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The state of climate change adaptation research in Bangladesh: a systematic literature review

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Abstract
Climate change is severely affecting livelihoods, especially in developing countries, where adaptation strategies are becoming crucial. While the body of empirical research on adaptation is steadily growing, the status of such research in Bangladesh has received little attention. This paper reviews 106 articles on adaptation research in Bangladesh between 2007 and 2024, applying the social-ecological systems (SESs) approach. We see a significant annual increase in publications since 2014. Priority research topics and themes, such as community-based adaptation, ecosystem-based adaptation, gender, livelihood, adaptive capacity, governance, and mainstreaming, are gaining prominence in the literature. Only 5% of the studies we reviewed framed climate change adaptation as a system or applied any systematic approach. Most considered it a standalone process without identifying the bidirectional relationships between adaptation strategies and the encompassing SESs. There are only a few comprehensive studies on the outcomes or effectiveness of livelihood adaptation strategies implemented at the household level. Only a few studies mentioned the importance of the SESs approach without providing the system's structural components or conceptualizing adaptation as a social-ecological system. Therefore, introducing SESs-specific variables and conceptual relationships could bring a much-needed holistic analytical perspective to climate adaptation research.

Keywords Climate change adaptation · Climate change impacts · Conceptual approaches to adaptation · Social-ecological systems (SESs) · Bangladesh

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1 Introduction

Climate change is bringing unprecedented changes to social and ecological systems and their interactions (Fedele et al. 2020). By 2100, the global average temperature is likely to exceed pre-industrial levels by 1–5.7 °C, while the sea level could rise by 0.28–1.01 m (Fox-Kemper et al. 2021; IPCC 2022; WMO 2022). While climate change is expected to affect every country, they will not be affected equally (Adger et al. 2003). Bangladesh is one of the most vulnerable ones. In 2021, Bangladesh was assessed as the 7th most climate-affected and the 29th most vulnerable, but the 167th best-prepared out of 192 countries (Eckstein et al. 2021; University of Notre Dame 2022). Approximately 60% of its population lives in highly flood-prone areas—that is 101.89 million people. By the 2040s, about 18 million might be forced out of the coastal regions, river systems, and estuarine hotspots at a higher risk of experiencing severe climate-related events (Bangladesh Planning Commission 2018; BBS 2023; Islam et al. 2024). Climate-related hazards cost Bangladesh $3 billion a year; by 2050, this is predicted to add up to an additional 2% of GDP (World Bank 2021).

Bangladesh's vulnerability emerges from the dynamic interactions between biophysical, socio-economic, and institutional factors. The country's geographical location—downstream of the Himalayan mountains and within the funnel-shaped Bay of Bengal—exposes it to frequent floods, cyclones, and storm surges. Most of the country is low-lying, i.e., 80% of the landmass is floodplain, leaving the country highly vulnerable to floods. Cyclones, such as Sidr in 2007, caused devastating effects, affecting nine million people and resulting in a financial loss of $1.7 billion (Nahar et al. 2023). Slow-onset hazards include riverbank and coastal erosion, with an estimated 192 km^2 lost between 1989 and 2009, along with salinity intrusion and sea level rises, ranging from 2.5 mm to 5.73 mm per year (Sarwar and Woodroffe 2013). Projections also suggest that sea levels in the country will rise by 14 cm by 2030, 32 cm by 2050, and 88 cm by 2100. This accelerated rise can lead to increased erosion, saltwater intrusion, and displacement of communities (Shariot-Ullah 2024).

Beyond biophysical factors, socioeconomic vulnerabilities such as high population density, poverty, and poor quality of life, intensify Bangladesh's vulnerability to the impacts of climate change. The National poverty rate is 21.8% (ADB 2020), with extreme poverty concentrated in coastal, floodplain, and drought-prone regions. The Human Capital Index score of 0.46 reflects education, healthcare, and skills gaps, limiting communities' adaptation capacity (World Bank 2021). Agriculture employs 45.33% of the labor force but contributes only 11.38% to GDP, worsening income inequality (BBS 2024). Informal employment accounts for 85% of jobs, leaving workers without social protection from climate shocks (ILO 2024). Urban poverty is high in Dhaka and Chattogram, where climate migrants face job insecurity, poor housing, and lack of services (Rana and Ilina 2021).

Bangladesh has the world's largest mangrove forest, the Sundarbans, but rising sea levels and salinization threaten its ecosystems (Sarker et al. 2016). Inland freshwater (wetlands) and semiarid dryland ecosystems vital for aquaculture and agriculture are also at risk of flooding and droughts (Alam 2015; Ferdushi et al. 2019; Hossain et al. 2017; Islam et al. 2019). Additionally, misaligned infrastructural interventions such as embankments, polders, and large irrigation projects often cause siltation, drainage congestion, and ecosystem damage (Barbour et al. 2022). Human activities, such as agricultural encroachment and infrastructure development, further threaten these ecosystems (Adams et al. 2018), reducing essential ecosystem services and increasing the vulnerability of communities reliant on them (Hossain et al. 2015).

The disaster and climate risk atlas of Bangladesh, developed using the HEVR (Hazard, Exposure, Vulnerability, and Risk) model, quantifies the risks of climate hazards across the country (Nahar et al. 2023). It reveals that while Bangladesh as a whole is highly vulnerable to climate change, certain areas face heightened risks from specific hazards (Fig. 1). The southwestern coastal region faces salinity intrusion, storm surges, and coastal flooding, which threaten freshwater availability and biodiversity vital for agriculture-based livelihood activities (Hadi et al. 2021; Islam et al. 2023; Sharifuzzaman and Islam 2024). The southeastern and eastern coastal areas are highly prone to tropical cyclones, storm surges, and coastal erosion, endangering human settlements, fisheries, and infrastructure (Brammer 2014). The northern and northwestern regions, particularly Rajshahi, Bogra, Dinajpur and Rangpur districts, experience severe droughts, extreme heat, and prolonged dry spells, affecting groundwater availability (Alauddin and Sarker 2014; Hossain et al. 2016). The *haor* wetlands and northeastern floodplains, including Sylhet, Sunamganj, and Netrokona, frequently suffer from flash floods, which cause damage to rice crops (Ferdushi et al. 2019). The Chattogram Hill Tracts are highly susceptible to landslides, especially during the monsoon season, leading to casualties and infrastructural damage (MoEFCC, 2022). Additionally, the major river basins—including the Padma, Jamuna, and Meghna—are prone to seasonal flooding and riverbank erosion, resulting in displacement and loss of agricultural land (Alam et al. 2023). Urban areas, such as Dhaka, are increasingly affected by heat stress and waterlogging, exacerbated by rapid urbanization (Tabassum et al. 2024).

The descriptions above illustrate that Bangladesh's vulnerability to climate change impacts is influenced by the interactions between its people and the environment. The country is in the Ganges–Brahmaputra-Meghna delta, where low-lying land and a dense population are exposed to floods, cyclones, and rising sea levels (Brammer 2014). These environmental challenges are compounded by social issues such as poverty and weak institutions, creating a cycle of increasing vulnerability. For instance, when mangrove forests are lost, coastal communities lose their protection from cyclones and storm surges. Frequent floods damage crops, jeopardizing food supplies and incomes, while poor governance undermines the implementation of solutions. To effectively address these challenges, it is crucial to consider both social and ecological systems together, as they are deeply interconnected (Berkes and Folke 1998). Adaptation strategies designed with this approach can help tackle the root causes of vulnerability and enhance livelihood resilience.

Adaptation, or the adjustment of ecological, social, or economic systems in response to actual or expected climatic stimuli and their impacts, involves changes in processes, practices, and structures to lessen harm or increase benefits (IPCC 2022). This definition suggests that adaptation comprises physical adjustments in natural systems as well as political, social, economic, and institutional adjustments in human systems (Adger et al. 2003; Bartelet et al. 2022). Adaptation is highly context-specific (Wilson 2022). The forms and extent of adaptation vary according to socioeconomic conditions (which may call for incremental or transformational responses), biophysical factors, time (it may be proactive or reactive), and location.

Adaptation to climate change impacts is a complex and interconnected process involving various factors that affect (and are affected by) local ecosystems and livelihood practices (IPCC 2014). Like any system, adaptation constantly evolves and must change in response to evolving environmental conditions and social goals (Wise et al. 2014). To ensure effective implementation, adaptation strategies must be integrated across multiple scales, from individual households to regions and nations (Landauer et al. 2018). Given its multidimensional, multiscale, multilevel, and multi-actor nature, successful adaptation requires a deep understanding of the social-ecological systems (SESs) in which it occurs

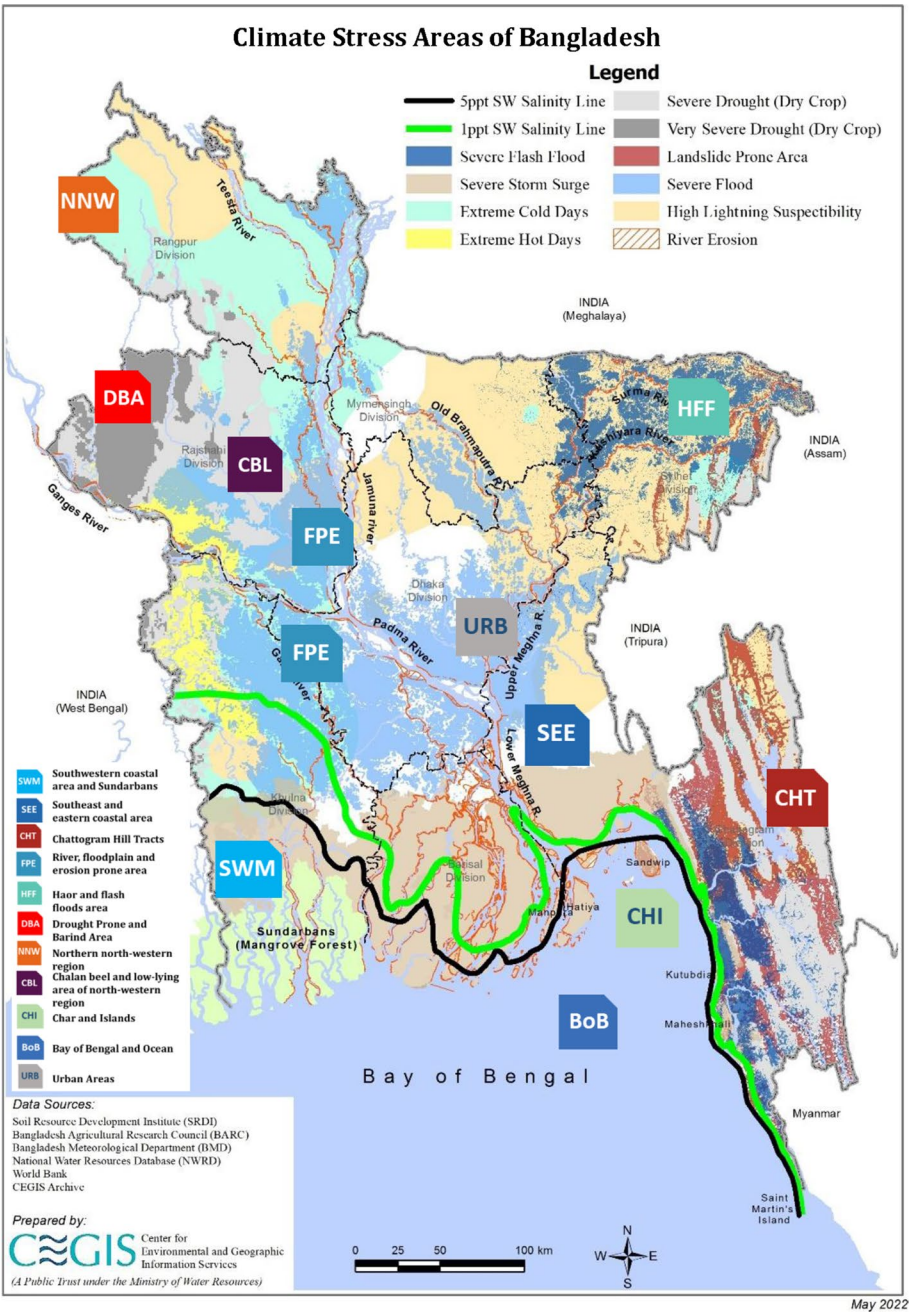

Fig. 1 Hazard and climate stress areas of Bangladesh. Source: National Adaptation Plan of Bangladesh (MoEFCC 2022)

(Adams et al. 2018; IPCC 2022; Salgueiro-Otero and Ojea 2020). Traditional economic, infrastructure, or policy responses cannot address adaptation by themselves; instead, a comprehensive approach is needed that considers them within the relevant ecological and social systems (Nelson et al. 2007).

The current conceptual approaches used to study adaptation strategies include the vulnerability approach (e.g., Füssel and Klein 2006; Füssel 2007; Turner et al. 2003), the risk-based approach (Bowyer et al. 2015; Brooks et al. 2005), the ecosystem approach (Reid et al. 2018), and the livelihood approach (Scoones 2009). The vulnerability approach mainly assesses the factors that make communities, ecosystems, and economic sectors susceptible to harm from climate change impacts (Nelson et al. 2007; Salam et al. 2021). The risk-based approach focuses on assessing and managing the risks associated with the impacts of climate change. This approach mainly focuses on physical hazards, potentially overlooking socioeconomic vulnerabilities (Bowyer et al. 2015). The ecosystem approach emphasizes the sustainability of the local natural environment but does not prioritize the way in which social and economic aspects of adaptation interact with ecosystems (Chong 2014). Originating from development studies, the livelihood approach emphasizes the assets, capabilities, and activities required for living (Clay 2017). However, this micro-level focus can overlook larger economic and environmental structures that may significantly influence adaptation strategies. These approaches help identify actors' adaptation needs, but with less attention to the systems the actors are part of. Such oversight can hinder knowledge transfer between research areas, such as ecosystems, biodiversity, vulnerability assessments, and adaptation strategies.

SESs are defined as nested, multilevel systems, including the social (human) and the ecological (biophysical) subsystems—the latter provides essential benefits to society in the form of food, water, or livelihood (Berkes and Folke 1998; Biggs et al. 2015). This structured way of conceptualizing social and ecological systems' interactions over a decision situation is called the SESs approach. It emphasizes that society and ecosystems are interdependent and intertwined and that they coevolve (Colding and Barthel 2019). The problems caused by climate change impacts, such as sea level rise, floods, droughts, and soil degradation, are rooted in the intertwined nature of human activities and ecosystems, which need to be investigated using the SESs approach (Biggs et al. 2021; Gain et al. 2020; Hossain et al. 2023). However, there remain considerable challenges to operationalizing the approach in adaptation research, given the lack of studies and comprehensive conceptual frameworks describing the constituting elements of SESs and their relationships with adaptation strategies (Hossain et al. 2023).

Regular, systematic assessment of the state, progress, key challenges, and prospects of adaptation activities are crucial for exploring knowledge gaps, emerging trends, and approaches to adaptation studies (Berrang-Ford et al. 2015; Ford et al. 2011). At the global level, several studies have reviewed the progress of adaptation research and mapped the trends in the current literature (e.g., Berrang-Ford et al. 2021; Nalau and Verrall 2021). At the national level, systematic literature reviews have identified emerging themes, trends, and strategic focuses in adaptation research (e.g., Ahmed and Khan 2022; Hoque et al. 2019; Rahman et al. 2018; Rijal et al. 2021). However, in Bangladesh, no studies have systematically reviewed the social and ecological factors motivating adaptation, the different conceptual approaches to adaptation, or how to apply the SESs approach. Such studies can inform future research and foster inclusive adaptation decision-making at the national, regional, and household levels.

To fill up this gap, we reviewed the scholarship on climate change adaptation in Bangladesh from an 18-year period (2007 to 2024) to provide an overview of what is known about adaptation measures undertaken, including the impacts people are adapting to, sectors of adaptation, socioeconomic attributes of the adapting households, types of strategies used, and the outcomes of these strategies. Thus, our research questions are:

1. What are the current trends in adaptation research in Bangladesh?
2. To what extent have social and ecological systems components been considered in adaptation studies in Bangladesh?
3. How can adaptation decision-making situations be conceptualized using the insights of the SES approach?

2 Materials and methods

2.1 Document selection

Our study is a systematic literature review. We searched the literature for research on adaptation responses to the impacts of climate change in Bangladesh. We chose to start the search period in 2001, the year of publication of the IPCC's Third Assessment Report, which marked the beginning of a stronger focus on adaptation in the climate change literature. However, we saw no papers fitting our selection criteria (research conducted in Bangladesh, and published in English, on farm-based, livelihood-centric climate change adaptation pursued by smallholder farmers) until 2007. Thus we included papers from 2007 through 2024. The search was conducted in the Scopus database using the search terms (climat*) AND (adapt*) OR (cop*) OR (adjust*) OR (resilien*) OR (risk* AND manag*) OR (risk* AND reduc*) OR (response*) OR (action*) AND (Bangladesh). This search returned a list of 1,113 documents. We also conducted a literature search using Google Scholar and extracted 74 papers.

2.2 Eligibility criteria

We limited our review to peer-reviewed papers, considered the highest standard of scientific evidence (Lame 2019). SI 1 presents detailed inclusion and exclusion criteria.

This study follows the three-phase screening strategy of Berrang-Ford et al. (2021): title and keyword screening, to identify articles that provide evidence of adaptation actions and strategies undertaken by individuals and communities; abstract, summary, or homepage screening, to identify documents aimed at directly reducing risk of or vulnerability to climate impacts; and full-text screening, to answer the research questions (Fig. 2).

In the first phase, we screened each article's title and keywords and found that 457 papers were related to adaptation. The other 730 papers were *not* about climate change adaptation. We extracted the 457 papers and read their abstracts: 62 were related to

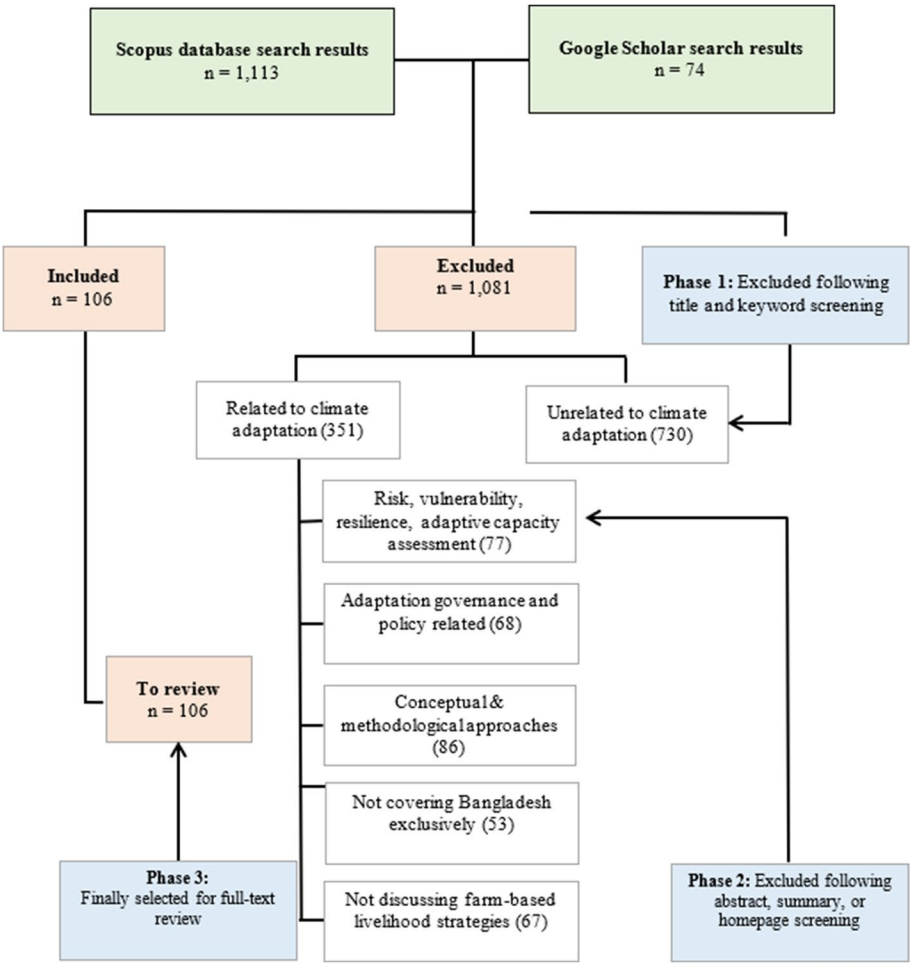

Fig. 2 Overview of the document selection processes

impact, risk, vulnerability, and resilience assessment; 54 were policy-related without empirical data; 86 were methodology-related; 53 studies did not exclusively cover Bangladesh; and 67 did not cover farm-based livelihood strategies. We now had 135 papers that were eligible for full-text screening. However, after the full-text screening, we found 29 articles that were not explicitly focused on adaptation but on vulnerability assessment and policy studies, and they were excluded. In the third phase, we had a final selection of 106 relevant articles to be reviewed for data extraction. To ensure eligibility and significance, they were cross-checked against the reference list on Bangladesh produced by the IPCC's Working Group 2 (IPCC 2007 2014 2022). SI 2 provides the complete list of selected papers.

2.3 Data extraction

We used both quantitative and qualitative methods to extract data from these 106 articles. On the quantitative side, we included categorical (e.g., area of study) and continuous (number of papers published) data types for analysis.

For qualitative data extraction, we used seven broad themes: the purpose of the study, the key argument of the paper, its conceptual approach, key adaptation strategies discussed, factors of adaptation discussed, outcomes of adaptation discussed, and the components of social-ecological systems used. We also used six broad data categories: spatial scale of adaptation, thematic and sectoral focuses, research scale and temporal distribution, adaptation strategies, hazard considerations, and methods. These data were entered into an Excel spreadsheet for further analysis.

The research scale was coded as local, regional, or national, based on the geographical extent or the focus of analysis at which adaptation measures and responses were evaluated or considered (Landauer et al. 2018). Studies that specifically mentioned households or communities as their unit of analysis were considered local. Studies using the country's climate hotspots as units of analysis were considered regional. Studies that included case studies from all the climate hotspots or focused on understanding, planning, implementing, and evaluating national policies were categorized as national. Thematic focus refers to the general themes or topics considered relevant to livelihood adaptation. Sectoral focus refers to the sectors or domains affected by or involved in adaptation (Rahman et al. 2018).

The spatial distributions or case-study areas were grouped according to the six climate hotspots of Bangladesh (Bangladesh Planning Commission 2018). Temporal distribution refers to the trend of articles being published over time. Types of adaptation refer to various actions or measures undertaken by households to address the impacts of climate change. We categorized adaptation as behavioral, cultural, ecosystem-based, institutional, technological, and infrastructural in forms (Berrang-Ford et al. 2021).

2.4 Data analysis

The articles were analyzed based on the review themes and categories developed for data extraction. Quantitative data extracted from analytical categories and bibliographic information (such as year of publication or document type) were analyzed using basic descriptive statistics. Qualitative data was synthesized using content analysis to identify thematic patterns in the research and key characteristics of adaptation actions (types of strategies, the goal of adaptation, and the mechanisms involved).

The content analysis involved reading the articles to find recurring patterns and themes (Vaismoradi et al. 2013). We first extracted relevant textual information from the selected papers in a spreadsheet according to the themes developed for data extraction. Second, we read the texts carefully and repeatedly, taking note of key information such as the purpose and objective of the study and the main arguments and findings. Third, we categorized and labeled these notes based on the core thematic categories. Relevant portions of text were manually assigned to appropriate themes during this process (Ford et al. 2011). Fourth, we identified and grouped recurring themes using frequency analysis. The selected papers' social and ecological components (indicators) were classified using the eight core concepts of Ostrom's SESs framework (McGinnis and Ostrom 2014; Ostrom 2007, 2009): *resource systems, resource units, governance systems, actors, social, economic, and political*

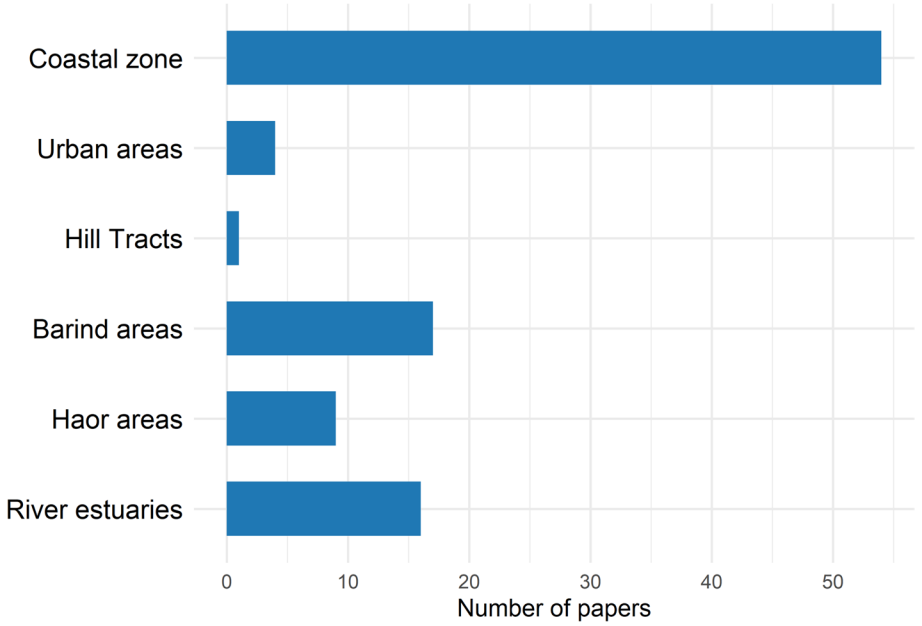

Fig. 3 Geographical (climate hotspots) distribution of the reviewed papers

settings, related ecosystems, interactions, and outcomes. Coded indicators were retrieved, arranged, and recorded under the SESs framework components.

3 Results

3.1 Literature on adaptation research

The number of papers on empirical adaptation research in Bangladesh generally increased during the review period (2007 to 2024). The rise steepened between 2014 and 2024 (presumably influenced by the IPCC's AR5, released in 2014), and the number of papers nearly doubled compared to 2007–2013. We categorized the spatial locations, geographical boundaries, and designated regions discussed in these papers according to the six climate change hotspots defined in the Bangladesh Delta Plan 2100 (Bangladesh Planning Commission 2018). The largest number of studies were conducted in the coastal zone (54), followed by the *barind* (a drought-prone area in northwestern Bangladesh) (17), river systems and estuaries (16), the *haor* (a unique wetland ecosystem in northeastern Bangladesh) and flash flood areas (9), urban areas (4), and the Chattogram Hill Tracts (1) (Fig. 3). Some papers studied multiple hotspots, but the coastal zone was the dominant case-study area.

Local household responses were frequently reported in the context of agriculture, food production, livelihood, and poverty (57 studies). Subnational (municipality and subdistrict) adaptation responses were extensively studied in the southwestern,

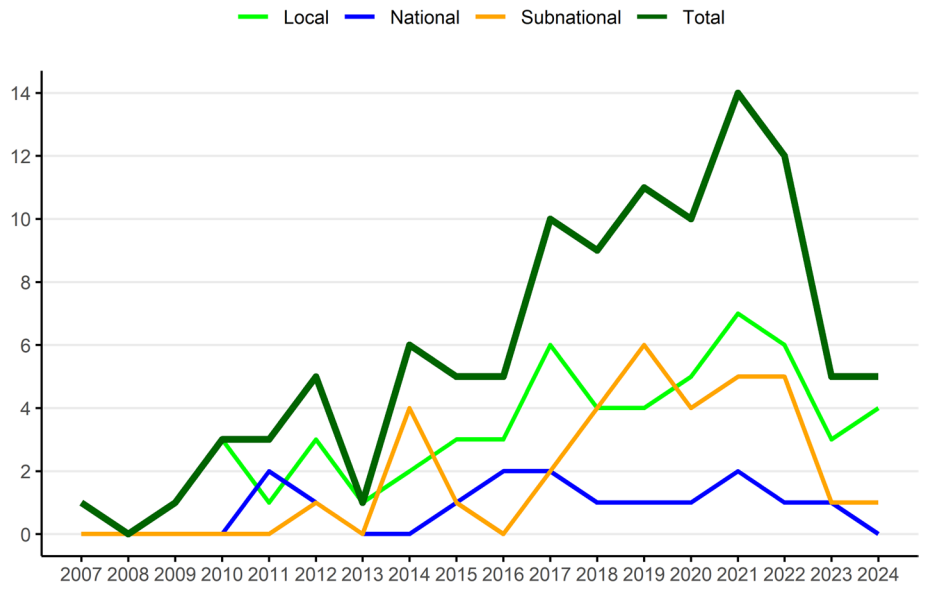

Fig. 4 Spatial and temporal distributions of reviewed papers from 2007 to 2024

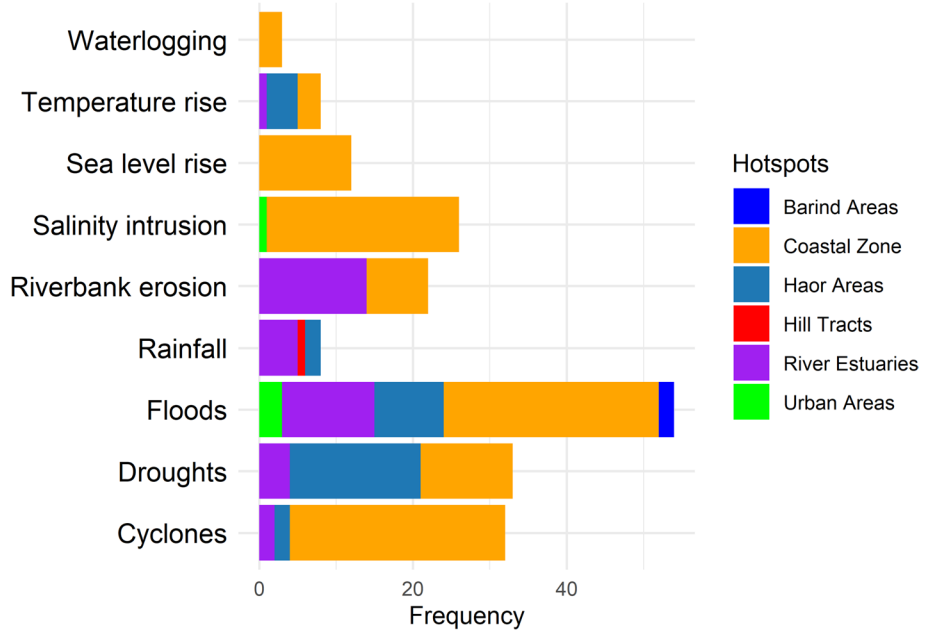

Fig. 5 Frequency of hazards reported in the reviewed papers across climate hotspots

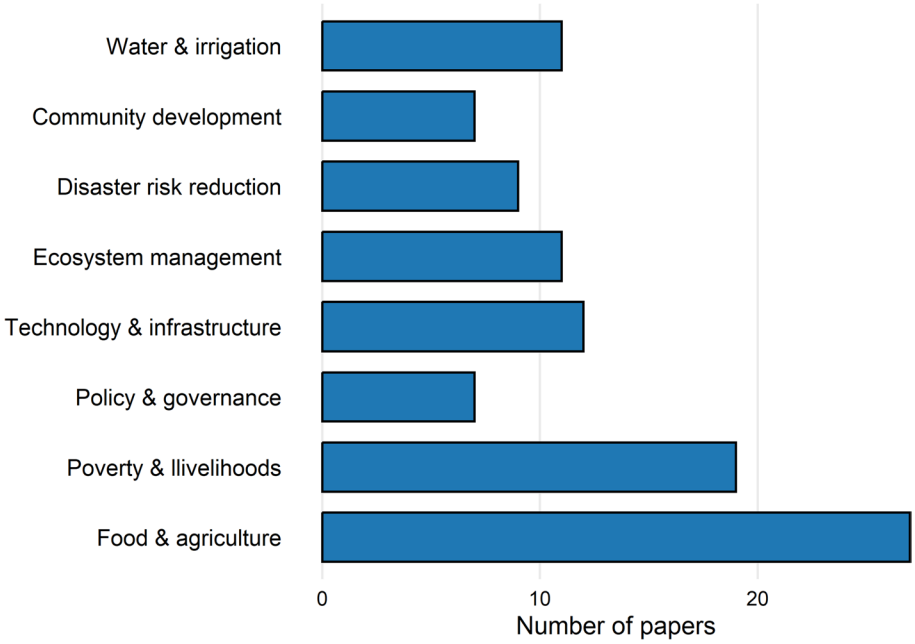

Fig. 6 Thematic and sectoral focuses of the reviewed papers

northwestern, and northwestern regions (34 papers). Adaptation measures at the national level received less attention (15 papers) (Fig. 4).

3.2 Current trends in adaptation research

In the reviewed papers, the most commonly mentioned hazards were floods (54 studies), droughts (33 studies), cyclones and storm surges (32 studies), salinity intrusion (26 studies), riverbank erosion (22 studies), and rainfall variability (14 studies). Adaptation was also associated with rising sea levels, temperatures, and waterlogging. Of these hazards, precipitation variability was a particularly dominant motivator of adaptation in *barind* areas. In *haor* areas, the threat of flash floods spurred adaptive responses. Flooding, salinity intrusion, cyclones, and storm surges were drivers in the coastal zone. Riverbank erosion was the primary driver in the river systems and estuaries (Fig. 5).

The focus of papers varied between economic, infrastructural, and ecological sectors, covering food and agriculture (27 papers), poverty and livelihoods (19), technology and infrastructure (12), water and irrigation (11), ecosystem management (11), disaster risk reduction (9), community development (7), and policy and governance (7) (Fig. 6). We found no studies discussing adaptation strategies in the context of multiple resource sectors.

Thematic and sector focus also varied across regions. Studies on the *haor* and flash flood areas mostly covered poverty and livelihoods, while studies in the *barind* areas focused on food and agriculture. In contrast, studies conducted in the coastal zone focused on government-led planned adaptation strategies involving non-resource sectors such as technology, coastal settlements, and infrastructure.

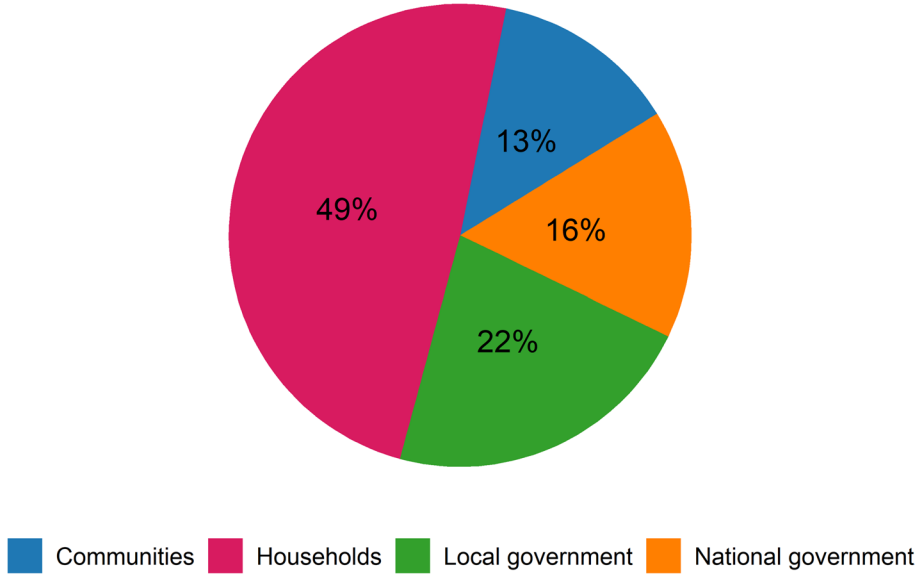

Fig. 7 Levels and actors responding to climate change impacts reported in the reviewed papers

With regard to the stakeholders involved in adaptation, individual households were the most frequently mentioned (49%), followed by local government (22%), national government (16%), and communities (13%) (Fig. 7). NGOs were found working with all these actors to facilitate adaptation responses. Studies focused on lower-income groups and, among these vulnerable groups, on communities near the epicenter of hazards, such as coastlines, riverbanks, floodplains, island areas, and low-lying areas.

3.3 Major conceptual approaches to adaptation studies

Among the conceptual approaches taken by the reviewed papers, impact-based adaptation (prioritizing physical exposure to the impact) was dominant (24 studies). The vulnerability approach (prioritizing the sensitivity and adaptive capacity of the community) was the second-most common (19 papers). Fifteen emphasized locally led or community-based approaches (recognizing the importance of local knowledge and community engagement). Fourteen conceptualized adaptation from the development, policy, or governance perspective. Twelve papers used the livelihood approach (focusing on assets, resources, and income generation). Seven used an ecosystem-based approach (centering on the conservation and sustainable management of ecosystems). Six used the resilience approach. Less common were the system approach (5 papers) and the rights-based or political ecology approach (four papers).

Adaptation responses take the form of behavioral changes, ecosystem-based solutions, institutional regulatory guidelines, infrastructural changes, and technological innovations (Berrang-Ford et al. 2021). Most adaptation responses or options documented in the literature were behavioral in nature (76% of studies), with many also institutional (36%), technological (33%), infrastructural (29%), and ecosystem-based (24%). Behavioral responses involved changes in crop calendar, livelihood, and income diversification.

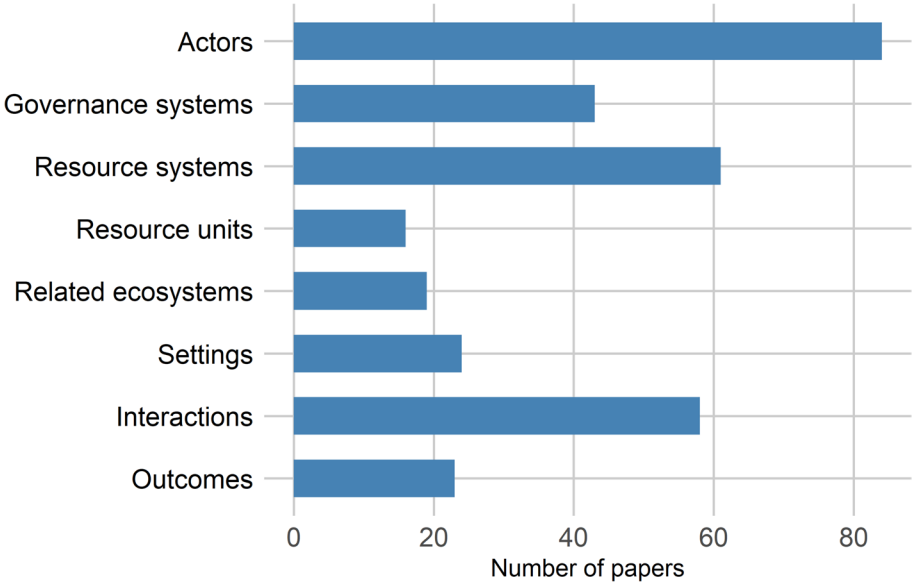

Fig. 8 Coverage of the SESs framework's components in the reviewed papers

Reported institutional forms of adaptation included access to credit facilities and improved agricultural extension services. Technological adaptation responses included forecasting, integrated pest management, and mechanization of farm activities. Infrastructural adaptation responses included building roads, drainage, polders, power supply, embankments, and coastal protection. Ecosystem-based responses included the regeneration of wetlands, local ecosystems, soil management, coastal afforestation, and mulching. Technological and infrastructural responses were common, most notably in the southwestern region, particularly in the water sector. Behavioral adaptation was most common in the northern part of the country. Institutional responses were reported most frequently in the northeastern region. Ecosystems or nature-based responses were used across all regions, most notably in riverine and flood-prone areas. The adaptation responses documented in the literature are shown in SI 3.

Outcomes reported in the papers included higher returns per unit land area, change in farm productivity, higher crop yields, change in income from farming activities, well-being consequences, soil conservation, irrigation efficiency, and adaptive capacity to climate impacts. Twenty-three papers provided implicit or explicit evidence that adaptation activities mitigated climate risks. Five discussed adaptation outcomes in the context of enhancing resilience. Just two papers evaluated risk reduction outcomes after adaptation implementation.

3.4 Components of the SESs covered in adaptation research

Of these papers, most covered one or several components of SESs with respect to various indicators or determinants of households' adaptation choices, but without referring to them as dimensions, subsystems, indicators, or components of SESs.

The most studied component was *actors*, found in about 80% of articles. The *governance systems* component was studied in 43 papers. The second most studied was *resource systems*, found in 61 papers, and *resource units*-related indicators, in 16. The *related ecosystems* component was reported in 19 papers, and indicators related to the *settings* component, in 24. *Interactions* were the third most studied component found in 58 papers, and 23 mentioned *outcome* indicators (Fig. 8). Of all the reviewed papers, 14 studied only one component (*actors*); 25 studied two components, 33 studied three, 18 studied four, and 7 studied five. Four papers studied six components (*resource systems, resource units, governance systems, actors, related ecosystems, and settings*) without attributing their indicators to SESs.

The leading ecological indicators considered were farm size (43%), water availability (36%), soil fertility and salinity (27%), distance to resource systems (24%), and crop yield (21%). Of the social variables, the papers covered household income (78%), education level (69%), experience in farming (63%), access to extension services (42%), credit facilities (37%), and off-farm livelihood opportunities (18%). Among climatic variables, people's perception of the magnitude, intensity, and potential impacts of extreme events were most frequently used to understand the motivations behind adaptation decisions.

4 Discussion

4.1 Summary of the findings and opportunities for adaptation research

The number of papers on adaptation to climate change impacts in Bangladesh has steadily grown, though their geographical distribution is still uneven. The *barind* and *haor* areas are still underrepresented compared to the coastal zone. However, the two areas are essential to the national economy and biodiversity conservation (BBS 2019). It appears that adaptation research is driven by the study areas' relative physical vulnerability and exposure rather than their value of ecosystem services. We also note that most studies use a single case study design, focusing on one area of study. There is a need to develop a framework with common components to integrate diverse social and ecological characteristics from different climate hotspots of the country and inform comprehensive adaptation solutions. Many studies advocate interdisciplinarity (e.g., Haque et al. 2020), but integrating insights from fields as diverse as ecology, sociology, economics, and political science can be difficult without a coherent framework.

The early literature on climate change impacts in Bangladesh focused on the coastal region and its physical vulnerability. Socioeconomic vulnerability and adaptation-focused research across the country only emerged in the late 2000s. It suggests the country's geophysical exposure and socioeconomic vulnerability to climate change (Saroar and Routray 2010) that remain the dominant focus of adaptation studies. As climate change continues to affect opportunities for farming activities, contemporary papers focus on the food and agriculture sector (Hoque et al. 2022). However, these vulnerability or sector-specific studies may fail to explain the multidimensional interactions and challenges associated with adaptation strategies.

There was little evidence of growth in the number of papers that applied any SESs lens. The number of papers analyzing adaptation processes as systems is insignificant compared to other approaches, such as mainstreaming, locally led adaptation, ecosystem-based adaptation, or resilience. More holistic and intersectoral approaches are rare. Climate stimuli,

such as floods, cyclones, and droughts, are taken to be the primary motivators of adaptation—rather than any social or economic objectives, such as income, market incentives, or traditional lifestyles. However, adaptation depends not only on hazards or socioeconomic conditions but also on people's interactions with and dependence on ecosystems in the form of livelihood activities (Pelling 2010). This underscores the need for an integrated approach to adaptation that captures the relationships between people, the local ecosystems that provide livelihoods, and the impacts of climate change (Hossain et al. 2023).

So far, the climate change adaptation literature mainly focuses on vulnerability assessments, potential adaptation choices and their determinants, barriers to adaptation, and households' climate perceptions (Ahmed et al. 2022; Anik and Khan 2012; Habiba et al. 2012; Hasan and Kumar 2019; Kabir et al. 2021; Sarker et al. 2013). Most studies explain farmers' adaptation choices in the context of households' socioeconomic and demographic status (Delaporte and Maurel 2016; Fenton et al. 2017; Islam et al. 2020). However, they do not provide sufficient evidence on how social and ecological attributes are related and affect one another in the context of farmers' varying adaptation choices. Evidence on the effectiveness of adaptation strategies after implementation is also scarce (Haque et al. 2020; Kulsum et al. 2021; Pouliotte et al. 2009). Yet this is imperative to shed light on current strategies' contribution to livelihood improvements and inform policies.

Most of the studies we reviewed focused on how social systems (e.g., economic and livelihood activities) could adapt to climate change impacts, without recognizing the need to consider the corresponding ecological systems (e.g., Jordan 2014). Fewer studies systematically examined how adaptation occurs in social and ecological systems (e.g., agroeconomic systems) and how these systems influence each other. Most of the studies focused on either physical impacts (e.g., hazards) or socioeconomic vulnerability (e.g., poverty), but not on the interdependent system of ecosystem, livelihood activities, and institutions that need to adapt as a whole. Consequently, crucial gaps remain in identifying multidimensional variables that can capture the complexity of the interactions between social and ecological systems. For example, agricultural practices (a social factor) may depend on local water availability and soil health (ecological factors). Simultaneously, those same agricultural practices can impact the ecosystem through land use change, groundwater extraction, or soil degradation. However, measuring the full range of these interactions is complex. Gaps in identifying the diverse variables make it difficult to fully understand or predict the outcomes of adaptation strategies.

Most reported adaptation measures were implemented at one scale (the household). How these household-scale adaptation strategies are nested within larger scales such as farm, community, region, or nation has not been explored. Yet these cross-scale interactions are critical to understanding the barriers to and enablers of adaptation actions at the household scale (Moser and Ekstrom 2010). Studying the interconnectivity between scales is essential, as implementing specific initiatives at one scale may affect outcomes at larger or smaller scales (Adger et al. 2005). For example, a single initiative at the national scale (subsidies on farm machinery, say) can facilitate several household-scale adaptation responses (such as mechanization of farming, crop diversification, and soil conservation). Most studies have focused on agriculture, reflecting households' economic dependence on this sector (e.g., Arfanuzzaman et al. 2016). Yet studies of how this sector is coupled with water, fisheries, wetlands, infrastructure, technology, or governance are rare.

Studies also generally assume that household-level adaptations will be highly effective, without evaluating them empirically (e.g., Collins 2014; Hoque et al. 2017). This lack of outcome evaluations is a significant research gap. Most of the reported

adaptation interventions were aimed at short-term risk reduction at the household scale, as opposed to long-term strategic planning across multiple scales (such as households, communities, and ecological zones). This short-termism and individual-scale consideration could unintentionally increase vulnerability and make future adaptation more difficult (Wilson et al. 2020). Another way to say it is that most of the adaptation responses reported in this literature were incremental, targeting short-term climatic shocks and lacking long-term adaptive responses to climate change. But such transformational measures (changes in social–ecological relationships, such as shifting from agriculture to aquaculture in coastal areas) are urgently needed in Bangladesh (Islam et al. 2022; MoEFCC 2022).

From the early 2010s, studies have emphasized gender, political ecology, and social capital approaches to adaptation (Alam et al. 2016 Masud-All-Kamal et al. 2021; Rotberg 2010). Contemporary studies increasingly focus on policy and governance (Alam et al. 2020; Ayers et al. 2014 Ayers 2011; Ishtiaque et al. 2021; Islam and Nursey-Bray 2017)—approaches that emphasize how locally-led adaptation strategies could be integrated into larger sectoral development planning (mainstreaming). Like the work on climate finance, this approach feeds into the question of funding. Bangladesh is already spending $1 billion annually on climate change adaptation. In the medium term (up to 2030), the country will require at least $12.5 billion, or around 3% of GDP, for climate action (World Bank 2022). However, the literature provides little information on how governance aspects are related to or influence adaptation decision-making.

A few of the studies we reviewed (five) advocated a system approach to adaptation research (Haque et al. 2020; Haque 2021; Huq et al. 2015). However, these studies mostly considered relationships between social processes and did not apply any framework that systematically captures the multiple dimensions of adaptation. This emphasis on system perspectives is likely to strengthen following the release of IPCC's AR6, which strongly emphasizes the interactions among climate, ecosystems, and society (IPCC 2022). Across the board, conceptual approaches to adaptation have been driven by the development orientation of global climate change institutions (IPCC, UNFCC, Green Climate Fund, and so on) rather than the local adaptation goals or sustainability of SESs.

These studies concentrated on the actors and sectors where adaptation happens. However, to understand the complexity of adaptation strategies, it is necessary to integrate additional related sectors and actors (Nelson et al. 2007). Although every case and its context are unique, a common set of components is essential to integrate diverse findings and develop associations among diverse fields of study (McGinnis and Ostrom 2014) that can help us develop inclusive adaptation policies. Many studies use variables in general terms without distinguishing their system characteristics (e.g., Kabir et al. 2021; Khan et al. 2022). This lack of detail can reduce the complexity of adaptation research, treating it solely to study climate impacts rather than multifaceted processes involving social, ecological, and institutional factors. Characterizing variables according to system characteristics can help us understand the interrelationships between farmers' adaptation decision-making and its social and ecological determinants. There is a need for an approach that does not focus on the problem in isolation but looks at how it influences and is influenced by other related processes (Hossain et al. 2023). This is why we propose adaptation decision-making situations are conceptualized in the context of SESs and their constituting components.

4.2 Knowledge gaps and the scope for future research

Adaptation research in Bangladesh has made considerable progress, but several knowledge gaps need to be addressed in future research. Box 1 outlines the areas for future research.

Box 1. Areas for future research

SES-based research. Climate change adaptation is a multifaceted challenge that requires an integrated approach. The SESs approach analyzes the underlying interconnectedness between variables and their future directions. System-based research designs using multidimensional variables under a multi-level, multi-tiered framework may be more applicable to adaptation decision-making and understanding the complexities involved in adaptation planning and implementation. The SES approach can help farmers understand how their actions are connected with ecological and social factors, such as soil health, water availability, market conditions, and policies. Thinking from an SESs perspective can also enable farmers to avoid maladaptive actions as they consider preserving long-term adaptive capacities over short-term economic benefits.

Cross-sectoral and institutional approaches. Climate change adaptation often involves a range of sectors, such as water, agriculture, health, infrastructure, and ecosystems. This is necessary because climate change does not affect one sector but a whole chain of sectors and their interactions. It suggests the importance of recognize the sectoral interdependencies in adaptation studies. So, future research should develop and operationalize frameworks that facilitate cross-scale institutional integration. Institutional integration can ensure resource allocation and utilization efficiency through maintaining coordination among related sectors, and local, regional, and national institutions, ensuring that adaptation policies align with community needs. Developing effective integration mechanisms can also strengthen the scalability of adaptation strategies.

Integration of autonomous and planned adaptation. Locally-led autonomous adaptation strategies embody valuable traditional knowledge of local ecosystems and livelihood practices. Yet, there is a lack of an established approach to integrate these practices into national adaptation planning. An integrative approach can identify trade-offs and synergies between different types of adaptation strategies. For example, Bangladesh's large-scale flood control, drainage, and irrigation projects were primarily constructed to enhance agricultural productivity and food security, while coastal embankments were designed to protect communities from storm surges. Although these measures have played a crucial role in reducing climate-related risks, they were not originally conceived as a planned adaptation to climate change. Given the increasing impacts of climate change, future research should explore how these existing infrastructures can be retrofitted or integrated into autonomous adaptation planning

Assess the effectiveness of adaptation strategies. The reviewed literature provides limited evidence on the effectiveness of adaptation strategies. While some research has examined monetary (increased farm income, cost savings) and production-based (yield stability or increase) outcomes, a more comprehensive approach, i.e., resilience-based assessment, is necessary to evaluate the effectiveness of adaptation strategies. The success of adaptation strategies is often reflected in avoiding harm and improving households' adaptive capacity over time. It makes measuring the effectiveness of adaptation strategies with cross-sectional data challenging. However, using longitudinal data, monitoring changes in key ecological, economic, institutional, and learning variables can provide valuable insights into adaptation effectiveness. To ensure adaptation strategies achieve their goals, future research should focus on developing robust evaluation and monitoring tools and metrics

Methodological perspective. Future research should prioritize applying system analysis tools, e.g., network analysis, system dynamics modeling, and causal loop diagrams, to explore and explain the complexity involved in adaptation decision-making. These tools can help identify key drivers, feedback, and interactions within social-ecological systems, providing a holistic view of adaptation processes. Network analysis can identify key social-ecological linkages that influence farmers' adaptation behavior. System dynamics modeling can simulate long-term adaptation decision-making under different climate scenarios. Exploring causal relationships among social and ecological variables can uncover underlying drivers, leverage points, and barriers to adaptation. These tools can help to design more effective policies and strategies under increasing climate uncertainty

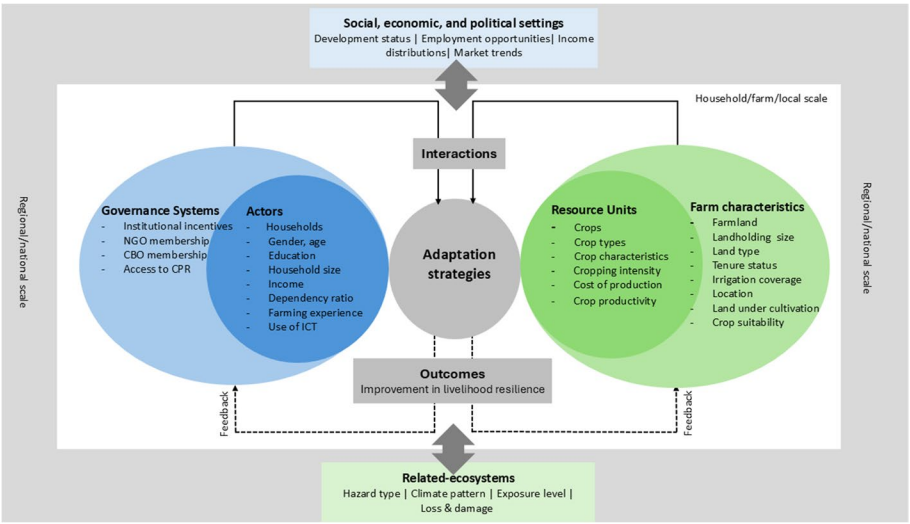

Fig. 9 Adaptation social-ecological systems framework

4.3 Applying an SESs framework in adaptation research

Most studies explained adaptation strategies from a socioeconomic, demographic, or climate impact perspective, focusing on the agency or capacity of the actors implementing the strategies (Ahmed et al. 2021; Al-Amin et al. 2019; Brouwer et al. 2007; Jordan 2014). Those studies that considered households' adaptation choices on multiple dimensions did so without applying any systematic conceptualization of adaptation processes. Studies mostly referred to specific adaptation strategies, focusing on particular ways of adjusting to the effects of climate change (e.g., Emran et al. 2021). The literature also lacks a conceptual approach that can integrate adaptive policy management to keep pace with evolving climate challenges. Addressing these knowledge gaps becomes more pressing as climate change, ecosystems, and adaptation processes become more entangled.

Given the above knowledge gaps, we conceptualize adaptation actions, initiatives, strategies, or practices through a conceptual framework based on the SES approach (Berkes and Folke 1998), which can comprehend adaptation holistically, and which is missing at present. This framework is conceived on the core conceptual components of Ostrom's SES framework (see Fig. 9). It describes six interacting components, or subsystems: *resource system, resource units, governance systems, actors, settings (social, economic, and political), and related ecosystems*—along with their *interactions* and *outcomes* (McGinnis and Ostrom 2014; Ostrom 2007, 2009). The subsystems are nested and interdependent, as indicated by the color shading in the figure. The characteristics of the subsystems determine the pattern of *interactions*. *Interactions* are decision situations, where adaptation choices are made, and they are implemented by the *actors*.

The first-level subsystem, *actors*, reflects socioeconomic and demographic characteristics, such as income, household size, and use of information technology, which immediately affect farmers' adaptation decisions at a given time. In adaptation studies, *actors* are farmers who take steps toward adaptation. *Governance systems* set institutional arrangements for adaptation and regulate farmers' access and use of *resource systems*. The latter

reflect farm characteristics, such as landholdings, cropping intensity, and irrigation, that set the biophysical conditions for adaptation strategies. *Resource units* (such as production cost and production amount) are part of *resource systems* and act as incentives for adaptation. The outermost subsystem, *settings*, sets the broader social, economic, and political conditions (enabling or inhibiting) where farmers implement their adaptation strategies. *Related ecosystems* determine the climatic conditions to which farmers adapt. The *resource systems*, *resource units*, *governance systems*, and *actors* subsystems are nested within *settings* and *related ecosystems* (McGinnis and Ostrom 2014). Any changes in higher-tier sub-systems (variables) can impact adaptation processes at a lower scale. Classifying and arranging variables across different scales demonstrates the cross-scale operability of this framework.

We place climate change *adaptation strategies* at the point of *interactions* of the social and ecological systems. Adaptation strategies are actions taken by households to maintain or improve their farming activities and, thus, their livelihood. Adaptation strategies mediate the linkages between social and ecological systems. *Actors* decide on adaptation strategies based on available resources, rules, information, economic incentives, and climate conditions and must balance ecological sustainability with social well-being. *Interactions* lead to *outcomes*. Evaluation of *outcomes* is crucial to effectively managing adaptation strategies (agricultural activities). Dashed arrows in the diagram indicate feedback from *outcomes* to system components, underscoring the dynamic nature of the framework. In this framework, *outcome*s of interactions can be evaluated by measuring the improvements in livelihood resilience indicators.

Our outcome evaluation criteria are developed based on Speranza et al. (2014)'s livelihood resilience indicators. In line with their work, we categorized indicators into three broad dimensions: resource (buffer) capacity, institutional (self-organization) capacity, and learning capacity. Resource capacity measures livelihood capitals or assets that help maintain households' livelihood activities (e.g., farming). Institutional capacity refers to collective action, self-reliance, and the effectiveness of social networks for livelihood activities. Learning capacity means the capacity to use knowledge and skills for livelihood purposes. Livelihood resilience is achieved when resource capacity exists and remains stable, self-organization is promoted, and learning takes place (Speranza et al. 2014). The framework's subsystems and their indicators are detailed in SI 4.

Adaptation strategies that fail to address social and ecological systems simultaneously or achieve their goals at the cost of each other can lead to maladaptation (Eriksen et al. 2021; Rahman and Hickey 2019). The SES framework effectively balances these systems and can provide researchers with an integrated perspective for investigating adaptation. The framework's components provide a common language that integrates knowledge from multiple disciplines and organizes variables for case comparison (Binder et al. 2013; Hinkel et al. 2014). By aligning insights from ecology, economics, sociology, and governance, the framework can help identify adaptive measures that are ecologically sustainable and socially beneficial in the context of changing climate.

The SESs framework is mainly applied at the community or resource sector level (Partelow 2018), and its use at the household level could be challenging. To address this challenge, we contextualized the first-tier components in line with the household-scale adaptation variables. For example, *resource systems* have been contextualized as the farmland's biophysical conditions. The SESs approach also faces criticism for operational difficulty (Nagel and Partelow 2022; Schoon and Leeuw 2015; Stojanovic et al. 2016). The approach's interdisciplinarity can make it hard to implement, especially in policymaking, where straightforward guidelines are often preferred. However, analytical complexity is

unavoidable as climate change becomes more intertwined with social, economic, and ecological systems (Reed et al. 2013). Adaptation strategies may reinforce existing vulnerabilities without addressing the complexities rather than reducing them.

5 Conclusions

We systematically reviewed the trends in adaptation research in Bangladesh from 2007 to 2024 through the lens of the social-ecological system approach. We have identified specific knowledge gaps in scholarship to inform future adaptation research using the SES approach. The number of studies in this field increased across the review period, with a significant acceleration starting around 2014. While the topics have become more varied, the literature remains concentrated on understanding the nature of household-level adaptation strategies and exploring their determinants. The *systematic* study of adaptation processes and their decision-making contexts remains scarce. The knowledge gaps and future implications discussed in the literature (e.g., transformative response, adaptation pathways, adaptive governance) suggest the need for a holistic, multi-scalar framework that integrates adaptation strategies within a system of concern, such as coastal agriculture. Given the conceptual limitations we see in the current literature, we propose a conceptual framework for climate change adaptation that integrates the social and ecological systems that determine households' adaptation decision-making.

Our findings have significant implications for adaptation research. The proposed framework represents a conceptual broadening over the current actor-oriented approaches, which mainly focus on isolated processes rather than considering adaptation strategies as complex, interlinked systems. Variables identified in this study could guide national-level adaptation strategies, such as the Delta Plan 2100 and the National Adaptation Plan of Bangladesh (2023–2050), to identify leverage points in the implementation of local-level adaptation projects. Moreover, with its multiscale focus, our framework can be applied to identify location-specific enablers of and barriers to farm-level strategies that can feed into developing agroecosystem-based adaptation policies.

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Data availability The data supporting this study's findings are openly available.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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