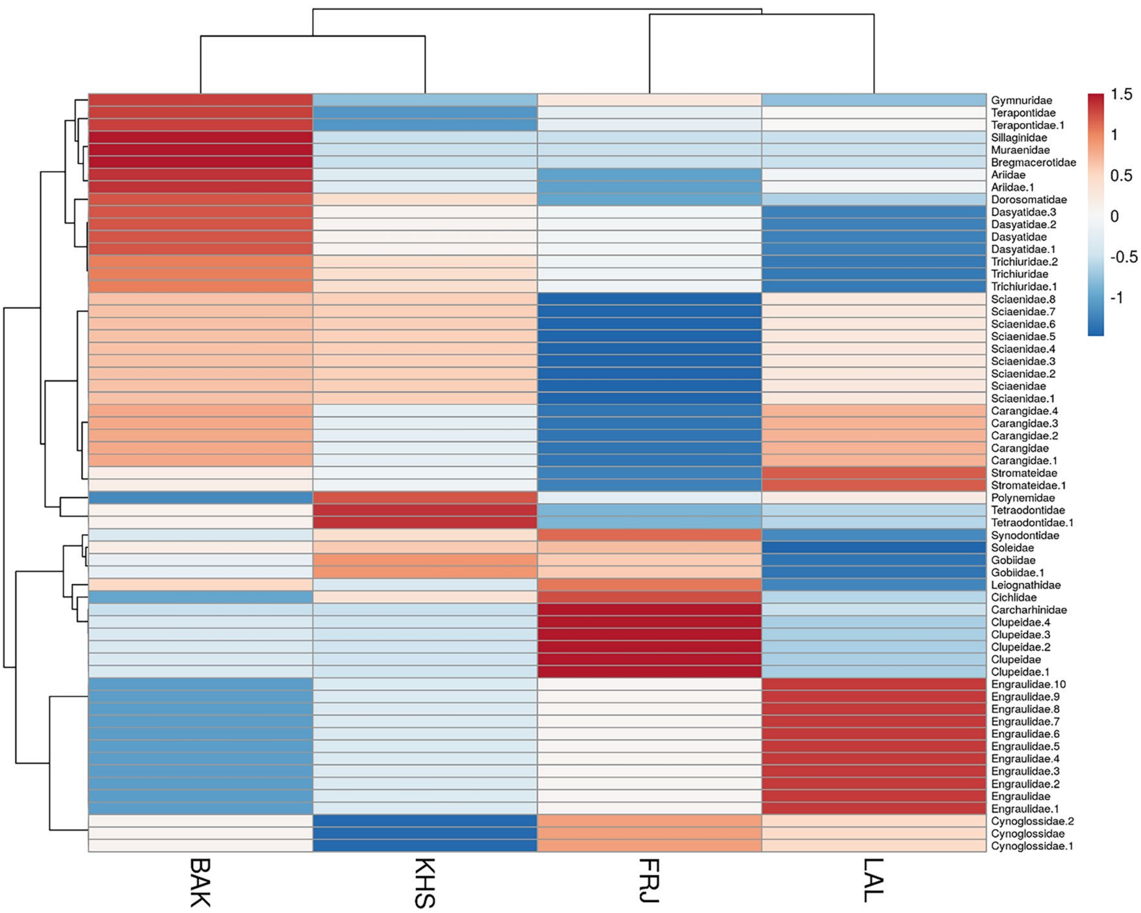

FIGURE 7 | Hierarchical clustering of fin fish species availability using taxonomic profiles at the family level. [Leftmost cluster contains species more abundant in BAK. The middle cluster has species with higher abundance in FRJ and LAL (red) but lower in BAK and KHS (blue)].

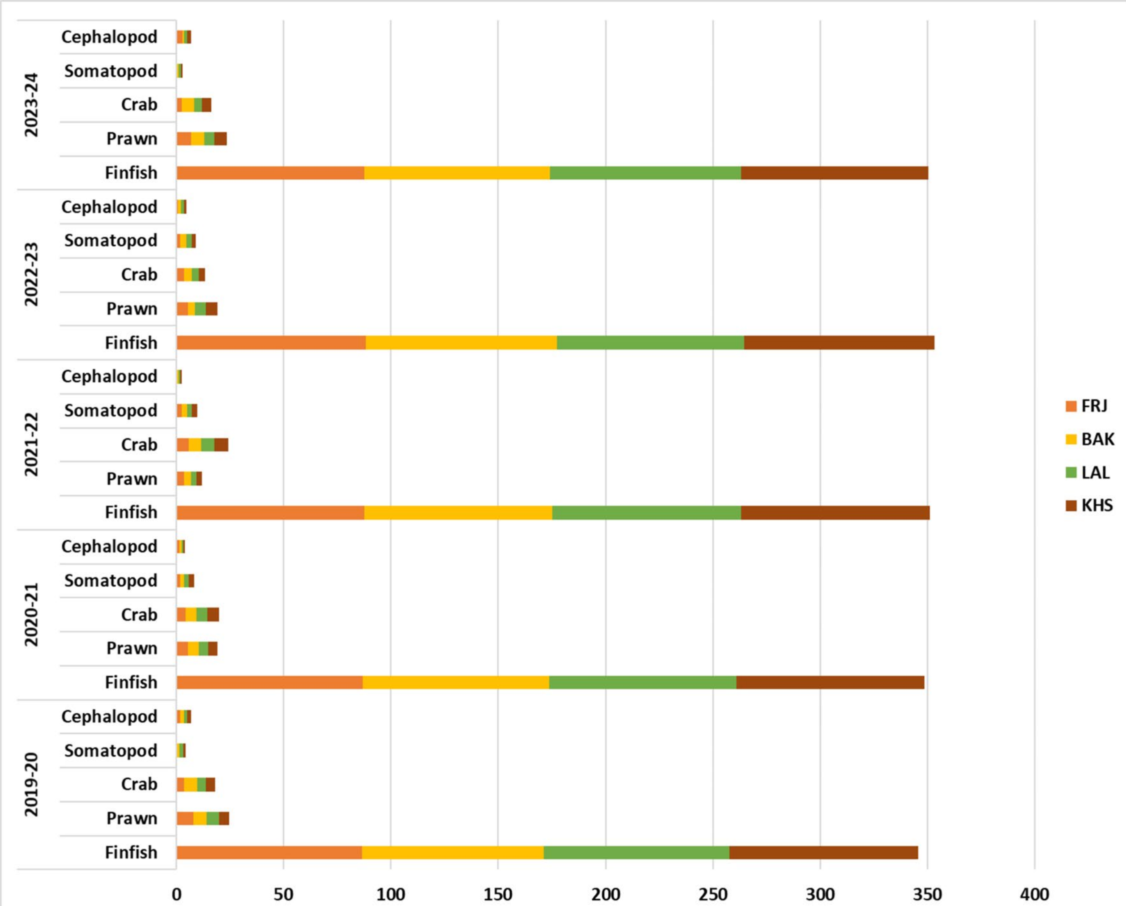

FIGURE 8 | Percentage contributions of various catch components in Bag net landings.

habitats favorable for species from Clupeidae (*Setipinna taty*, *Coilia dussumieri*), Synodontidae, and Sciaenidae. These locations show consistent catch composition, as supported by field data from 2023 to 2024, which recorded over 87% finfish contributions dominated by these taxa. In contrast, species in KHS clustered more distantly from FRJ and LAL, indicating lower similarity (below 60%) and suggesting unique assemblages possibly affected by greater anthropogenic influence, pollution, and salinity intrusion due to upstream freshwater limitations. Lower fish diversity and altered community structures at KHS may also be compounded by sedimentation and canal-based effluent inputs. Dendrogram linkage distances further validate these differences, separating BAK and KHS from the FRJ–LAL, indicating greater dissimilarity. These statistical distinctions suggest that fish community composition is not homogeneous but spatially structured. Similar results were also confronted in the Meghna Estuary, Bangladesh, that environmental factors like salinity, temperature, and so on, play a direct role in fish assemblage structure (Shaha et al. 2022). The other catch components include 12 species of prawns, five species of crabs, cephalopods (mainly comprising juvenile *Sepiella inermis*, *Sepia aculeata*, and *Loligo duvauceli*), and stomatopods (*Harpiosquilla* spp. and *Squilla* spp.). However, the lucrative hilsa shad (*Tenualosa ilisha*) is generally not targeted by WBNF operations; only stray individuals of *T. ilisha* were often encountered in bag net catches in the winter.

Analysis of the WBNF during the study period revealed that the maximum finfish catch was obtained from the site LAL landing center (approximately 89.31%) during 2023–2024, followed by FRJ at approximately 87.45%. Prawns accounted for roughly 3.16% to 7.84% of the total landings in the year (Figure 8). In 2023–2024, finfish contributed significantly to the total catch across all sites, with the highest proportions observed at LAL (89.31%) and FRJ (87.45%). Shrimp contributed between 3.16% and 7.84%, with the highest share at BAK. These trends remained relatively consistent over the study period, although minor fluctuations were observed, particularly following cyclonic events. Although the percentage contribution of major catch components was similar in all landing centers, the species catch composition was distinctly different for different stations because of the variations in the area of operation of bagnets (Table 2). In 2023–2024, finfish contributed significantly to the total catch across all sites, with the highest proportions observed at LAL (89.31%) and FRJ (87.45%). These trends remained relatively consistent over the study period, although minor fluctuations were observed, particularly following cyclonic events. Shrimp contributed between 3.16% and 7.84%, with the highest share at BAK. At the FRJ and LAL camp, the catches were dominated by *Setipinna taty*, which contributed 38.16% and 44.60%, respectively, of the total fish catch. Whereas at BAK camp, species like *Coilia dussumieri* contributed 35.94% of the total catch and KHS contributed equal catch of *Coilia dussumieri* and *Setipinna taty* (23.09%).

3.3 | Economic Details

The expenditures of WBNF are mainly divided into some broad aspects such as camp establishment cost near the landing center, crafts and gears maintenance cost, fuel cost for boats, ice cost for the preservation of fish, feeding costs of the laborers, daily labor wages, 4-month contracted fishers cost, fish handling, drying, and processing costs (Figure 9). The maximum amount spent on establishing camps and labor wages in the WBNF expenditure. Large camp owners spend around 25–40 lakhs for initial establishment, whereas small camps cost around 2–5 lakhs (2400–5800 USD), substantially higher than many other artisanal fishing operations. The salaries of head fishers, other fishers, and land workers are mainly fixed for a 4-month fishing period, and their charge for one season (4 months) varies between Rs. 0.75 lakhs (870 USD) and 3 lakhs (3500 USD), depending on the size of the camps. The salaries of other land workers and fishers are also on a contract basis for 4 months, depending on their workload. The number of daily laborers fluctuates depending on the availability of fish. Daily laborers' wages vary from Rs. 350 to 450 (4 to 5 USD) per day.

TABLE 2 | Average Species abundance in different landing sites during 2019–2024.

Species	FRJ	BAK	LAL	KHS
Anodontostoma chacunda	0.01	3.62	1.1	0.54
Cynoglossus arel	—	2.56	0.5	0.13
Coilia dussumieri	1.25	33.63	3.7	23.09
Eupleurogrammus muticus	1.05	2.58	0.8	0.26
Harpadon nehereus	15.15	5.68	6	11.06
Johnius aneus	0.2	4.1	0.4	0.05
Johnius carouna	—	3.12	0.1	1.01
Lepturacanthus savala	5.54	11.75	0.4	10.92
Otolithoides pama	1.15	2.7	1.5	0.95
Scoliodon laticaudus	0.87	—	0.4	0
Setipinna taty	38.16	14.27	44.4	23.09
Sardinella gibbosa	17.62	0.59	6	1.9
Deveximentum insidiator	13.05	2.17	25	6
Trichiurus lepturus	2.81	1.01	3	12
Others	3.14	12.3	6.7	9

Economically, WBNF plays a vital role in sustaining local livelihoods by directly employs over 4000 seasonal workers across the study areas. In addition to these workers, fishing laborers, as well as local fresh fish and dry fish retailers, derive significant benefits from the WBNF. Several allied livelihoods, including ice factories, grocery shops, and temporary supply outlets, also sustain their businesses through the economic activities generated by this fishery. Although disaggregated GDP contribution data specific to WBNF are not officially reported, estimates suggest that the Sundarbans fisheries sector contributes around 15%–20% to the district-level fisheries GDP in South 24 Parganas, West Bengal and within this, bagnets constitute one of the largest seasonal contributors due to the high volume of dry fish production for regional and national markets. Importantly, WBNF also supports regional food security by supplying affordable dried fish, which forms a staple protein source for marginalized rural households.

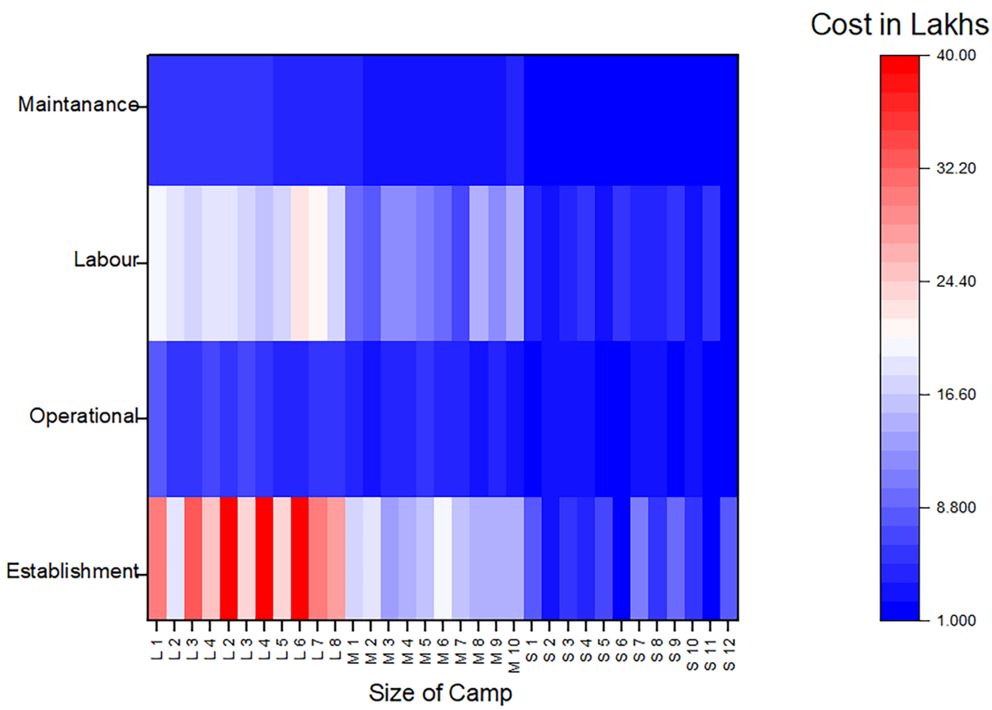

FIGURE 9 | Expenditure for WBNF in different sizes of camps (S: small, M: medium, L: large camps).

The profit of the camp owners fluctuates based on fish catch and market prices (mainly dry fish). Middlemen also influence the net profit and loss of these camp owners. Long hairfin anchovy (*Setipinna taty*), locally known as *laal pata*, provides the maximum benefit in the dry fish market (price around Rs. 180–220 per kg), but depending on the market price, species like Bombay duck (*Harpadon nehereus*) and hairfin gangetic anchovy (*Setipinna phasa*) fetch high costs around Rs. 300–450 and Rs. 800–1000 per kg accordingly. The market price of the fish reflects average ranges over the study period, though inter-annual variability was observed depending on catch volume and demand. The net profit of the camp owners varies between 35% and 65% of the total investment depending on a particular year and landing center (Figure 10). It is observed that in the year 2020–2021, there is a sudden decrease in the profit percentage. According to the fishermen's perception, this may be due to the COVID-19 pandemic and multiple cyclones, such as Amphan and Yaas, disrupting the WBNF during this year. However, overall, there is a significant decrease in profit percentage in all landing sites. The highest profit was observed at LAL during 2021–2022 (approximately 68%).

Intermediaries or middlemen play a pivotal role in the marketing chain of WBNF products, particularly dried fish. These middlemen manage all logistics, transportation, and storage to ensure steady supply chains and typically advance credit to camp owners, allowing them to continue fishing operations. In return, camp owners are often bound to sell their produce through these middlemen. This system benefits camp owners by providing immediate liquidity and access to established marketing networks but simultaneously reduces their bargaining power and share of profit. In years of low catch or low market demand, the dependency on intermediaries can lead to debt accumulation, locking camp owners into a cycle of financial vulnerability. Thus, while intermediaries facilitate market access, their dominance in price setting and profit distribution significantly affects the overall economic sustainability of the WBNF supply chain, with camp owners often receiving reduced returns compared to the value generated in downstream markets.

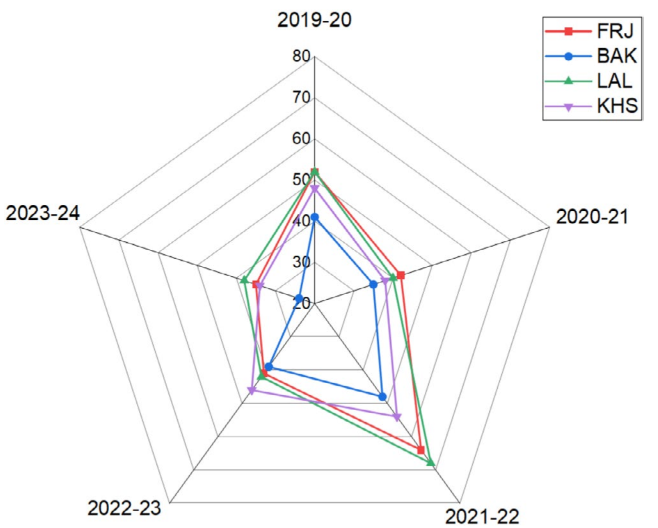

FIGURE 10 | Profit percentage of all four landing centers from 2019 to 2024.

3.4 | Marketing Channel

WBNF relies on a marketing channel network to connect fishers with customers, processors, and exporters. In this network, fishers are the primary producers, and they can connect with the wholesale, retail, and export markets via different middlemen or agents. Profit distribution across the chain reflects the dominance of middlemen. Camp owners receive the lowest margin, with net profits often reduced by 5%–10% due to intermediary commissions. Wholesalers typically add a further 15%–20% mark-up before distributing to regional retailers. Retailers, especially in export-linked hubs, earn the highest profit share, with margins ranging from 25% to 35% depending on species and quality. This price structure highlights the unequal distribution of economic benefits, while middlemen and exporters capture significant margins, and camp owners remain economically vulnerable despite shouldering the initial investment and production risks. Thus, the marketing chain is efficient in terms of volume distribution but inequitable in profit-sharing, reinforcing the dependency of producers on intermediaries. For instance, during the COVID-19 pandemic and other cyclonic storms in 2020 (Amphan), 2021 (Yash), disruptions in transportation, storage, and market demand caused sharp declines in profitability, despite sustained production costs. These types of external shocks cascade through the marketing chain, amplifying economic risks for fishers while intermediaries remain comparatively secure. Climate-induced damage to dried fish supply chains is a critical revenue source for WBNF disruptions documented in Bangladesh's Satkhira region, where cyclones destroyed 60% of drying infrastructure (Hossain et al. 2022). Transportation delays and spoilage correlate with findings from Vietnam, where flood-damaged roads increased post-harvest losses by 25% (Tran et al. 2024). The collapse of jetties and cold storage in FRJ reflects systemic underinvestment in climate-resilient infrastructure, a gap highlighted in India's National Fisheries Policy (Rajeev and Bhandarkar 2022). Decentralized solar-powered drying units (e.g., piloted in Tamil Nadu) could mitigate reliance on weather-dependent sun-drying.

Some of the high-priced species, that is, *Tenualosa ilisha*, *Polynemus paradiseus*, *Coilia dussumeiri*, *Eleutheronema tetradactylum*, *Pampus argentius*, *Harpadon nehereus*, *Etroplus suratensis, Johnius gangeticus, Sardinella longiceps*, large Prawn, large Crabs, Squid, and so on, are freshly transferred to wholesale and retail local markets for fetching a better price. The other catches from the bag net are traditionally sun-dried. Anchovy, Ribbon, sole, and croaker fish are used mainly for fish drying. Bycatch is not waste in this WBNF; they are used to make fish meal. Based on interviews and market assessments (2019–2024), approximately 60%–65% of the dried fish produced is supplied to different north-eastern states of India, such as Assam, Meghalaya, and Tripura, as well as 10%–15% of dried fish exported to SAARC countries like Bangladesh and Nepal, via middlemen, while the remaining 20%–30% is sold in local markets in West Bengal. In this fisheries sector, a significant profit share is coming from valuable dried fish for human consumption, which is 82.57%, followed by fish meal 11.49% and fresh finfish and shell fish selling (5.47% and 0.47%, respectively) (Sruthy et al. 2020). The fish meal is sold to districts such as Midnapore, Bardhaman, and even other states like Andhra Pradesh after drying.

3.5 | Gender Perception in WBNF

A good number of women from the local fishing community are actively engaged in various post-harvest fishing activities in the WBNF. While men take on the primary roles of fishing and harvesting, women contribute substantially to post-harvest time (Table 3). In large and medium-sized fishing camps, approximately 10–15 women are employed in post-harvest activities, whereas in smaller camps, the number ranges from 8 to 10. Across the four study sites, an estimated 1400–1600 women are seasonally employed in post-harvest activities, representing nearly 70%–80% of the total post-harvest workforce. These women, aged between 25 and 65 years, predominantly hail from nearby areas, including Fraserganj, Bakkhali, and Haripur. Most of these women are hired on a daily wage basis, earning approximately Rs. 350 (4$) per day for an 8–10 h work shift. Whereas in the case of males, the daily wages vary from Rs. 400 to 500 (4.5 to 5.5 $) per day. Beyond their camp duties, many of these women further support their household economy by selling small fish in local markets. Their contributions not only sustain the industry but also empower them as essential stakeholders in the region's fishing trade.

The post-harvest losses due to climatic events constantly threaten the dried fish trade, a sector supporting 40% of FRJ's women workers. The findings of this study underscore the disproportionate impact of climate change on women engaged in post-harvest fisheries activities in West Bengal. The heightened vulnerability of women fish workers during cyclones and floods aligns with existing literature on gender-differentiated climate risks in small-scale fisheries (Koomson 2021). Specifically, the flooding of drying yards, contamination of fish stocks, and destruction of temporary shelters following Cyclones Amphan (2020) and Yaas (2021) exacerbated economic precarity, as women—who dominate fish drying and local market sales—faced immediate income losses. The disruption of post-harvest activities due to extreme weather events not only reduces daily earnings but also deepens household economic insecurity, particularly for female-headed households (Chaudhary et al. 2025). Furthermore, damage to rural transport infrastructure limits women's access to markets, marginalizing their participation in trade and fisheries governance—a pattern observed across Global South small-scale fisheries (Auld 2021).

TABLE 3 | Role of gender in post-harvest fisheries in WBNF.

Post-harvest activities	Men	Women
Fish washing	+++	+
Fish sorting	+	+++
Fish cleaning	+	+++
Fish grading	+	+++
Fish drying	+	+++
Dry fish sorting	++	++
Packing	++	++
Selling	+++	+

Note: + to +++ denotes low to high participation.

Across the study sites, women consistently reported limited involvement in decision-making related to camp operations, marketing, or financial matters, along with their earnings often regulated by male household members. Traditional gender norms in the Sundarbans fishing communities restrict women's participation in public decision-making, confining their recognized contributions to domestic work and post-harvest activities. Economically, wage disparities and dependence on male-dominated networks of intermediaries further weaken women's bargaining power. Social expectations, along with the absence of formal representation in cooperatives or fishery committees, reinforce their marginalization. Several women also noted that, despite being central to post-harvest activities, they never have the opportunity to market dried fish themselves or negotiate prices directly with buyers. Integrating women's perspectives into community structures could enhance adaptive capacity by broadening the decision-making base and ensuring that management strategies reflect the needs of the entire community.

3.6 | Vulnerability Assessment

The WBNF is significantly vulnerable to overfishing and climate change-related phenomena, such as sea level rise. The fishermen have observed a substantial decline in catch per unit effort (CPUE) during the last 15 years, with a significant impact on their overall well-being. The decrease in CPUE may be attributed to pollution, land development, juvenile fishing, water quality degradation, and overexploitation. The decrease in the percentage contribution of *H. nehereus* and *S. phasa* is particularly worrisome as it has been an essential component in the success of the fishery. These fish species are renowned for their high yield and high price on the dried fish market. The increasing frequency of cyclones and storm surges in the Bay of Bengal in recent years has further exacerbated the precarious situation by altering the catch composition. Beginning with Bulbul and Foni in 2019 and Amphan in 2020, Yaas in 2021 severely affected Sundarbans each time. Cyclones impact fish biodiversity, fish catch, and fishing infrastructure, including camps, fish drying areas, crafts, gear, and water quality, resulting in severe economic hardship for the fishing community. Apart from this, the informal debt system and multiple middlemen marketing channels cause more tension for the fishers.

The present study provides a framework for assessing the potential impact and vulnerability of WBNF to climate-change-related phenomena. The fishers made up the largest share (91%), followed by the fish traders (9%) in WBNF. The age distribution of the fishers included 73% who were above 50 years, 18% between 40 and 50 years, and 9% who were under 40 years. Ten percent of the participants had attained secondary education, but a significant percentage (80%) had educational qualifications lower than the secondary level. Participants have observed a decrease in the depth of the estuarine zone during the last 15 years due to sea level rise. The average decrease in depth in BAK was 4.52 m. Without exception, all the fishers unanimously agreed on the alteration in fish reproduction within the examined region. The respondents' perception of CPUE experienced a significant decline in 15 years, dropping from 80 to 900 kg/boat/day to the current range of 24–200 kg/boat/day. In general, species richness declined by 14.33% due to the increased presence of motorized fishing crafts and the increased use of fishing tools.

Most respondents noted that *Setipinna taty* is a climate-resilient fish species, whereas a significant decline was observed in the catch of *Setipinna phasa*, *Scomberoides* sp., and *Eupleurogrammus muticus* in terms of species abundance. Before the repeated cyclonic events of Bulbul, a majority (68.39%) of the local communities relied on these fisheries for their livelihood. Nevertheless, the dependency on fisheries has diminished. The stakeholders' response filtered 10 drivers. Eight drivers are WBNF fisheries, and 2 indicators characterize climate change, that is, temperature and rainfall (Table 4). Specifically, as the sea level rose, catch species richness and CPUE decreased, while the number of gears increased. The total WBNF landings fluctuated between 2080.6 and 35844.6 metric tons per season, with average CPUE values ranging from 93.72 to 53.12 kg from 1994 to 2000 (Mitra et al. 2001). Several studies have yielded similar findings, including Datta et al. (Dutta et al. 1975), Mitra et al. (1997), and Pillay et al. (Pillay and Ghosh 1962). The present study, which utilizes a stakeholders' perception-based methodology, effectively demonstrates the vulnerability of WBNF to the changing climate. It is crucial to develop suitable adaptation strategies and implement climate-resilient practices to increase the capacity of fishermen and ensure a sustainable livelihood in the future.

TABLE 4 | Drivers used for vulnerability index construction.

Drivers	Range	Vulnerability relationship
Education qualification	Below 10th standard = 0 Above 10th standard = 1	−
Caste	Respondent opinion	−
Sea level rise	Decadal study (15 years)	+
Catch species richness decrease	Decadal study (15 years) via Respondent opinion	+
Catch per unit effort	Decadal study (15 years) via Respondent opinion	+
Number of gears increased	Respondent opinion	+
Number of motorized boats increased	Respondent opinion	+
Shift in fish spawning season	Respondent opinion	+
Temperature increase	Decadal study (15 years)	+
Changes in rainfall pattern	Decadal study (15 years)	+
Different adaptation strategies	Respondent opinion	+

The values and indices of every sub-component, as well as the Livelihood Vulnerability for all four study areas, are described in Table 5. The vulnerability score of all major components is shown in Figure 11. The study indicates that the impact of natural disasters and climate change is higher in FRJ than in all other areas. The climate hazards in these areas cause extensive damage to fishing camps and drying yards, with several camps reporting infrastructure losses of up to 40%–60% during major cyclonic events. Cyclones also lead to multi-week disruptions in fishing operations due to gear loss, navigation hazards, and safety concerns at sea. Sea level rise accelerates salinity intrusion and erosion, shrinking the usable fishing and processing space along the shoreline. The socio-demographic profile is more vulnerable in LAL, whereas livelihood adaptation strategies are at high risk in FRJ. Food security is a significant issue in KHS compared to other places. In terms of overall vulnerability, particularly concerning livelihood strategies, social networks, and climate change, FRJ is the highest. Though KHS faces the lowest vulnerability in all other aspects, water is still an issue for this area.

In this LVI-IPCC framework, Natural Disasters and Climate Variability are contributing factors to exposure, while health, food, and water are responsible for the sensitivity calculation. The adaptive capacity is calculated with the Socio-Demographic Profile, Livelihood Strategies, and Social Networks. The LVI-IPCC scores for each study area are highlighted in Figure 12. The study revealed that FRJ exhibits the highest vulnerability index (0.402) due to its high exposure to hazards like cyclones and sea-level rise and lower adaptive capacity. BAK, despite higher exposure than KHS and LAL, shows relatively stronger adaptive capacity. BAK has a stronger institutional linkage with the state fisheries department and better-developed market linkages that reduce dependence on intermediaries. Further, the diversified livelihood engagement, that is, tourisms, shops, and transportation business, makes the place better in adaptive capacity. Sensitivity is consistently high across all locations, suggesting that dependence on fisheries and related livelihood structures makes all sites particularly vulnerable. Significantly high dependency on bag net fisheries and limited economic resources make the FRJ area more susceptible to climate exposure.

Set bagnets, which catch a significant number of species, have a negative influence on biodiversity and fisheries compared to other methods (Ahsan 2015). SSánchez-Triana and Paul (2014) observe that brackish-water fish species are replacing freshwater species, disrupting traditional fisheries that relied on predictable migration patterns. Myers and Mertz (1998) found that commercially harvested fish stocks are overexploited, with fishing mortality up to four times higher than natural mortality. This type of commercial fishing has a significant impact on ecosystem resources, including their evolution (Krishnan and Talwar 2021). Management goals must be established democratically and politically, taking into account the perspectives of the public, stakeholders, and other interest groups (Jorgensen et al. 2007). Effective management measures can

TABLE 5 | Livelihood Vulnerability Index sub-component index for FRJ, BAK, KHS, and LAL.

Sub components	FRJ	BAK	KHS	LAL
Dependency ratio	0.100	0.150	0.117	0.183
Female-headed fisher's households	0.032	0.019	0.026	0.034
Average age of female head of fisher's household	0.010	0.200	0.075	0.200
Fishers not attended school	0.340	0.437	0.526	0.483
Fishers dependent solely on fisheries as income source	0.863	0.901	0.754	0.821
Fisher's family member employed apart from fishery sector	0.485	0.369	0.421	0.533
Average fisheries Livelihood Diversification Index	0.462	0.340	0.380	0.260
Fishers don't get any subsidies	0.983	0.866	0.927	0.946
Fishers raising animals	0.655	0.548	0.596	0.422
Fishers involved in agriculture	0.133	0.214	0.349	0.265
Fishers don't have fishermen card	0.024	0.018	0.037	0.015
Fishers belong to fishers association	0.425	0.460	0.363	0.282
Fishers belong to community-based organizations	0.765	0.732	0.626	0.654
Average borrowed: lend money ratio	0.200	0.833	0.010	0.667
Fishers invloved in NGOs/SHGs	0.213	0.141	0.099	0.052
Fishers don't have bank account	0.685	0.530	0.763	0.643
Distance to nearest health center	0.100	0.200	0.750	0.625
Fishers suffering from water-borne disease	0.043	0.068	0.052	0.065
Fishers physically fit during 4 months	0.956	0.985	0.882	0.968
Fishers use mosquito net	0.144	0.214	0.082	0.124
Female get good sanitation	0.526	0.481	0.287	0.347

(Continues)

TABLE 5 | (Continued)

Sub components	FRJ	BAK	KHS	LAL
Fishers depend solely on fishing	0.780	0.860	0.690	0.740
Fishers buy fish from outside	0.872	0.758	0.761	0.827
Average months fishers struggle to find food	1.000	1.000	0.500	0.667
Fish diversity index	0.300	0.600	0.450	0.150
Fishers use firewood for cooking	0.120	0.083	0.045	0.061
Fishers make dried fish for future/sell	0.286	0.364	0.245	0.320
Fishers don't get constant water supply	0.060	0.040	0.090	0.120
Fishers reporting water resource conflicts	0.110	0.060	0.250	0.180
Fishers utilize natural water source	0.860	0.880	0.920	0.840
Fishers don't get safe drinking water	0.140	0.240	0.210	0.260
Average number of cyclones in past 10 years	1.000	1.000	1.000	1.000
Fishers don't receive proper warning about the natural disasters	0.019	0.014	0.021	0.016
Fishers or family members with severe injury or death as the result of natural disasters	0.041	0.026	0.013	0.029
Average water depth decreases in study years	0.500	0.330	0.166	0.300
Mean standard deviation of average maximum temperatures (yearly) in past 10 years	1.000	1.000	1.000	1.000
Mean standard deviation of average minimum temperatures (yearly) in past 10 years	1.000	1.000	1.000	1.000
Mean standard deviation of average rainfall (yearly) in past 10 years	1.000	1.000	1.000	1.000
Fishers reported erratic rainfall pattern	0.442	0.390	0.195	0.263
Fishers reported high temperature	0.626	0.518	0.593	0.462
Fishers reported Wind power changes	0.385	0.346	0.296	0.214

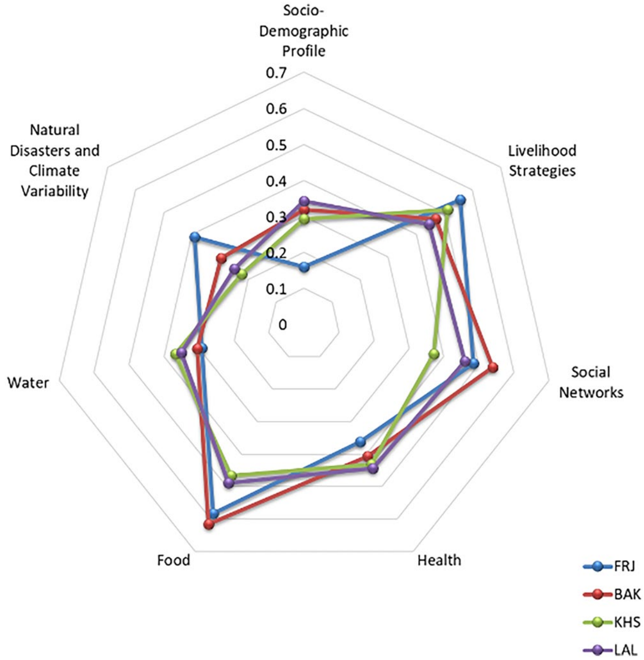

FIGURE 11 | Vulnerability spider diagram of the major components of the Livelihood Vulnerability Index (LVI) for all study areas.

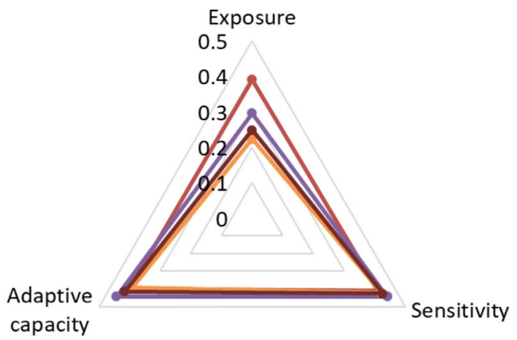

FIGURE 12 | LVI-IPCC score of each study area (0 indicates low contributing factor; 1 indicates high contributing factor).

promote sustainable conservation and management of fisheries resources.

3.7 | Community Learning From Past Experience

The results showed that the sustainability of risk mitigation techniques had been much improved by experiential learning and further transformative learning, which was influenced by previous experiences with climate change and fishing activities. In all four sites, community meetings held after disasters provided spaces where fishers collectively discussed losses, shared coping mechanisms, and identified new strategies. Learning also occurred informally within households, where older fishers passed on their experiences of disaster preparedness, gear protection, and alternative income sources to younger generations. Fishermen and local stakeholders applied lessons learned from past difficulties to develop more effective coping mechanisms for mitigating economic losses. Fishermen across the study sites reported developing adaptation strategies. Communities were better able to adjust to shifts in situations, reinforce their resilience, and guarantee the long-term sustainability of small-scale fishing techniques by utilizing both traditional and contemporary advanced knowledge (Table 6). During the COVID-19 pandemic, an estimated 22%–35% of households temporarily shifted to small-scale backyard pond aquaculture, while others engaged with alternative income sources. Some camps were relocated to less vulnerable zones after repeated cyclones like Amphan and Yaas. To manage tidal water entry and protect their camps, communities started constructing temporary embankments near the sea shore. But during the adaptation, the community faces lots of challenges. While aquaculture provided a supplementary income, it was also constrained by limited technical knowledge and access to credit. Although solar or mechanical dryers can offer more hygienic processing and reduce weather-related constraints, they are often expensive and may also displace a significant number of laborers engaged in post-harvest activities.

Some external factors such as government and non-governmental organizations (NGOs) can significantly contribute to the resilience and sustainability of fishing communities through financial assistance, training, policy support, and infrastructure development (Table 7). Their participation can ensure that communities are prepared with the knowledge, skills, and resources necessary to adapt to environmental hazards, economic challenges, and climate change. These interactions between traditional knowledge and technological and institutional interventions contribute to co-managed approaches for sustaining fisheries under changing environmental conditions.

3.8 | Future WBNF Resilience

The future resilience of winter migratory bag net fisheries in the Sundarbans depends on adaptive strategies that integrate ecosystem conservation, community-driven solutions, and policy reforms. Climate change, habitat degradation, and economic uncertainties threaten sustainability, necessitating the restoration of mangroves, the adoption of sustainable fishing practices, and the development of alternative livelihoods, such as aquaculture and ecotourism. But their widespread implementation is constrained by multiple barriers. High initial investment costs often discourage fishers from adopting new technologies or entering alternative livelihoods. Limited access to training and infrastructure further reduces their ability to transition successfully. Additionally, cultural preferences for traditional fishing methods generally slow down the adoption of innovative practices. Similarly, relocation reduced immediate risks, but it is costly as well as does not eliminate long-term exposure to future cyclones. Strengthening local governance, early warning systems, and financial safety nets can enhance fishers' resilience and adaptability. Technological advancements, such as AI-driven fish stock assessments and improved weather forecasting, will further support resilience. By fostering cross-sector collaboration and community participation, winter bag net fisheries can remain viable, ensuring long-term food security and economic stability. Resilience strategies proposed for WBNF are closely aligned with site-specific findings from the vulnerability and learning assessments. Establishing adaptive co-management mechanisms and risk-sharing arrangements, including collaborative planning between fishers, NGOs, and

TABLE 6 | Community members' learning for risk reduction and future resilience.

Learning aspects	Experiential learning	Transformative action
Risk mitigation	1. Mapping of extreme weather events, declining fish stocks, and resource conflicts 2. Developing a seasonal fishing calendar to predict fish migration and availability 3. Conservation and restoration of Mangrove areas 4. Applying local traditional knowledge	1. Relocating fishing camps to less risk-prone areas 2. Preparing embankments in coastal areas 3. 3. Changing perception toward risk and moving from reactive coping to preparative adaptation
Early warning systems	1. Difficulty interpreting official weather warnings 2. Enhancing community radio and extending coverage to reach fishermen at sea	1. Integrating Indigenous Knowledge with Official Warnings
Preparedness	1. Strengthening community-based organization 2. Building multipurpose cyclone shelters 3. Strengthening local-level institutional coordination	1. Fund raising for disaster time
Response	1. Risk-taking for livelihood sustainability 2. Temporary migration in response to extreme weather	1. Alternate livelihood occupation 2. Moving to town for better livelihood opportunities
Recovery	1. Strengthening local leadership for effective planning 2. Food storage facilities and disaster-resilient buildings	1. Addressing long-term livelihood rehabilitation

TABLE 7 | Role of Govt and NGOs in capacity building of fishing communities.

Activities	Specific activities	Resilience implications
Institutional Capacity Building	1. Providing technical support on sustainable fishing techniques and bycatch reduction 2. Conducting emergency response training, including First Aid training 3. Advocating for disaster risk reduction integration in fisheries policies 4. Establish fishery co-management bodies with local fishers, NGOs, and government agencies.	1. Enhances fishers' safety during extreme weather events 2. Strengthen sustainable fisheries governance and risk-informed planning.
Community Capacity Building	1. Developing local fisher networks for knowledge sharing and collective action 2. Organizing awareness campaigns on climate risks, conservation, and responsible fishing 3. Informing communities about alternative income sources 4. Conduct disaster preparedness training and effective resource management. 5. Safeguarding children's education and health	1. Reducing fishery-related risks and damages 2. Improves livelihoods, strengthens adaptive capacity, and ensures sustainability

government agencies, can directly address the high LVS of FRJ area. Similarly, livelihood diversification strategies, such as freshwater fish farming or small-scale tourism, are particularly relevant for LAL.

Selective fishing nets can reduce bycatch, but high initial costs and limited access to juvenile fishes, which are in very high market demand as fish meal, restrict their adoption across all WBNF camps. Freshwater fish farming can provide an alternative income source, but saltwater intrusion during cyclones and potential conflicts with traditional fishing areas must be managed to avoid ecological degradation. Scaling up these strategies will therefore depend on balancing economic benefits with ecological and social feasibility. Support mechanisms such as subsidies, training programs, cooperative management, and institutional support can enhance adoption rates while maintaining long-term sustainability.

The following recommendations can be taken for policy reforms for sustainable fishing practices:

- Proper enforcement of seasonal regulations for fishing
- Strict Gear specification
- Introduce fair pricing, credit access, and cold storage facilities
- Promote digital platforms and e-commerce for fisher-to-consumer sales
- Encourage small-scale fish processing to capture higher market value
- Fair wages for fishermen
- Financial and Technological support
- Government & Policy Support
- Reducing deep-sea bottom trawling

4 | Discussion

The Sundarbans is highly vulnerable to sea level rise, which has led to the submersion of key fish breeding areas and changes in estuarine salinity. Hazra et al. (2002) highlight that the region has already experienced significant land loss due to erosion, affecting fishing communities that depend on shallow water habitats for WBNF. Climate change-induced temperature fluctuations in water bodies have disrupted the migration patterns of economically important fish species. Rashid (2019) reported that changing temperatures are leading to a decline in cold-water fish species that were once abundant in the winter months in Bangladesh's side of Sundarbans, and the same report also recorded at the Indian side in the present study. The altered temperature regime affects spawning cycles and larval development, further impacting WBNF. Mitra (2019) notes that extreme weather events such as Cyclone Amphan in 2020 caused massive damage to fisheries' infrastructure and led to fish stock depletion, and the same finding was also recorded from the present study. With an average production of 28,536.7 metric tonnes, this unique four-month WBNF contributes approximately 51.2%–82.5% of the fish production from the Hooghly Matlah estuarine system (Mitra et al. 1997, 2001; Nath et al. 2004). According to a study conducted by Talwar et al. (2013), artisanal winter migratory bag nets perform as well as regular nets do, with a 5% catching efficiency. Despite the increased operational costs of winter bag net fishery, various factors have been supported to make this practice commercially viable. The prevalence of calm weather conditions in the lower estuary throughout winter creates an ideal environment for operating stationary bag nets. In addition, the lower estuarine region has an abundance of fish and shellfish that are favorable to the WBNF throughout the season. This abundance is approximately 11–50 times greater than the average availability in the upper and intermediate zones of the estuary (Dutta et al. 1975). Studies have revealed a significant shift in the species composition of winter bag net fisheries over time, particularly in terms of target species. Historical records from 1997 indicated that the catch predominantly comprised small-sized but economically valuable species such as *Polynemus paradiseus* and *Pampus* spp., which together accounted for nearly 80% of the total landings (Paul et al. 1997). Other species, including *Harpodon nehereus*, *Pama pama*, *Setipinna* spp., *Trichiurus* spp., *Tachysurus jella*, and various prawns, were recorded as secondary components of the catch. However, current data indicate a marked change, with *Setipinna* spp. and *H. nehereus* now emerging as the dominant contributors to winter bag net landings. This alteration in species composition is likely a result of overexploitation of the previously dominant species, leading to a decline in their populations. Additionally, changing environmental conditions, particularly due to climate variability and anthropogenic stressors, may have further influenced species distribution and availability.

The decline in catch composition, particularly the sporadic occurrence of *Tenualosa ilisha*, may be strongly linked to climate-induced alterations in the estuarine environment. As a migratory species highly sensitive to changes in the environment, *T. ilisha* requires a delicate balance of environmental conditions for successful spawning and upstream migration (Rahman 2011; Hossain et al. 2016). However, increasing salinity intrusion due to sea level rise and reduced riverine discharge likely disrupts its life cycle and migration patterns. Additionally, the estuarine fisheries of the Sundarbans are increasingly exposed to frequent and intense cyclones (e.g., Amphan in 2020; Yaas in 2021), which can cause sudden changes in water temperature, turbidity, and nutrient load (Makwana and Patnaik 2025). Such events lead to short-term habitat destruction and long-term shifts in fish community structure, favoring more resilient or euryhaline species like *Setipinna taty*, *Coilia dussumieri*, and *Harpodon nehereus*. These species have now emerged as dominant components of the catch, replacing the previously abundant but more environmentally sensitive taxa such as *Polynemus paradiseus* and *Pampus* spp. (Gupta et al. 2023; Sumon et al. 2025). These findings suggest that climate change, through its direct and indirect effects on estuarine hydrology and habitat conditions, is a major driver of the ongoing shifts in species composition and fishery productivity. Integrating long-term environmental monitoring with fisheries data is essential to develop climate-resilient strategies for sustainable resource management in the Sundarbans region.

The changing patterns of the WBNF from 1995 to 2024 are compared in Table 8, which shows an increase in the number of fishermen and boats but a significant decrease in the number of fish landing per boat; the results were obtained while comparing data from Paul et al. 1997 with present data. In previous data, the landing centers were Fraserganj, Bakkhali, Upper Jamboo, Lower Jamboo, and Kalisthan. However, in the present data, only Fraserganj, Bakkhali, Lalganj, and Kalisthan were collected as Jamboo Island is banned for fishing. There has been a significant increase in the total catch from the WBNF, corresponding to an increase in fishing efforts since 1960–1961, which reached a peak of 25,909.5 tons in 1995–1996 (Dutta et al. 1973; Paul et al. 1997). However,

TABLE 8 | The changing pattern of the bag net fisheries of Fraserganj cluster.

Fishery characteristics	Year		Change in 28 years
	1995–1996	2023–2024	
No. of camps	135	235	74.07% increase
No. of fishermen	3900	6275	60.90% increase
No. of Bagnets	892	950	6.50% increase
No. of fishing boats	316	374	18.35% increase
Nonnotarized	177	—	No nonnotarized boat
Motorized	139	374	169.06% increase
Total landings (tonnes)	25909.5	21970.1	15.20% decrease
CPUE (kg/NT)	83.39	26.53	70.34% decrease

this did not last long, and the catch was drastically reduced to 21,970.1 tons from 2023 to 2024. The CPUE steadily decreased with increasing fishing efforts and reached its lowest recorded value of 26.53 kg/NT from 2023 to 2024. The general trend in reducing the percentage contribution of *H. nehereus* (28.08% in 1985–1986 and 16.72% in 2016–2017) noticeably prevailed with our recent studies (Saigal et al. 1987; Krishnan and Talwar 2021). The average species abundance across four landing sites namely, Fraserganj, Bakkhali, Lalkuthi, and Kakdwip-Harinbari Sector (KHS) revealed distinct spatial variations in species distribution and dominance. Species *S. taty* emerged as the most dominant species, with the highest abundance at Lalkuthi (44.4), followed by Fraserganj (38.16) and Kakdwip-Harinbari (23.09), indicating its wide ecological adaptability. Species like *Coilia dussumieri* showed a strong preference for Bakkhali (33.63), while *Harpadon nehereus*, a commercially important species, was most abundant in Fraserganj (15.15) but also occurred moderately at other sites. Similar patterns have been reported in earlier studies from the Sundarbans estuarine system, where Setipinna, Coilia, and Harpadon were consistently dominant across seasonal and spatial gradients (Mukherjee et al. 2013; Pantulu 1966). Site-specific trends were also evident for species like *Deveximentum insidiator* and *Sardinella gibbosa*, which peaked at Lalkuthi (25.0) and Fraserganj (17.62), respectively. Ribbon fish namely *Lepturacanthus savala* showed relatively high abundance in Bakkhali (11.75) and Kakdwip-Harinbari (10.92), suggesting favorable habitat conditions in these areas. Several species such as *Anodontostoma chacunda, Johnius aneus*, and *Otolithoides pama* were more prevalent at Bakkhali, while species like *Scoliodon laticaudus* appeared only at Fraserganj and Lalkuthi, indicating selective habitat occupancy. In contrast, species such as *Cynoglossus arel* and *Johnius carouna* were absent from some sites, suggesting a sporadic distribution.

Climate change has exerted a varied influence on the WBNF, disrupting both ecological stability and economic viability. Our findings align with global evidence that coastal fisheries are disproportionately affected by climatic extremes (Malhotra 2025). The heightened intensity of cyclones like *Amphan* (2020) and *Yaas* (2021) trends observed in the Bay of Bengal region, where rising sea surface temperatures have increased cyclone frequency by ~20% since 2000 (Jena and Patnaik 2024). Such events correlate with our respondents' reports of damaged infrastructure and rising operational costs—a pattern similarly documented in Bangladesh small-scale fisheries after Cyclone Sadr (Islam et al. 2020). The decline in catch-per-unit-effort (CPUE) underscores climate-driven ecological disruptions. Rising sea temperatures and altered salinity gradients have displaced target species (e.g., Hilsa (*Tenualosa ilisha*)) to deeper or estuarine zones (Rahman 2013). This forces fishers to extend trips, increasing fuel costs—a phenomenon observed in Kerala's fisheries, where CPUE dropped by 30% post-2010 (Natarajan et al. 2023).

The impact of climate change in post-harvest activities is consistent with studies in coastal Bangladesh and India, where climate shocks disproportionately erode women's livelihoods due to their reliance on climate-sensitive, informal value chains (Miah 2021; Bharadwaj et al. 2022). The destruction of drying yards in FRJ after Cyclones Amphan and Yaas (Sen 2021) underscores the need for decentralized, climate-resilient infrastructure, such as solar-powered drying units (Ejedegba 2024). Future research should quantify migration shifts using species distribution models (SDMs) and assess gendered impacts, as women in fish processing face disproportionate job losses (Deeg 2023). The long-term decline in profitability in climate-sensitive zones like FRJ underscores the disproportionate risks faced by communities reliant on fisheries—a pattern observed across tropical small-scale fisheries (SSFs) globally (Smith and Basurto 2019). Resilient drying infrastructure (e.g., elevated platforms, saltwater-resistant storage) could mitigate post-harvest losses (Adhikari and Ghimire 2025). These findings highlight the urgent need for gender-sensitive adaptation strategies. Finally, inclusive governance reforms must ensure women's representation in fisheries management to address systemic inequities (Njuki et al. 2021).

Adaptive co-management represents a collaborative governance model where fishers, community members, government organizations, and NGOs share decision-making responsibilities to manage fisheries sustainably (d'Armengol et al. 2018). In the WBNF, locally elected fisher committees can collaborate with state fisheries departments and NGOs to oversee camp licensing, regulate fishing gear, and strengthen early warning systems. Our findings align with studies in the Sundarbans, where cyclones *Amphan* (2020) and *Yaas* (2021) eroded fishers' adaptive capacity, reducing annual incomes by 0.53% (Saha, Hazra, et al. 2022). The lack of diversification strategies exacerbates vulnerability, as seen in Odisha, where households without alternative livelihoods faced higher poverty rates post-cyclones (Khatoon et al. 2025). Conflicting interests between camp owners and daily wage laborers, dependence on intermediaries in the marketing chain, and the absence of strong institutional support mechanisms may limit collective action. Building trust among stakeholders, ensuring transparency in decision-making, and providing legal and policy backing are therefore essential for overcoming these barriers. Bridging organizations serve as platforms for integrating diverse forms of knowledge and coordinating key tasks such as resource access, stakeholder engagement, trust-building, conflict resolution, and networking, thereby fostering effective cooperation (Berkes 2009).

The present study highlights that FRJ requires urgent intervention to improve its adaptive capacity through livelihood alterations, climate-adaptation strategies, and socioeconomic infrastructural development. Whereas KHS and LAL exhibit better resilience, demonstrating the potential of strong social networks and diversifying livelihoods in mitigating climate risks. Enhancing livelihood diversification is crucial for reducing dependency on climate-sensitive fisheries. Enhancing disaster preparedness and response systems in FRJ is a pressing need for the sustainable future of small-scale fisheries. Investing in community education and utilizing social media to strengthen adaptive capacity can lead to a better and more resilient future. By addressing these key factors, policymakers and stakeholders can work toward reducing climate vulnerability and ensuring sustainable livelihoods for fishing communities in the Sundarbans.

5 | Conclusion

The rapid depletion of natural resources and biodiversity threatens the Sundarbans' ecosystem and the livelihoods of rural fishers. WBNF remains effective, with artisanal nets outperforming regular ones in catching larger fish. While mechanization has not yet displaced manpower, its increasing pace may impact future employment. Fish prices remain stable, ensuring minimal market risk through an efficient marketing mechanism. However, vulnerability assessments highlight the area's susceptibility to climate change, underscoring the need for mitigation strategies. Disaster management initiatives and climate awareness programs are essential to safeguarding fisher livelihoods and ensuring the sustainability of this traditional fishery. The adoption of environmentally friendly technologies, such as selective nets or solar dryers, should be evaluated not only for their immediate benefits but also for their ecological impacts, labor implications, and cost–benefit balance.

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