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Studies on adaptive capacity to climate change: a synthesis of changing concepts, dimensions, and indicators

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Adaptive capacity was recognized as one of the critical components of vulnerability assessment in 2001 by the Intergovernmental Panel on Climate Change. Adaptive capacity extends beyond the mere accumulation of resources to encompass the willingness and ability to transform available resources into adaptive actions. In this context, adaptive capacity denotes the ability of social-ecological systems to adjust to the negative effects of environmental change or recovery from it. Hence, enhancing adaptive capacity enriches the ability to cope with a wider spectrum and greater magnitude of climate impacts. Based on the literature review and content analysis, this study explores the foundational concepts of adaptive capacity and further assesses the evolving focus on concept, scale, geographical emphasis, dimensions, and indicators through a systematic review. The findings underscore that adaptive capacity constitutes a multidimensional and interdisciplinary research domain characterized by a range of dimensions and indicators, and diverse methods and techniques at various geographic scales. The study found that adaptive capacity research has predominantly centered on asset-based analyses within the Sustainable Livelihoods Framework in the earlier stage. However, since the past decade, the focus has shifted to indicators like agency, technology, innovation, governance, knowledge, information, and infrastructure, besides climate variability and socio-economic and cultural diversity. It is suggested that to bridge the gap between adaptive capacity and actual adaptation action, policy interventions need to be targeted. The study concludes that, despite abundant research and available literature on climate change and adaptation, there is still a lack of context-specific understanding, particularly from an insider's perspective in South Asia.

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Introduction

The global policy framework identifies mitigation and adaptation as two key strategies to address the effects of climate change. Mitigation focuses on human interventions to reduce greenhouse gas (GHG) emissions as a cause of climate change, whereas adaptation involves making adjustments to anticipated climate changes and their impacts, depending on the capacities of systems, institutions, humans, and other organisms (González Ornelas and Muñoz Meléndez 2021). Adaptive capacity (AC) plays a crucial role in shaping adaptation decisions and actions (IPCC 2007). In 2001, the Intergovernmental Panel on Climate Change (IPCC) recognized adaptive capacity as a critical component of vulnerability. Since then, the concept of adaptive capacity has gained substantial attention from researchers focusing on socio-ecological and environmental changes, leading to a notable surge in research activity as an evolving field of research (Datta and Behera 2022; Siders 2019; Smit and Wandel 2006; Vallury et al. 2022).

Vulnerability is commonly construed as an amalgamation of a system's exposure, sensitivity, and adaptive capacity (Adger 2006; Smit and Pilifosova 2003; Smit and Wandel 2006). Whereas, adaptive capacity comprises both biophysical and socio-economic factors that enhance human capability to adapt to and recover from the adverse impacts of climate change (Engle 2011). Consequently, higher sensitivity and exposure escalate vulnerability, while adaptive capacity serves to reduce systemic vulnerability. In this sense, exposure refers to the condition of individuals, infrastructure, housing, production capacities, and tangible human assets situated in areas prone to hazards. Sensitivity reflects the degree to which people rely on affected resources. Adaptive capacity represents a system's ability to mobilize resources in response to stresses and shocks, constituting an invaluable latent attribute. It enhances a system's resilience in dealing with a diverse array and varying scales of climate impacts (Brooks et al. 2005; Engle 2011; Holling 1973; Smit and Wandel 2006). The level of adaptive capacity pivots on the flexibility to embrace change and the proficiency in utilizing resources for implementing adaptation measures.

Adaptive capacity can be seen as a prerequisite to facilitate adaptation actions. It encompasses socio-economic and biophysical components, along with the agency to activate those elements into actions during shocks and stress periods (Engle 2011; Nelson et al. 2007), prevention, and post-disaster management. In this context, adaptive capacity emerges as a positive attribute of a system that can lessen the vulnerability associated with climate change (Engle 2011). Therefore, adaptation practices are deeply tied to adaptive capacities (IPCC 2007) and the willingness and ability to translate the available resources into adaptation actions (Cinner et al. 2018). Adaptive capacity encompasses a range of factors, including economic resources, technology, information and skills, infrastructure, institutions, and social factors that enable adaptation (IPCC 2014). In the latter half of the current decade, the institutional role and implementation mechanism are emphasized as the backbone of effective adaptation, and weak governance mechanisms and institutional understanding of context-specific adaptation have identified adaptation gaps in several literatures (Adapt 2019; Berkhout and Dow 2023; IPCC 2022; UNEP 2021).

Adaptive capacity is multidimensional and context-specific. It varies across countries, communities, groups, and individuals (Smit and Wandel 2006) and as a highly interdisciplinary research field, it employs a diverse array of scales, methods, and techniques (Siders 2019). The concept of transformative adaptation is leading climate change and adaptive capacity studies to adopt transdisciplinary approaches, highlighting the importance of collaborative methods that integrate diverse knowledge systems

and disciplines to tackle climate challenges effectively (Hellin et al. 2022; Leal Filho et al. 2021).

South Asia, with 1.8 billion inhabitants, stands as a densely populated region with a high rate of population growth. One-third of the population, however, still lives below the poverty line in this region. The region has also been identified as a climate change hotspot. Due to its complex topography with social and cultural diversity, two-thirds of its citizens live in rural areas and rely on rain-fed agriculture (World Bank 2021). The agricultural sector is particularly vulnerable in this region since rising temperatures exacerbate drought conditions and unpredictable rainfall patterns negatively impact agricultural activities. Farming in South Asia is facing several climate risks, such as droughts, floods, and crop pests and diseases (Aryal et al. 2021). There is growing evidence that the consequences of climate change will exacerbate these problems, resulting in food insecurity and hunger, as well as increasing prices of agricultural products (Aryal et al. 2020). Despite this, existing studies in South Asia have not adequately addressed the factors affecting farmers' adaptive capacity. In this context, the objective of this research synthesis is to examine the evolving concept of adaptive capacity, its determinants, and the geographical focus of the available studies over time with a due focus on farmers' adaptive capacity in South Asia. This study also seeks to pinpoint the primary dimensions and indicators employed in adaptive capacity research, explore gaps, and suggest potential directions for future studies that can contribute to devising a better climate change adaptation policy and action.

Methods and materials

This paper has adopted the research synthesis approach to assess the extensive range of existing literature on adaptive capacity and its systematic review. The methods and process of the article search, selection, and collection largely followed a systematic literature review method, which conceptually and practically considered a suitable approach to increase methodological transparency and consistency in synthesizing the findings (Berrang-Ford et al. 2015; Pullin and Stewart 2006).

The Google Scholar advanced search, and the Web of Science title search platforms were used for the literature using the keywords "adaptive capacity." The search literature covered the period from 1973 up to 2022. Based on the search criteria, Google Scholar yielded 3530 articles, and 1873 articles from the Web of Science published in the last 50 years. In addition, 12 websites of international peer-reviewed journals relevant to climate change adaptation and socio-ecological sciences were also accessed. The search for articles was based on the criteria of relevance to the topic, recent publication, and high citation frequency. Many of those papers were repeated searches from Google Scholar and Web of Science, which were filtered during the systematic review process and excluded repeated papers as per the framework presented in Fig. 1.

The inclusion criteria to select the relevant articles for the final review were set as (a) prioritizing review papers that already summarized the results of conceptual and empirical studies, in general, e.g., Siders (2019) and Vallury et al. (2022), (b) inclusion of articles that addressed determinants of adaptive capacity (i.e., dimensions and indicators), (c) the geographic search of empirical studies was prioritized to South Asia, and (d) further, inclusion of studies that focused on thematic issues like rural livelihoods, agriculture, and fisheries in South Asia. A total of 175 full-length articles that matched the criteria were selected for final review and analysis.

The selected articles were arranged in chronological order and assigned geographic codes to analyze temporal and spatial coverage. A content analysis was conducted to examine the selected

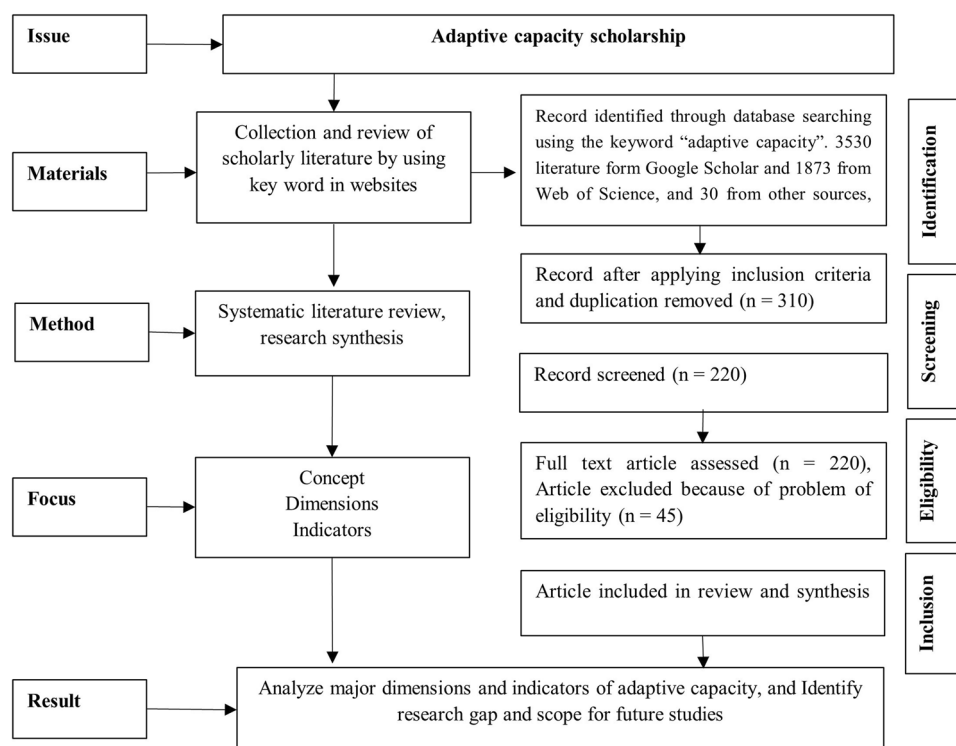


Fig. 1 Study framework and systematic review process (modified after Moher et al. 2009; Berrang-Ford et al. 2015).

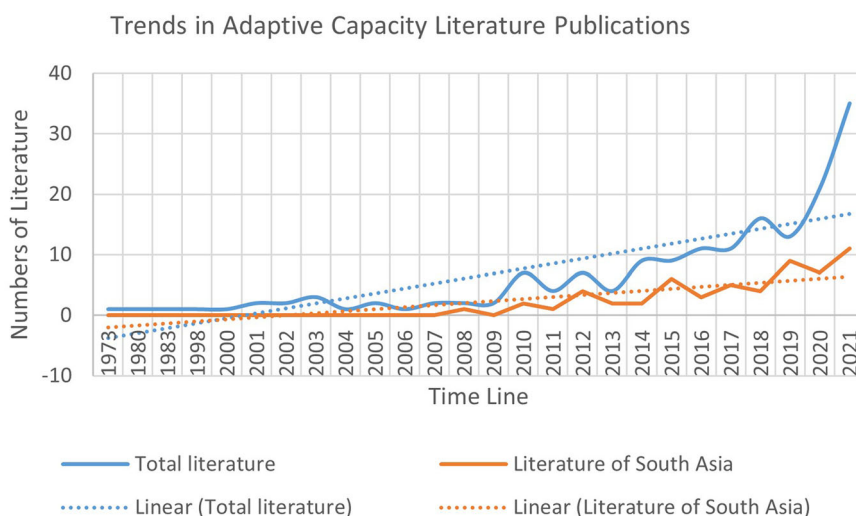


Fig. 2 Trend in adaptive capacity literature publication.

articles. An analysis matrix was developed in which basic information about the study, conceptual approach, dimensions and indicators, findings, and the research gaps were entered. The review matrix provided critical insight into the study approaches, methods, and findings.

Findings

Publication trend, scale, and methods of analysis. Studies on adaptive capacity have been increasing over time. Before 2000, very limited literature on adaptive capacity was found. The number of studies on adaptive capacity had a smooth growth trend between 2000 and 2015 and proliferated between the period 2010 and 2020. The adaptive capacity literature of South Asia almost follows a similar trend with global literature (Fig. 2).

Community is found to be the most common unit of analysis for adaptive capacity studies when geographic scale is considered. Among the 175 studies covered in this paper, 48% ($n = 84$) were community-level studies. There was relatively lower coverage on regional, national, and global scales with 10.86%, 9.71%, and 4%, respectively. In total, 23% ($n = 48$) of papers were on theoretical discussion (Fig. 3).

A wide range of quantitative, qualitative, and mixed research methods and techniques have been used in adaptive capacity research. Out of the 175 publications, 44.57% ($n = 78$) applied quantitative methods, and 20.57% ($n = 36$) applied mixed methods. Similarly, 29.14% ($n = 51$) were review-based studies and used different methods (i.e. by combining qualitative and quantitative methods) Only 5.71% ($n = 10$) employed qualitative methods (Fig. 4). The studies have covered a wide range of sector-

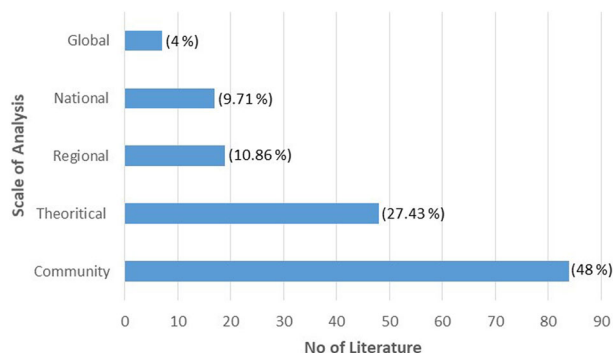


Fig. 3 Scale of analysis of adaptive capacity studies.

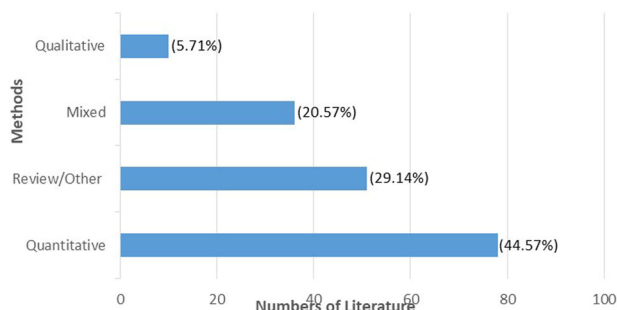


Fig. 4 Methods applied in adaptive capacity studies.

specific and topical scales. There is a strong focus on resource-based livelihood, agriculture, and fishing, with the indicators largely aligned to a sustainable livelihood approach. It has found that, out of the 175 selected studies, 48% ($n = 84$) are from Asia, out of which 33.71% ($n = 59$) are from South Asia. Similarly, 16.57% ($n = 29$) are from Africa, and only 6.29% ($n = 11$) are from America and Europe. Furthermore, 29.14% ($n = 51$) are general articles, especially review-based studies, and cover different geographical regions.

Dimension and indicators used. The central question in adaptive capacity research revolves around identifying the factors that determine a household's adaptive capacity. Scholars have employed various indicators and research frameworks to assess these determinants. Based on the dimensions or applied frameworks, the available studies on it can be grouped into three primary categories. The first category of studies exclusively relies on the Sustainable Livelihood Framework (SLF), offering a research approach to evaluate diverse livelihood assets to achieve sustainability in various contexts (Scoones 1998). The second category of research predominantly adopts a modified SLF as its research basis. Scholars within this category modify the SLF by introducing additional dimensions to the framework. The third category of studies deviates from the SLF and introduces alternative dimensions. For instance, Gupta et al. (2010) emphasized the importance of institutions in enhancing adaptive capacity. The adopted dimensions and indicators of adaptive capacity are summarized in Table 1.

Discussion

Changing definition and research focus of adaptive capacity. Adaptive capacity is assessed primarily concerning climate change. Previously, it was termed as a coping capacity (IPCC 2001). Thereafter, many scholars have conceptualized it in different ways, such as a system's flexibility to better cope with stresses (Adger and Agnew 2004), resource management and

mobilization (Armitage 2005; Nelson et al. 2007), tools to manage risk (Wall and Marzall 2006), resilience and capacity to adjust to change (IPCC 2007), and a system's ability to manage exposure and sensitivity (Preston and Stafford-Smith 2009). In the later decade, the focus was on social-human-ecological aspects, such as the responsive capacity of a social actor (Gupta et al. 2010), the latent potential of socio-ecological systems (Engle 2011), the ability of systems, institutions, humans, and organisms to adjust (IPCC 2014), the willingness and ability to translate available resources into effective adaptation action (Cinner et al. 2018). Adaptive capacity refers to the ability of social-ecological systems to adapt to, navigate, and recover from the impacts of environmental change (Vallury et al. 2022). The adjustment process of human and natural systems, along with institutional frameworks, policies, and plans that establish adaptation goals, define responsibilities and commitment mechanisms, coordinate among stakeholders, and build adaptive capacity, will support sustained adaptation actions (IPCC 2022). The most common definitions over time are summarized in Table 2.

The concept of adaptive capacity has endured significantly from a coping strategy for climate variability (IPCC 2001) to encompass the ability to adjust not only natural systems but also human systems, institutions, and other organisms (IPCC 2022). The earlier definition was more nature-centric, whereas the later one places a greater emphasis on human systems and other organisms including the natural system.

The conceptual shift can be observed in adaptive capacity research. Gupta et al. (2010) played a major role in reshaping its research by placing "institutions" at the core of studies using qualitative methodology. Consequently, many researchers began incorporating institutions and governance as crucial determinants of it in their studies. Cinner et al. (2018) emphasized the significance of "agency" as a key determinant, highlighting its role in converting resources into effective adaptation actions. Initially, livelihood assets were considered as the primary determinant but later institutions and agencies were identified as the critical determinants of adaptive capacity.

This study found a predominant use of quantitative methods in adaptive capacity research, with 44.7% of papers employed quantitative methods, whereas qualitative methods were used far less frequently, accounting for only 5.71%. Scholars most often used quantitative methods with statistical analysis for large-scale comparison and ranking of the adaptive capacity of multiple countries (Brooks et al. 2005; Siders 2019). However, the application of the qualitative method is gradually increasing, primarily to explore the specific vulnerability and capacity context of individual communities. The increase of focus on qualitative methods at the community scale reflects that there is increasing awareness of research practice on context-specific adaptation. The diverse socio-cultural and physical environments underscore the importance of the "no one size fits all" adaptation principle.

In terms of research scale, this study found that the community level was the most dominant, with 48% of studies focusing on this scale. This was followed by a gradual decline in studies at the regional, national, and global levels (Fig. 3). Siders (2019) reported similar findings, indicating that community and household levels were the key unit of analysis in adaptive capacity research, with each accounting for 20% of the publications. Vallury et al. (2022) found that 26.5% ($n = 76$) of adaptive capacity studies were conducted at the community level, but some overlaps were also found in community-level studies, as an aggregated adaptive capacity of households.

Similar to this study, Siders (2019) also found that national and international scales were among the least common in adaptive capacity research, representing only 3% ($n = 9$) and 2% ($n = 5$) of

Table 1 Summary of the adopted dimensions and indicators of adaptive capacity.

Dimension	Adopted indicators	Number of references
Physical assets	Access to irrigation, types of irrigation, road accessibility, proximity to the market, farm tenure, farm size, access to electricity, number of livestock, mobile phone, radio/TV, access to health services	15
Human assets	Education, skill, health status, farming experience, dependency ratio, number of adult populations, population capable of working	14
Financial assets	Types of income source, income from remittance, annual income, income from farming, ownership of livestock, access to financial services, amount of loan, total savings	12
Social assets	Membership in social organizations, social networks, social exclusion, collective action, support from the community, cooperation in farming activities, social cohesion	8
Knowledge, information, and communication	Availability of weather information, access to weather information, mechanism of information interpretation/sharing, access to agricultural input, knowledge of improved climate-adaptive seed varieties	8
Diversity and flexibility	Type of livelihoods, flexibility in decision-making, access to markets, access to climate information, capacity to deal with hazards, and access to modern farm input	5
Institutions and agency	Informal community institutions, formal institutions, local taboos participation in specific activities, community rules restricting access and use of resources, authority, disaster relief assistance, and government subsidies	4
Infrastructures and services	Transport, extension services, financial services, and education services	4
Technology and innovation	Investment in new occupations/sectors/technologies, knowledge of seed varieties, adaptation to new practices, and access to soil fertility retention techniques	4
Governance	Local-level policy/legislation, transparency in decision-making, and climate change-related interventions	4
Natural assets	Access to drinking water, access to grazing land, access to forest resources	3

A detailed table of dimensions and indicators is described in Supplementary Materials 1 and 2.

Table 2 Synthesis of the changing definitions and conceptual focus of adaptive capacity.

Reference	Definition	Shifting focus
IPCC (2001)	The capacity of a system to respond to climate change involves moderating risks, seizing opportunities, and coping with the consequences	Coping capacity
Smit and Pilifosova (2003)	A system's ability to adapt to climate change involves reducing adverse effects or capitalizing on beneficial ones	System ability
Adger and Agnew (2004)	The capacity of a system to change its characteristics or behavior in response to external stresses	System flexibility for coping stresses
Armitage (2005)	An essential aspect of resource management is the capacity to experiment and develop innovative solutions in a complex social and ecological environment	Resource management ability
Wall and Marzall (2006)	A system's characteristics enable it to recognize changes or threats, assess them, choose a solution, and implement risk management processes and tools	Risk managing tools
Nelson et al. (2007)	Prerequisites for adaptation, including physical and social elements, and their mobilization.	Resource mobilization ability
IPCC (2007)	A system's ability to respond successfully to climate variability and change includes adapting behavior, resources, and technologies	System response to change
Preston and Stafford-Smith (2009)	The ability of a system to adapt in order to better manage its exposure and sensitivity to climatic influences	System ability for managing exposure and sensitivity
Gupta et al. (2010)	The characteristics of institutions that foster and support creative societal responses to both short- and long-term impacts	Response capacity of society
Folke et al. (2010)	Part of resilience is the ability to adapt to changing external factors and internal processes while continuing development along the current trajectory	Capacity to adjust to change
Engle (2011)	A latent property of an individual, community, or socio-ecological system that is activated in response to a crisis or opportunity	Latent property of a socio-ecological system
IPCC (2014)	The ability of a system, institution, person, or organism to adapt to potential harm, seize opportunities, or respond to consequences	Ability to adjust to potential harm
Aase (2017)	A joint outcome of flexibility, resilience, and innovation	Flexibility
Cinner et al. (2018)	The willingness and ability to turn resources into effective adaptive actions	Will to convert resources to action
IPCC (2022)	The process of adapting to current or anticipated climate impacts to minimize damage or seize opportunities in human systems, and adjusting natural systems with human intervention to facilitate this adaptation	Process of adjustment of the human and natural system

studies, respectively. Data constraints were noted as a possible reason for this trend. Adaptive capacity research has addressed a range of topical sectors. Some studies have concentrated on a single hazard and its impacts on related sectors, while others have

focused exclusively on specific sectors, such as agriculture or water resources. Consistent with these findings, agriculture-based livelihoods, communities, and fisheries were identified as the most common sectors of study (Vallury et al. 2022).

Siders (2019) found that the majority of research on adaptive capacity was carried out in the developed world: 19% in Europe and 19% in North America. However, a recent study by Vallury et al. (2022) stated that 34% of studies on it are from Asia, followed by North America (20%), Europe (15%), Oceania (13%), South America (11%), and Africa (7%). However, the developing world is the most vulnerable, and adaptive capacity is their utmost concern (Klein 2009). Yet, scholars of adaptive capacity research are predominantly from the global north with the study area being the global south (Siders 2019). In Siders' review, only half (48%) of the studies were conducted in Africa with an African researcher as the first author, and European and North Americans representing the other half. No scholars from Africa or South America were the first authors of research conducted in North America or Europe. Within the continent, there is the majority of high to middle-income countries in adaptive capacity research (Vallury et al. 2022). Although the geographical focus has been gradually shifting to the developing world over time, most of the research has been led by scholars from developed countries.

Changes in dimensions. Initially, studies on adaptive capacity were exclusively instituted on the SLF. The SLF provides a research framework that evaluates diverse livelihood resources intending to achieve sustainability in various contexts (Scoones 1998). In this milieu, livelihood encompasses a combination of material and social assets, along with actions aimed at securing a means of living (Chambers and Conway 1992). Scholars within this domain emphasize the availability of livelihood assets; human, physical, natural, financial, and social, as the primary underlying determinant of adaptive capacity. Therefore, they commonly employed the asset pentagon as a research framework and used corresponding indicators. Research studies conducted by Datta and Behera (2022), Defiesta and Rapera (2014), Fosu-Mensah et al. (2012), Holland et al. (2017), Hua et al. (2017), Naher and Khulna (2012), Pagnani et al. (2021), and Teklewold et al. (2013) are the examples of this category. Scholars often describe accessible natural resources as natural assets in areas where households utilize those resources for livelihood activities. Physical assets encompass fundamental personal or communal infrastructures, facilities, and tools essential for carrying out livelihood activities. Financial assets refer to available and accessible wealth crucial for investing in livelihood activities (Choden et al. 2020; Nawrotzki 2012; Williges et al. 2017). Human assets encompass the knowledge, skills, working capacity, and health status of household members required to achieve livelihood objectives. Social assets include networks, group memberships, trust, and relationships as integral aspects of social life (Chepkoech et al. 2020; DFID 1999).

The second category within adaptive capacity scholarship adopts a modified SLF as its research outline. In this group, scholars introduce additional dimensions to the SLF, addressing criticisms that the original form of SLF overlooks critical determinants of adaptive capacity, such as innovation, technology, information, and governance. Studies falling into this category include Abagat et al. (2017), Thathsarani and Gunaratne (2018), Selm et al. (2018), Chepkoech et al. (2020), Jamshidi et al. (2020), Mesfin et al. (2020), Singh (2020), and Zhang et al. (2022). For example, Abagat et al. (2017) used human, physical, and financial resources, information, and livelihood diversity as determinants of the adaptive capacity of farming households in the Philippines. Abdul-Razak and Kruse (2017) applied social capital, economic resources, awareness and training, institutions, infrastructure, and technology as key determinants of adaptive capacity. Jamshidi et al. (2020) considered economic, social, and

human resources, as well as institutional capabilities, as determinants of adaptive capacity. In a similar vein, Singh (2020) introduced economic, technological, institutional, social environmental, and geospatial dimensions, along with corresponding indicators, to measure adaptive capacity. Zhang et al. (2022) used climate change, labor migration, and human, financial, social, natural, and physical assets as a dimension for investigating adaptive capacity.

The third category of adaptive capacity studies departs from SLF considerations and introduces alternative determinants. Gupta et al. (2010) identified dimensions such as variety, learning capacity, room for autonomous change, leadership, resources, and fair governance, utilizing a unique approach with 22 indicators arranged in an adaptive capacity wheel. This approach is different from the conventional asset-based method for assessing adaptive capacity. Jones and Boyd (2011) recognized values, beliefs, norms, and physical and ecological factors as impediments to adaptation. Nantui et al. (2012) used knowledge, accessibility, availability, and consultations as determinants of adaptive capacity in rice farmers. Lockwood et al. (2015) reviewed local networks, reciprocity, government trust, information behavior, finance and infrastructure, labor and time, adaptive management, risk behavior, innovation, and governance as dimensions considered in adaptive capacity studies. Bouroncle et al. (2017) used satisfaction of needs, resources for innovation, and action as dimensions to investigate the adaptive capacity of farmers. Cinner et al. (2018) proposed five essential domains for framing adaptive capacity: the flexibility to change strategies, the ability to prepare and act collectively, the ability to learn, and the agency's role in deciding whether or not to change. Singh (2020) examined Indian farmers' perspectives on climate change adaptation decision-making, employing dimensions such as biophysical, socio-economic, and extension services to measure adaptation decisions. Figure 5 synthesizes the major dimensions of adaptive capacity studies and their evolving trends over time.

The SLF remains a prominent and widely applied research framework that scholars have adopted extensively to analyze adaptive capacity, valuing its focus on people and its capacity to facilitate the creation of standardized measures on a national scale (Lockwood et al. 2015). However, critiques have emerged that the SLF overlooks crucial components of adaptive capacity beyond the asset base and this framework may not be sufficient to comprehensively assess the entire spectrum of it. In response to these critiques in subsequent years, scholars have expanded the framework's scope, acknowledging knowledge, information, institutions, agency, diversity and flexibility, infrastructure, services, and governance as significant determinants of adaptive capacity.

Changes in indicators. Measuring adaptive capacity is challenging because it is fundamentally a measurement of latent response capacity to climate change and related disasters. Different scholars have applied a wide range of indicators to assess adaptive capacity. The scholars who fundamentally used the SLF argue that increased livelihood assets would enhance the adaptive capacity. The commonly used indicators are summarized in Table 1.

Several studies have shown a correlation between farming experience and adaptation practices (Defiesta and Rapera 2014; Nhemaehena and Hassan 2007). Education and training make farmers more aware of the impacts of climate change and appropriate adaptation strategies (Ali 2017; Mottaleb et al. 2017). With extensive farming experience, farmers learn how climate change will affect agricultural production and how to cope with it. Consequently, educated household heads are more likely to

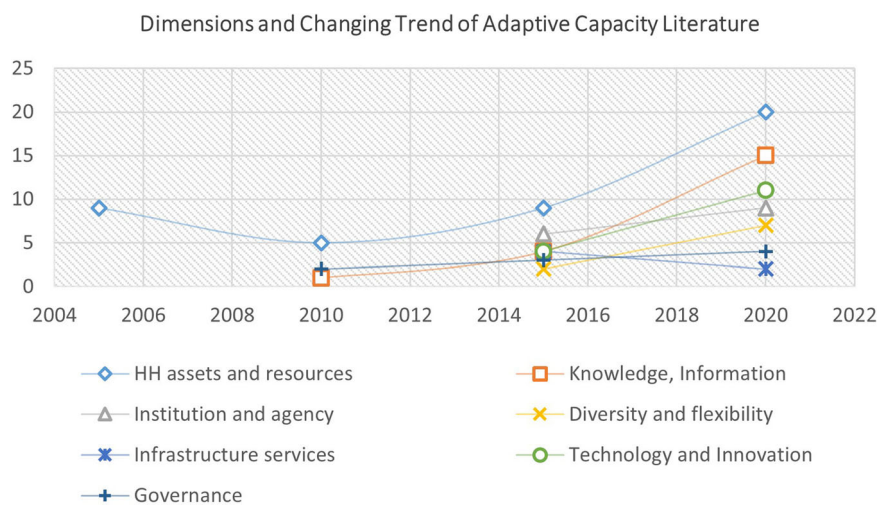


Fig. 5 Changing trend of dimensions of adaptive capacity.

practice adaptation actions than the less educated (Deressa et al. 2009). Experience and training further enhance their decision-making ability in investing in assets that contribute to increasing adaptive capacity (Choden et al. 2020).

Connectivity and proximity to the road-head impact people's mobility and thereby enhance access to the market, financial institutions, and healthcare facilities, as well as relevant information on farm input, technology, and training, which can lead to better agriculture production. Families with limited access to healthcare tend to have more health problems, which limit their working ability and productivity (Choden et al. 2020). Therefore, proximity and accessibility to healthcare facilities are also critical indicators of human capital. Membership in social groups and community positions, as well as community support systems, enhance individual and social networks and allow them to learn and exchange relevant information. The household size positively contributes to adaptive capacity (Choden et al. 2020). Education, training, experience, and belief systems are identified as significant determinants of household adaptive capacity, as they enable to understand the problem of climate change and devise solutions using local and scientific knowledge (Osumanu et al. 2017).

Diverse sources of income enhance household financial stability by reducing risk when one source of income is affected by climatic shocks (Chepkoech et al. 2020). Therefore, the number of household income sources and access to credit facilities, remittances, annual income, and loans are often considered key indicators of financial capital. There is generally a positive relationship between remittances and adaptive capacity. Remittance-receiving households have better access to financial institutions than non-recipient households (Banerjee et al. 2017; Musah-Surugu et al. 2017). Moreover, households' adaptive capacity is further advanced by social networks and expertise received from host countries (Jha et al. 2018). Access to credit ensures investment in more capital-intensive technology, as well as farm input, which improves flexibility to adjust production strategy in anticipated climate circumstances; thus, farmers can recover faster (Chepkoech et al. 2020; Sahu and Mishra 2013). However, limited access to credit facilities remains a major barrier to investing in adaptation. Having more agriculture mercenaries is beneficial to farmers' livelihoods, poverty alleviation, and enhancing their adaptability (Wang et al. 2019). Differences in the access to and control of resources also lead to different adaptive capacities among men and women (Pickson and He 2021). Therefore, farmers' households' adaptive capacity is largely

determined by access to and the judicious use of those assets (Jamshidi et al. 2020).

The adaptive capacity of households is determined by multiple factors, including the accessibility and availability of resources, the diversity, and flexibility of decision-making, the presence of formal and informal institutions (such as organizations and rules), governance policies, structures, and functions, investment priorities, the adoption and use of technology, and innovation. Information is the most influential factor in adaptation (Kibue et al. 2016). The availability, accessibility, and precise interpretation of weather information support timely decision-making. However, for effective adaptation action, people must have the decision-making power, willingness to act, and freedom to mobilize those components. Agency emerges as a key player in stimulating and mobilizing other elements of adaptive capacity (Cinner et al. 2018). Notably, recent studies have started incorporating such indicators, marking a shift from earlier studies that predominantly focused on asset-based indicators. In South Asia, studies often focus on indicators such as dependency ratio, land ownership, landholding size, farm tenure, soil quality, types and access to irrigation, access to extension services, road access, number of income sources, remittances received, access to credit, farming experience, education level, access to health services, membership in social organizations, community positions held, and weather information (Datta and Behera 2022; Lamichhane et al. 2022; Pandey et al. 2017). However, the indicators related to institutions, innovation, agency, and governance are still lacking in the studies.

Identified gaps in the existing literature. Socio-economic and ecological factors are significant in determining adaptive capacity. However, several gaps in its studies have been identified. Adger and Vincent (2005) found the representation of vulnerable socio-ecological systems, along with the inclusion of marginalized segments in decision-making structures and processes, remains an understudied area. Similarly, no space has been given to the local knowledge of environment, resource management, and climate change adaptation. Access to natural, financial, and societal resources is influenced by factors such as gender, class, race, age, physical ability, and educational level. However, there has been insufficient focus on improving equity in resource access (Abedin et al. 2019). Studies have shown that those living in poverty, racial minorities, and the elderly are particularly vulnerable to climate-related hazards, with limited adaptive capacity. Among these

factors, gender has been extensively analyzed topic concerning climate change (Erwin et al. 2021; Szewrański et al. 2018). But issues related to gender equality and social inclusion regarding climate change adaptation remain comparatively understudied in the South Asia region (Goodrich et al. 2022). Given the minimal attention to policy concerns in existing studies, there is an urgent need to identify pertinent policy questions and key actors involved. Furthermore, it is equally critical to conduct longitudinal studies for a better understanding of feedback across a level, spatial scale, and over time (Vallury et al. 2022). The crucial role of identity and place attachment in maintaining and ensuring system resilience is highlighted (Cinner et al. 2018). Importantly, adaptive capacity research from an insider perspective remains notably lacking in the developing world.

Quantitative methods hold a predominant position in adaptive capacity studies, facilitating comparisons and rankings of adaptive capacity levels across various scales. Especially, there is a lack of adaptive capacity research that concentrates on multi-scale analyses (Murthy et al. 2015). However, qualitative studies play a crucial role in shaping adaptation programs and interventions at the household and community levels (Chepkoech et al. 2020). It is imperative to conduct in-depth investigations on the role of off-farm and non-farm adaptation options for effectively addressing the adverse impacts of climate change (Datta and Behera 2022). The quantitative analysis method has limitations in effectively capturing how communities and farmers adapt, their capacity to adapt, and potential maladaptive practices. Future research should also focus on qualitative methods to investigate adaptive measures, and the risks of maladaptation, and explore the sustainable solutions.

There are several limitations to an indicator-based deductive assessment. Indicators offer indicative information specific to a context but lack explanatory depth in results. The expert-driven deductive approach, excluding a community's perspectives on its adaptive capacity, could benefit from the integration of participatory methods alongside quantitative or qualitative approaches for a more comprehensive interpretation of results (Abdul-Razak and Kruse 2017). However, these methods often prioritize the internal logic of data, neglecting regional differences and other contextual realities. To strike a better balance between internal results and real-world conditions, future studies are encouraged to employ a combination of subjective and objective aspects (Hua et al. 2017). Additionally, collecting qualitative data from key informants is recommended to enhance an in-depth understanding of the issues (Chepkoech et al. 2020) that helps in capturing the local socio-cultural and environmental context.

The systems-thinking approach would support researchers in conceptualizing integrated economic, social, and political issues, and actions toward improving adaptive capacity (Nguyen et al. 2021). Researchers are suggested to focus on gaining a nuanced understanding of the relationship between adaptive capacity indicators within specific contexts (Bettini et al. 2015; Siders 2019). Thus, a pragmatic understanding of the adaptation process is deemed necessary, avoiding a strict reliance on comprehensive lists of quantitative indicators and exploring trade-offs among its determinants (Brooks et al. 2005; Siders 2019). Despite a gradual shift in the geographical focus of adaptive capacity research from developed to developing regions, scholars from the global north continue to dominate the field (Siders 2019).

Conclusion

Along with the growing impact of climate change, the scope of adaptive capacity research is increasing across the globe in general and in South Asia in particular. The determining factors, dimensions and indicators of adaptive capacity have changed over

time, with a conceptual shift from a biophysical to a socio-ecological system approach. In the beginning, most studies were based on an asset-based framework, but later on, scholars incorporated other dimensions such as information, institutions, governance, and agencies as key determinants of adaptive capacity. Conceptual changes also demand changes in methodological aspects. Prior studies on adaptive capacity primarily used indicator-based quantitative methods to compare the degree of adaptive capacity on a particular scale. Studies have now started to explore the determinants of adaptive capacity within specific community and household contexts by applying participatory qualitative methods.

Adaptive capacity research is conducted with two distinct purposes: identifying barriers and constraints to adaptation practices within groups, and comparing adaptive capacity across groups to inform resource allocation decisions. As these two goals may be achieved with different methodological approaches, researchers should understand this divide to be able to frame their conceptual and methodological approaches and determine what indicators and methods to use based on their research goals. Importantly, as households and communities have specific socio-cultural, economic, political, and environmental contexts, context-specific studies at local and regional levels should be in priority that would help to formulate policies to address adaptation constraints. Future research should assess the context-specific determinants in diverse socio-physical environments. Importantly, climate change effects in the case of South Asia can be diverse depending upon the complex topography, social-cultural setting, and livelihood strategies.

Data availability

Data generated during this analysis are provided as Supplementary Materials.

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Author Contributions

PSC: conceptualization, methodology, writing, editing, communication, supervision, and finalization. TRB: literature searching and compilation, initial draft, preparation of figures, assisted in methodology preparation and finalization. SS: methodology, reviewing, and editing. NRK: methodology, editing, and reviewing. YZ: editing, reviewing, literature support, and support in methodology. JY: literature collection, editing, and reviewing. LL: reviewing and editing. BP: literature collection, reviewing, formatting support, and submission support. SCR: reviewing and editing. MNI: reviewing and editing. KRP: literature collection and compilation. All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare no competing interests.

Ethical approval

Ethical approval was not required as the study did not involve human participants.

Informed consent

Informed consent was not required as the study did not involve human participants.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1057/s41599-025-04453-3>.

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