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Building a Household Heat Vulnerability Index for Farming Communities: Evidence from Two Case Study Sites in Rural Bangladesh

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Abstract

Extreme heat is an emerging threat to rural livelihoods in South Asia, yet existing heat vulnerability assessments often overlook household-level experiences. This study develops and validates a Household Heat Vulnerability Index (HHVI) based on subjective heat-risk perceptions for farming communities in Bangladesh. Survey data from 362 farming households in drought-prone Natore and salinity-prone Khulna were used to construct the HHVI from 22 indicators representing exposure, sensitivity, and adaptive capacity dimensions of the IPCC AR4 vulnerability framework. Indicators were identified through literature review, qualitative interviews, and pilot testing, then normalized and aggregated into a composite index. Households in both regions experienced high heat exposure; however, vulnerability differs substantially across locations and households. Mean HHVI scores were higher in Natore (0.531 ± 0.057) than in Khulna (0.484 ± 0.059; $p < 0.001$). While exposure and sensitivity varied only modestly across sites, adaptive capacity showed the largest difference among the vulnerability dimensions. Differences in irrigation practices, access to early warning information, housing conditions, and exposure to compound hazards highlight how local environmental and household circumstances contribute to contrasting vulnerability. The positive association between HHVI scores and subjective heat-risk perceptions supports the index's validity. These findings demonstrate that similar heat exposure can produce unequal vulnerability outcomes. Household-level assessments provide insights that could be missed by temperature-based or census-derived approaches. Moreover, household approaches can support more targeted heat adaptation planning for farming communities facing increasing climate extremes.

Keywords: Extreme Heat, Household Vulnerability Index, Farming Communities, Climate Change Adaptation, Bangladesh

Number of Words: 8,442 (text-title to acknowledgements=6042; 7 figures+1 table: 8X300= 2400)

1 Introduction

In South Asia, heat extremes are getting prolonged and intense compared to longer-term 1950s baseline climatic conditions, and this trend is projected to continue towards the end of the century, with estimates of a roughly 50% increase in frequency (Ghosh et al., 2025; Singh et al., 2026). This rise in humid heat extremes during the monsoon persists not only during the day but also at night, resulting in a growing number of fatalities in extreme cases (Ghosh et al., 2025). Even though the impacts of extreme heat cut across sectors, some sectors bear the brunt of heat stress, where workers remain exposed to outdoor heat, such as agriculture and construction (Dasgupta et al., 2024). The disproportionate burden of broader climate change and heat stress falls on agrarian communities, who lose work capacity as high as 50% in South Asia, Southeast Asia, and Sub-Saharan Africa (de Lima et al., 2021). These conditions add an extra load on women in farming communities, as they have to take on more work in addition to household chores due to heat stress (Southard & Randell, 2022).

Even though there is a push to include more socio-demographic dimensions to measure heat vulnerability, biophysical metrics (e.g., Wet Bulb Globe Temperature, heat index) and indicators (e.g., temperature, humidity) still dominate (Kamal et al., 2024; Watkins et al., 2021). There is increasing research on heat vulnerability; however, most of these studies focus on urban areas of the Global North, and primarily rely on aggregate data collected from national censuses, surveys, and secondary satellite or modeled data (Ebi et al., 2021; Gibb et al., 2024; Hondula et al., 2015). While such assessments are valuable, aggregated data do not capture the heterogeneity of perceptions and behaviors of individuals in response to extreme events and miss spatial detail that is valuable for local planners and practitioners (Watkins et al., 2021). Therefore, a gap remains in measuring and understanding self-reported perceptions and lived experiences at the household-level, especially in rural areas of the Global South (Mertz et al., 2009).

People living in rural areas in and near the tropics remain exposed to extreme heat, especially those whose livelihoods depend on agriculture and have limited resources to cope with and adapt to heat stress, compared to those in urban areas (Sharma et al., 2022). Countries in South Asia account for almost twenty-five percent of the global population (Dokuru et al., 2024), where high temperatures and humidity have and are projected to further increase health and livelihood risks during the summer season (Im et al., 2017), especially for agrarian communities due to their reliance on rainfed agriculture and limited adaptive capacity (Aggarwal & Sivakumar, 2011; Sainath et al., 2025). Bangladesh is one of the South Asian countries at high risk due to increasing heat extremes, particularly given its reliance on an agrarian economy that is prone to multiple recurrent disasters, impacting the lives and livelihoods of farming communities (Md. A. Al Mamun et al., 2025; Chowdhury et al., 2022).

Research on personal heat exposure suggests that studies based on biophysical weather station data cannot capture the different lived realities of individuals, even though they might be living in the same geographic area, as their experiences could be unique from each other (Hondula et al., 2021). Therefore, there is a need to develop indices that capture both biophysical and socio-demographic indicators, enabling answers not only to what and where, but also to who and why (Cutter et al., 2009; Watkins et al., 2021; Wisner, 2016).

There are methodological limitations in measuring vulnerability, including indicator selection, aggregation, and validation (Cutter et al., 2009). Most studies measuring vulnerability rely on secondary data (e.g., census data) at the national scale and take an inductive approach, which may lead to the inclusion of indicators that are not relevant to local disaster risk contexts (B. Ahmed & Kelman, 2018; Watkins et al., 2021). Therefore, using primary data from fieldwork is more reliable for representing localized contexts (B. Ahmed & Kelman, 2018). Another key limitation is that

findings from vulnerability indices are not validated with actual outcomes, especially at the household scale (Watkins et al., 2021).

Most rural studies in Bangladesh focus on climate vulnerability (A. Ahmed et al., 2026; Ahsan & Warner, 2014; Hasan & Kumar, 2019) and/or livelihood vulnerability (A. Al Mamun et al., 2023; Mudasser et al., 2020), where extreme heat, when accounted for, is one of the peripheral hazards. Even though there is one recent study on the impacts of heat waves on rural farmers, the researchers focused on an ethnic minority group using qualitative methods (M. A. Rahman et al., 2024). Therefore, to the best of the authors' knowledge, this study is among the first to attempt to measure rural extreme heat vulnerability among farming communities in Bangladesh using household survey data.

Even though there is a newer AR5 framework from the IPCC, this study uses the IPCC AR4 framework due to its widespread use in measuring composite indices and its comparability with prior studies (Estoque et al., 2023; Ishtiaque et al., 2022). Using 22 indicators from rural household survey data across the exposure, sensitivity, and adaptive capacity dimensions, this study provides a framework for constructing, validating, visualizing, and comparing extreme heat vulnerability based on two agro-ecologically contrasting sites.

The following questions guided this study:

- How can household survey-derived indicators be used to assess heat vulnerability among rural farming households?
- How does vulnerability differ across contrasting agro-ecological settings characterized by drought and salinity stress?

2 Study Area

Bangladesh is among the world's most climate risk-prone areas, experiencing multiple disasters annually, and extreme heat poses a new hazard for rural labor (Karim & Mimura, 2008; M. M. Rahman et al., 2024). Multiple meteorological studies recently documented increasing heat risk in Bangladesh based on the Wet Bulb Globe Temperature indicator (Kamal et al., 2024) and data from the Bangladesh Meteorological Department (M. M. Rahman et al., 2024) and suggest that the number of days with maximum temperatures exceeding 36 degrees is increasing in the south-western region of Bangladesh, which overlaps with the study sites of this research, causing heat stress and heat-related illnesses (Kamal et al., 2024; M. M. Rahman et al., 2024).

Approximately 41% of the employed labor force in Bangladesh is directly engaged in agriculture, whereas indirect livelihood dependence could be as high as 70%, with a GDP contribution of 11.5% (Md. R. Ahmed, 2024; Salam et al., 2021). Due to high agrarian dependence, particularly in rural areas, temperature extremes result in health and income shocks (Bakhtiar & Karim, 2025). Furthermore, dependence on natural rainfall and flooding cycles renders farmers highly susceptible to the adverse effects of climate change and extreme heat events (Md. R. Ahmed, 2024).

Coastal and inland regions of Bangladesh differ significantly in their agro-ecological characteristics, and the hazards they face are diverse, profoundly affecting agricultural practices, productivity, and vulnerability. Coastal regions, such as Khulna, experience soil and water salinity, which limits the types of crops that can be grown (Emran et al., 2021). Coastal areas are also at a high climate risk due to frequent cyclones, storm surge, and sea level rise that lead to crop loss and damage to infrastructure (Shampa et al., 2023). In contrast, inland regions like Natore face a different set of challenges. For example, drought and groundwater shortages lead to water scarcity, which in turn reduces agricultural productivity (Jahura et al., 2024). Although coastal and inland regions differ, they both experience

heatwaves, which further exacerbate the existing challenges faced by farmer communities, necessitating a comparative analysis to understand the complex socio-ecological vulnerability.

To capture contrasting scenarios across two agro-ecological regions that experience extreme heat, locations were identified using data from the Bangladesh Agro-Meteorological Information Service (BAMIS). Three rural clusters were identified, of which two sites (Figure 1) were chosen due to logistical feasibility and their contrasting combinations of hazards: inland Natore (heat-drought) and coastal Khulna (heat-salinity). The inland site, Char Jazira in Lalpur Upazila, Natore, features smallholders with an intensified rice-mustard-Boro rice rotation (Hassan, 2015; Khan et al., 2017). Rice covers more than 70% of the land sown, along with pulses and oilseeds covering approximately 8% to 16% of the wider Rajshahi region (Amin et al., 2015; Mamun et al., 2024). In contrast, Phultala in Batiaghata Upazila is in the coastal Khulna division, and the main crops include rice, oilseeds, and vegetables (Islam et al., 2024). In salinity-prone Khulna, polders (earthen embankments) favor salt-tolerant Aman rice co-cultivated with brackish-water shrimp and crabs (Bhowmik et al., 2023; Bhuyan et al., 2023).

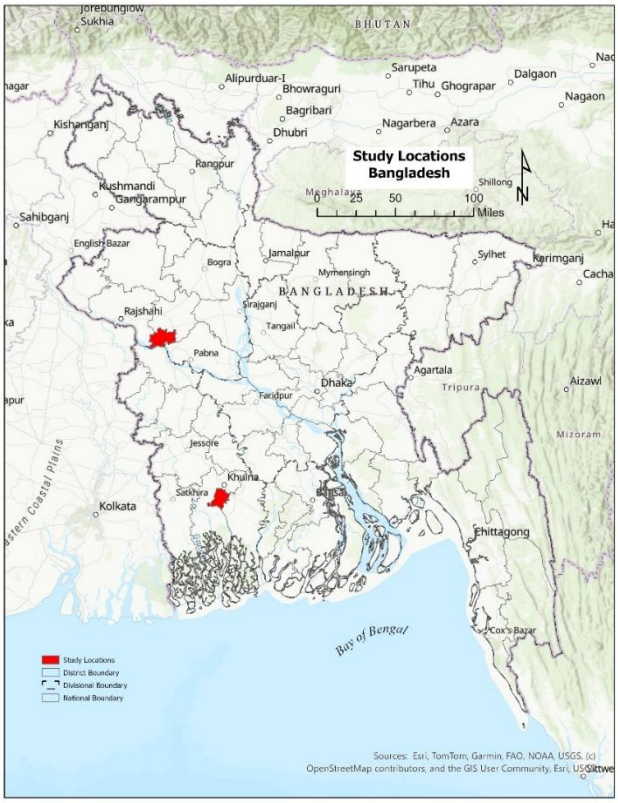


Figure 1: Map showing two selected study area locations (deep red) in Bangladesh.

3 Methods

3.1 Research Design and Data Collection

This study followed an exploratory sequential mixed methods design in which qualitative interviews with farmers and agricultural extension officers from the 2023 summer across Natore and Khulna informed the identification of locally relevant heat stressors affecting health, livelihoods, and adaptation strategies. A combination of interviews and literature review of heat vulnerability indicators informed the development of household survey questions, leading to the selection of 22 indicators to construct the household-level heat vulnerability index (HHVI) presented in this paper.

3.2 Sampling and Data Collection

Figure 2 illustrates the data processing and analysis steps used for the Household Heat Vulnerability Index (HHVI). Using systematic random sampling, survey data were collected from 362 households across two sites in February 2025. Before final data collection, the survey was piloted in August 2024 to assess whether the questionnaire aligned with the on-the-ground contexts at both study sites. For the household survey, this study covered two Mauzas from two different regions (the smallest administrative unit in Bangladesh), identified from BAMIS portal data as among the most heatwave-affected areas (Figure 1). Using the total number of households from the Small Area Atlas 2016, provided by the Bangladesh Bureau of Statistics, a sampling calculator was used to determine the number of households to be covered to achieve a 95% confidence level. The sample sizes for the two selected locations were 187 households in Char Jazira, Natore, and 175 households in Phultala, Khulna.

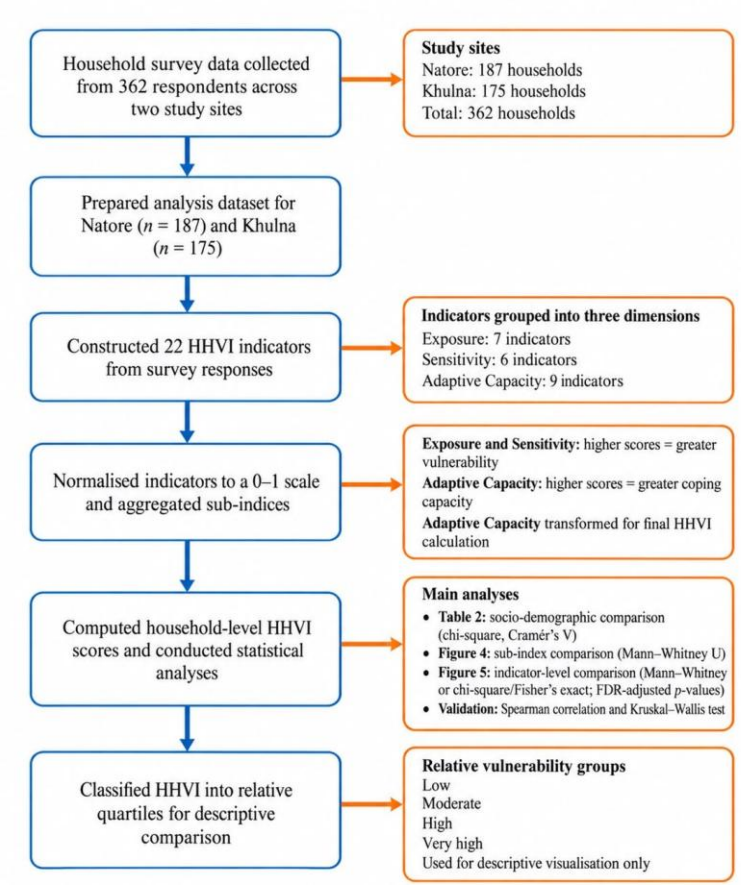


Figure 2: Flow chart summarizing the HHVI data processing and analysis pipeline. HHVI stands for Household Heat Vulnerability Index.

A systematic sampling technique was used for data collection, as a complete list of households was not available. The starting point was random, and every other household was covered by walking through the villages. Six local research assistants helped in collecting data (all university students in Bangladesh) who were studying Disaster Management and Resilience. All respondents were first asked if their households were primarily farming households. Then, information related to the research was shared to obtain oral consent, provided that the following criteria were met, before survey responses were collected. In every household, the research assistants first asked to speak with the adult (≥ 18 years) who leads the household's decision-making, including day-to-day farm-related decisions, usually the household head. If that person was absent, the second preference was a spouse or adult member who (a) actively participates in the farm management and (b) has lived in the village

for multiple years. Only one respondent from each household participated in the survey. Out of 362 households, 61 respondents were female, and 301 respondents were male. No monetary benefits were provided to respondents during the household surveys. Ethical approval for this project was granted by San Diego State University's Institutional Review Board (Protocol #HS-2023-0173).

3.3 Indicator Selection and Operationalization

The 22 Indicators for this study were identified using three processes: 1. a systematic review of heat and climate vulnerability literature helped identify indicators that are used often, 2. semi-structured interviews with farmers and agriculture officers helped identify local indicators relevant to heat stress, and 3. a pilot survey was conducted to validate and contextualize the survey questions. The indicators are grouped into three broad categories following IPCC AR4 dimensions-exposure (7), sensitivity (6), and adaptive capacity (9) presented in Table 1 with details on measurement methods and sources.

Table 1: HHVI indicators by dimension, measurement information, sources.

Dimension	Indicator	Measurement	Sources
Exposure	Heat frequency	Self-reported frequency of extreme heat events (0-4 scale)	Fieldwork
	Compound hazard frequency	Frequency of heat-drought or heat-salinity co-occurrence (0-5 scale)	(Harvey et al., 2014; Tran et al., 2022)
	Heat intensity	Perceived intensity rating (1-5 scale)	Fieldwork
	Average heat duration	Mean duration of longest heatwave experienced (days)	Fieldwork
	Work-hour reduction ratio	Summer/non-summer uninterrupted work hours ratio	Fieldwork
	Load-shedding during heat	Hours of electricity outage during peak heat (0-4 scale)	Fieldwork
	Housing heat-risk score	Composite of roof, wall, and floor material heat risk	(Budhathoki & Zander, 2019; Liu et al., 2024)
Sensitivity	Dependency ratio	(Members <18 + >65) / total household members	(Dintwa et al., 2019; M. M. Rahman et al., 2023)
	General health (reversed)	Self-rated health inverted (1=excellent → 5=poor)	(Osberghaus & Abeling, 2022; Quandt, 2018)
	Pre-existing condition count	Number of chronic health conditions reported	(Budhathoki & Zander, 2019; M. M. Rahman et al., 2023)
	Health-livelihood impact	Extent health problems affect livelihood activities (1-5)	(Budhathoki & Zander, 2019; Quandt et al., 2019)
	Crop impact score	Mean heat impact on 5 crop dimensions, such as, crop growth rate, crop health (0–3 scale)	Fieldwork
	Crop loss and damage	Binary presence of crop loss/damage due to heat	Fieldwork
Adaptive Capacity	Education level	Highest educational level completed (0-4)	(Liu et al., 2024; Quandt et al., 2019; Tran et al., 2022)
	Annual income (log)	Natural log of annual household income (BDT)	(Budhathoki & Zander, 2019; Osberghaus & Abeling, 2022)

Dimension	Indicator	Measurement	Sources
	Income source diversity	Number of distinct income sources	(Harvey et al., 2014; Liu et al., 2024; Tran et al., 2022)
	Loan access	Access to formal/informal credit (binary)	(Liu et al., 2024; Tran et al., 2022)
	Livestock asset score (log)	Log-transformed livestock asset value	(Budhathoki & Zander, 2019; Quandt, 2018)
	Irrigation type count	Number of irrigation types reported	(Jamal et al., 2022; Tran et al., 2022)
	Equipment access score	Agricultural equipment ownership/access score	(Quandt et al., 2019; Tran et al., 2022)
	Early warning access	Access to heat/weather early warning systems (binary)	(Budhathoki & Zander, 2019; Tran et al., 2022)
	Adaptation practices count	Number of heat adaptation strategies employed	(Budhathoki & Zander, 2019; Osberghaus & Abeling, 2022)

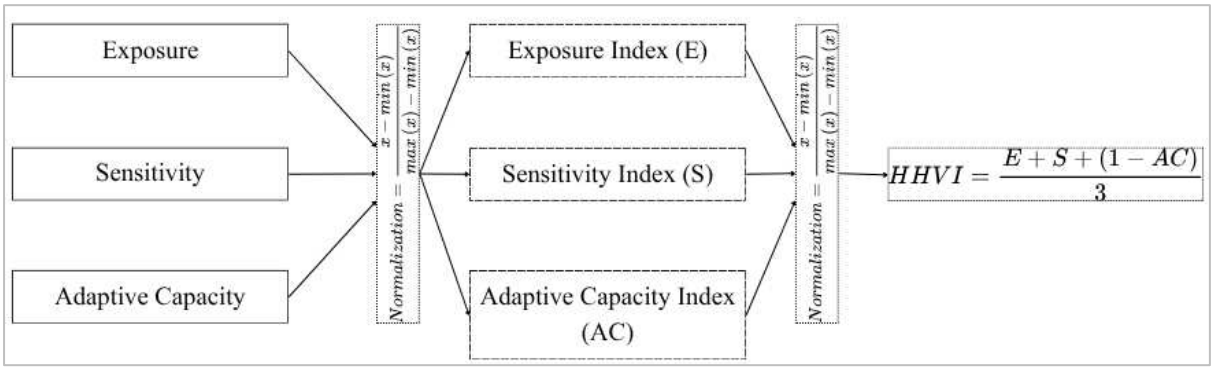


Figure 3: Conceptual framework for the Household Heat Vulnerability Index (HHVI), adapted from the IPCC AR4 framework. Each sub-index, Exposure (E), Sensitivity (S), and Adaptive Capacity (AC), is constructed from its respective indicator set (see Table 1 for the full indicator list).

3.4 Index Construction

All indicators were standardized using min-max normalization to the range 0 to 1. For the sub-indices, high exposure and sensitivity scores indicate greater vulnerability, whereas high adaptive capacity indicates the opposite. For example, a higher heat frequency increases vulnerability, but a higher education level reduces it. The sub-indices were computed as the unweighted mean of normalized indicators within each dimension (Figure 4). The final HHVI was computed as the mean of the three sub-index scores, with a range of 0 to 1, where 0 indicates the least vulnerable and 1 the most vulnerable relative to the sample of collected households. To align the directions from all three dimensions, the calculated adaptive capacity was deducted from 1, as shown in Figure 3. This equal-weight approach is a standard practice in vulnerability indexing, which helps compare across sites and contexts, as is the purpose of this study (B. Ahmed & Kelman, 2018; Watkins et al., 2021). Based on the results, households were classified into four relative categories-low, moderate, high, and very high using quartile thresholds across both sites to enable a comparison of study sites.

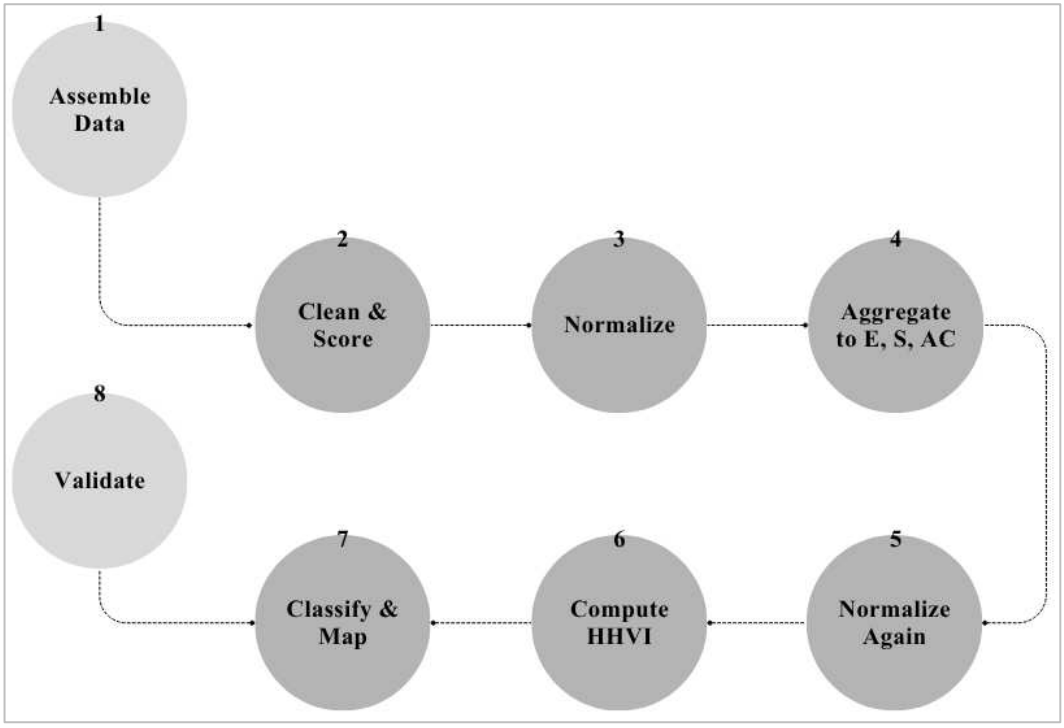


Figure 4: Steps to measuring the Household Heat Vulnerability Index (HHVI).

3.5 Validation of the Heat Vulnerability Index with Subjective Risk Perception

To evaluate whether the HHVI reflects how people experience and perceive heat-related risks, HHVI scores were compared with respondents' own assessments of their household's risk from extreme heat following Quandt (2018). Participants rated their risk on a four-point scale ranging from no risk to high risk. Across both study sites, households that perceived themselves to be at greater risk of heat-related impacts consistently had higher HHVI scores. Average HHVI scores increased steadily from the lowest to the highest perceived-risk categories in Khulna, Natore, and the combined sample. The index showed a positive association with households' self-reported heat-risk perceptions. Statistical tests confirmed a significant positive relationship between HHVI scores and perceived risk levels (Khulna: $\rho = 0.667$, $p < 0.001$; Natore: $\rho = 0.495$, $p < 0.001$; pooled sample: $\rho = 0.545$, $\chi^2 = 115.95$, df $= 9$, $p < 0.001$). Overall, these findings support the construct validity of the HHVI, indicating that it captures household-level heat vulnerability, which is consistent with how households themselves understand and experience heat-related risks.

4 Results

4.1 Sample Characteristics

A total of 362 respondents were surveyed, including 187 from Natore and 175 from Khulna. Overall, most respondents were male (83.1%), with males comprising 86.6% of the Natore sample and 79.4% of the Khulna sample. Educational attainment differed substantially between study sites. Nearly half of the respondents in Natore (44.4%) reported no formal education compared with 13.1% in Khulna. In contrast, secondary and tertiary education levels were more common in Khulna, where 38.9% had some or completed secondary education and 12.6% had attained higher secondary or above, compared with 17.1% and 0.0%, respectively, in Natore. Households were generally large, with a mean household size of 7.0 members (SD = 2.8). More than half of all respondents (55.2%) reported household sizes of 5-7 members. Mean household size was higher in Natore (7.8, SD = 3.4) than in Khulna (6.2, SD = 1.4). Annual household income averaged BDT 325,262 (SD = 103,850). Most

households (51.4%) reported annual incomes between BDT 200,000 and 300,000. Higher-income households were more prevalent in Khulna, where 31.4% reported annual incomes exceeding BDT 400,000, compared with only 2.1% in Natore. Farmland ownership also varied between districts. Overall, 13.0% of respondents were landless, although this proportion was considerably higher in Natore (23.0%) than in Khulna (2.3%). Larger landholdings (≥100 decimals) were more common in Khulna (25.7%) than in Natore (12.3%). Approximately 29.8% of respondents did not report farmland size.

Chi-square tests showed no statistically significant differences between Natore and Khulna in gender distribution ($\chi^2 = 3.35$, df = 1, $p = 0.067$) or age-group distribution ($\chi^2 = 8.70$, df = 4, $p = 0.069$). In contrast, significant differences were observed in educational attainment ($\chi^2 = 69.35$, df = 3, $p < 0.001$), household size ($\chi^2 = 46.19$, df = 3, $p < 0.001$), annual household income ($\chi^2 = 76.80$, df = 3, $p < 0.001$), and farmland size ($\chi^2 = 40.45$, df = 3, $p < 0.001$), indicating that the two study sites differed substantially in several socio-economic characteristics. Effect-size estimates using Cramér's V showed that differences between the two study sites were negligible to small for gender (V = 0.096) and age group (V = 0.155), but moderate to relatively strong for education (V = 0.438), household size (V = 0.357), annual household income (V = 0.461), and farmland size (V = 0.399).

4.2 Sub-indices, Indicator Results, and Cross-site Comparison

Figure 5 compares the mean normalized scores for the three HHVI dimensions between Natore and Khulna. Exposure was the highest-scoring dimension in both study sites, with significantly higher scores in Natore (0.682) than in Khulna (0.634; $p < .001$, $r = .258$). Sensitivity was also higher in Natore (0.336) than in Khulna (0.314), although the difference was relatively small ($p = .020$, $r = .123$). In contrast, adaptive capacity was significantly higher in Khulna (0.496) than in Natore (0.422; $p < .001$, $r = .378$), representing the largest absolute difference and effect size among the three dimensions. Together, these findings suggest that the higher overall heat vulnerability observed in Natore is associated with greater exposure and lower adaptive capacity, whereas differences in sensitivity play a comparatively smaller role. Thus, despite experiencing high levels of heat exposure in both study sites, households exhibit distinct vulnerability reflecting differences at the indicator level of each dimension.

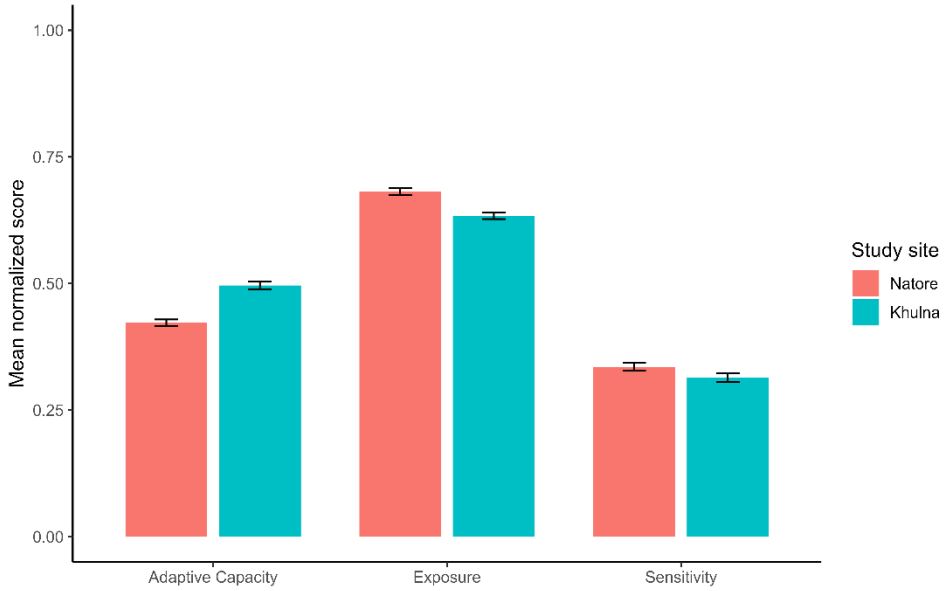


Figure 5: Sub-indices bar chart comparison between Natore and Khulna.

Indicator-level comparisons presented in Figure 6 identified several factors underlying differences in HHVI profiles between Natore and Khulna. After Benjamini-Hochberg correction for multiple testing,

eight of the 22 indicators differed significantly between sites. The largest difference was observed for irrigation access, which was substantially higher in Khulna than in Natore (mean normalized score: 0.459 vs. 0.063; adjusted $p < 0.001$; effect size = 0.717). Moderate differences were also observed for housing heat-risk (Natore: 0.669; Khulna: 0.511), compound-hazard frequency (0.908 vs. 0.727), and early-warning access (0.396 vs. 0.697), all with adjusted $p < 0.001$. Smaller but statistically significant differences were observed for crop impact, education, load shedding during heat, and work-hour reduction.

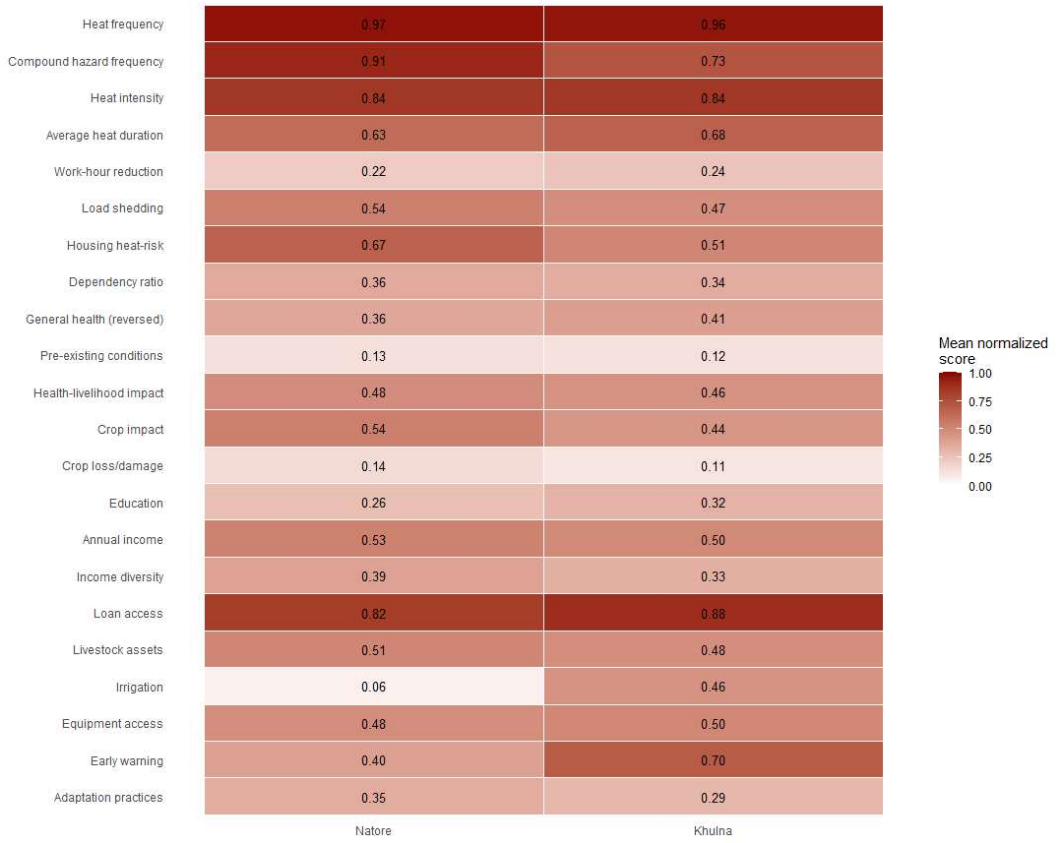


Figure 6: Heatmap of 22 indicators by site and dimension containing mean normalized scores.

In contrast, heat frequency and heat intensity were similar between the two sites and did not differ significantly after adjustment for multiple comparisons. Several other indicators, including average heat duration, dependency ratio, general health, pre-existing conditions, health-livelihood impact, equipment access, livestock assets, loan access, adaptation practices, crop loss/damage, and income-source diversity, also showed no statistically significant between-site differences after FDR correction.

These findings indicate that the difference in household heat vulnerability between Natore and Khulna is not driven uniformly across all 22 indicators. Instead, it is concentrated in a smaller set of context-specific indicators, particularly irrigation, early warning, housing conditions, and compound-hazard exposure. The particularly large difference in irrigation, together with higher early warning access in Khulna, is consistent with the higher adaptive capacity score observed in that site. At the same time, higher compound-hazard exposure and housing heat-risk in Natore indicate that differences in vulnerability also reflect place-specific exposure and livelihood conditions.

4.3 Heat Vulnerability Index Score Distribution and Vulnerability Classification

As shown in Figure 7, the distribution of HHVI scores in Natore shifted toward higher values compared to Khulna, resulting in higher median (0.54 vs. 0.48) and mean HHVI scores (0.531 ± 0.057

vs. 0.484 ± 0.059). Even though there is significant overlap, the difference between the two sites was statistically significant (Mann-Whitney U = 23,645, $p < 0.001$, r = 0.385), which indicates greater overall heat vulnerability among households in Natore. Moreover, individual household scores also reveal considerable heterogeneity within both locations.

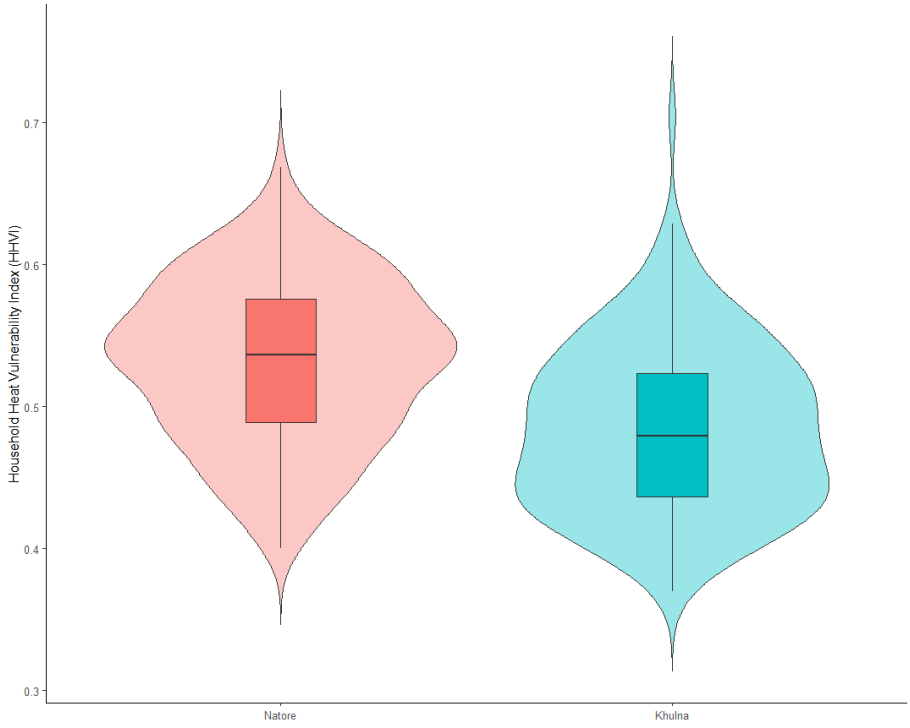


Figure 7: Comparison of overall heat vulnerability index scores between Natore and Khulna.

A classification scheme was developed using pooled quartile thresholds (Q1 = 0.457, median = 0.510, Q3 = 0.552) calculated from the combined sample of households across both study sites. It showed that 67% of households in Khulna fall within the two lower quartiles of the pooled distribution, whereas 66% of households in Natore fall within the two upper quartiles. These quartile-based categories represent households' positions within the combined distribution of vulnerability scores and are intended for comparative purposes only. Consequently, the results indicate that households in Khulna generally rank lower, and those in Natore generally rank higher, within the surveyed sample of 362 households; they should not be interpreted as absolute levels of vulnerability.

5 Discussion

The two research questions guiding this study were: 1. How can household survey-derived indicators be used to assess heat vulnerability among rural farming households? and 2. How does vulnerability differ across contrasting agro-ecological settings characterized by drought and salinity stress? Using 22 indicators from household surveys, this study developed a household heat vulnerability index and validated it based on subjective heat-risk perceptions of farming communities in Bangladesh. The findings demonstrate that household-level vulnerability cannot be explained by heat exposure alone. Although exposure was high across both agro-ecological settings, vulnerability differed substantially due to variations in adaptive capacity. Consequently, vulnerability emerged in different ways in drought-prone Natore and salinity-prone Khulna.

5.1 What the Heat Vulnerability Index Reveals that Biophysical Metrics Miss

The HHVI demonstrates that extreme heat exposure does not translate to uniform vulnerability across farming households. Even though farmers in both Natore and Khulna reported high heat frequency and exposure, their overall vulnerability varied considerably within and between sites. This finding emphasizes a long-standing argument within vulnerability scholarship that exposure alone is insufficient to explain why some households experience greater impacts than others (Cutter et al., 2009; Wisner et al., 2012).

In Bangladesh, recent climatological assessments showed substantial increases in the frequency, duration, and intensity of heatwaves across both inland and coastal regions (Farukh et al., 2025; N. M. F. Rahman et al., 2026). Consistent with these findings, households in both Natore and Khulna reported high heat exposure. However, HHVI scores ranged from 0.37 to 0.70 across the 362 surveyed households. This demonstrates substantial variation among households between and within sites.

Among the three HHVI dimensions, adaptive capacity showed the largest difference between Natore and Khulna. This suggests that greater access to adaptation resources may explain the contrasting vulnerability of the two studied sites. This finding aligns with previous heat-health vulnerability research in Bangladesh, which found that areas characterized by lower adaptive capacity and higher sensitivity experience greater heat-related risks (Mehrin et al., 2025). Moreover, these findings align with broader scholarship that highlights vulnerability as socially produced through unequal access to resources and opportunities (Wisner et al., 2010, 2012).

These findings suggest that assessments based only on temperature observations, remote sensing products, or other biophysical indicators may not capture household-level differences in vulnerability. By incorporating household-level experiences, livelihood conditions, and adaptation resources, the HHVI captures dimensions of vulnerability that exposure-based assessments could miss. Therefore, it provides a more detailed understanding of who is vulnerable to extreme heat and why.

5.2 The Role of Adaptive Capacity in Differentiating Heat Vulnerability

Adaptive capacity showed the largest difference between Natore and Khulna among the three HHVI dimensions. Both sites experienced similarly high heat exposure, and differences in sensitivity were modest. However, Khulna showed higher adaptive capacity than Natore. This highlights the importance of resource availability and access in understanding variation in heat vulnerability between the study sites.

Vulnerability and resilience research emphasizes that access to resources, knowledge, and institutions impacts the ability of people to respond to environmental stress (Adger, 2006; Ahsan & Warner, 2014; Wisner, 2016). The differences observed between Natore and Khulna align with this perspective. Additionally, prior work on drought-prone farming communities in Bangladesh showed that more educated farmers with access to resources such as institutional facilities are more likely to adopt adaptation strategies (Alam, 2015). Similarly, research in Kenya showed that irrigation strengthens livelihood resilience by building natural and financial capital (Quandt, 2018).

Irrigation showed the largest difference among the adaptive capacity indicators, with households in Khulna reporting more irrigation types than those in Natore. Khulna also had higher access to early warning. These resources may help farmers respond to heat and water stress by making timely decisions, such as keeping standing water in crop fields and adjusting work hours. Education may further enhance adaptive capacity by improving access to information and increasing households' ability to adopt new adaptation strategies (Alam, 2015).

Heat vulnerability is shaped by, and interacts with, broader place-based environmental phenomena. In Natore, heat interacts with drought-related water stress, and in Khulna heat interacts with salinity. These overlapping hazards increase the importance of adaptive capacity to buffer against multiple risks (Simpson et al., 2023). Households that possess greater adaptive resources are better positioned to manage not only extreme heat but also the cascading impacts that arise when heat compounds existing environmental stressors (Simpson et al., 2023).

These findings suggest the importance of considering adaptive capacity in heat adaptation planning. Improving access to agricultural resources, climate information, and institutional support could help households reduce heat risk. However, adaptation priorities need to reflect each community's specific needs and conditions.

5.3 How Local Environmental Conditions Shape Heat Vulnerability

Although both Natore and Khulna reported high heat exposure, they showed differences in vulnerability. These differences reflect their contrasting environmental conditions, agricultural systems, and household resources. Understanding these local conditions is critical, as vulnerability varies across farming communities.

In Natore, vulnerability is shaped by the interaction between extreme heat and drought-related water stress (Habiba et al., 2014). Agriculture in the region depends heavily on irrigation, making water availability important for crop production (Salman Chowdhury et al., 2025). Households in Natore reported higher exposure to compound hazards and greater heat-related crop impacts than those in Khulna. Moreover, Natore households reported fewer irrigation types and lower access to early warning information. These findings suggest that the interaction of heat and drought, along with limited adaptation resources, may contribute to higher vulnerability in Natore.

In Khulna, households reported interactions of heat and salinity-related environmental stress. Saline soils and water resources can constrain agricultural productivity and livelihoods in coastal farming systems (Pettigrew & McCauley, 2026). Despite these challenges, households in Khulna had higher adaptive capacity scores than those in Natore. They reported more irrigation types, greater access to early warning, and education. These differences are consistent with Khulna’s relatively lower overall HHVI scores. However, heat and salinity remain important concerns for people dependent on agriculture in coastal environments.

These findings illustrate the importance of understanding heat within a broader framework of compound and cascading risks. Heat can interact with existing hazards, such as drought and salinity, bringing additional challenges for farming households (Ashrafuzzaman et al., 2022; Sharma et al., 2022). Households may experience such challenges differently depending on their local environment, livelihood conditions, and resource availability. This finding supports calls for place-based vulnerability assessments that recognize the interconnected nature of environmental and social systems (Naylor et al., 2020; Wilhelmi & Hayden, 2010).

The comparison between Natore and Khulna suggests that adaptation strategies should be tailored to local settings. In drought-prone areas, water security may require greater attention, whereas in coastal environments, adaptation efforts may need to focus on managing the combined effects of heat and salinity. Understanding these locally specific vulnerability processes is therefore essential to designing heat adaptation planning.

5.4 Implications for Rural Heat Adaptation Planning

The HHVI provides valuable insights for rural heat adaptation planning by demonstrating differences in vulnerability dimensions among farming households. Existing heat assessments often focus on mapping heat exposure and identifying populations at risk (Hondula et al., 2021; Watkins et al., 2021). However, effective adaptation planning requires understanding household resources and access to

adaptation support. Household-level assessments like this study could help identify who needs additional support and where.

The findings highlight the importance of improving adaptive capacity for farming households. Improving access to climate information, education, and institutional support may strengthen households' ability to prepare for and respond to extreme heat. Agricultural extension services, local governments, and development organizations could integrate heat risk management into existing rural development and agricultural support programs.

In Natore, adaptation planning could prioritize water security and support for heat-affected agriculture. Households reported fewer irrigation types and lower access to early warning information than households in Khulna. Therefore, improving water management, climate information, and agricultural extension support could help farmers respond to heat-drought stress. Additionally, enhancing access to financial resources and livelihood diversification opportunities could facilitate long-term adaptation.

In Khulna, adaptation planning needs to address the combined challenges of extreme heat and salinity. Adaptation efforts could focus on heat-health preparedness and salinity management. Although Khulna demonstrated higher adaptive capacity than Natore, continued access to adaptation resources remains important for agricultural livelihoods. These findings highlight the need for place-based adaptation strategies that are directed according to needs at the household-level and local environmental conditions.

5.5 Limitations

Several limitations should be considered when interpreting this study's findings. First, this study is based on cross-sectional household survey data collected at a single point in time and therefore provides only a snapshot of heat vulnerability (Quandt, 2018). Second, although self-reported measures capture lived experiences, they may be subject to recall bias and subjective interpretation. This limitation is particularly relevant because household surveys were conducted during February 2025, outside the peak summer heat season in Bangladesh. Third, the HHVI was constructed using an equal-weighting approach, which assumes that all indicators contribute equally to overall vulnerability. While equal weighting is widely used in vulnerability assessment studies for its transparency and comparability, it may not fully capture the relative importance of individual indicators. Finally, the findings come from two agro-ecological settings in Bangladesh that represent heat-drought and heat-salinity contexts. The findings may not be directly generalizable to other farming communities with different environmental and socio-economic conditions. Applying the HHVI in different geographical and social contexts would require contextualization and validation to ensure indicators accurately reflect local drivers of vulnerability. Future studies could test the HHVI in different agro-ecological settings and examine household vulnerability dynamics.

6 Conclusion

This study developed a household heat vulnerability index to assess extreme heat vulnerability among farming households in two agro-ecologically contrasting regions of Bangladesh. Using 22 household-level indicators across exposure, sensitivity, and adaptive capacity, the HHVI captures variability in vulnerability that biophysical assessments could miss. The index's positive association with self-reported risk perceptions supports its validity.

Although households in both Natore and Khulna reported high heat exposure, Natore had higher overall vulnerability. While exposure and sensitivity varied modestly between sites, adaptive capacity showed the largest difference. Differences in irrigation practices, access to early warning, housing materials, and exposure to compound hazards highlighted their contrasting vulnerabilities.

Considerable variation in HHVI scores within communities showed that households occupying the same geographic location may experience vulnerability differently.

These findings suggest the need for place-based heat adaptation strategies that consider local environmental conditions and household resources. Improving access to agricultural extension services, early warning information, and institutional support could help farmer households reduce heat risk. Future research should test and refine the HHVI in other agro-ecological settings and examine how heat vulnerability changes over time. In a nutshell, this study shows that household-level assessments are valuable for understanding who is vulnerable to extreme heat and for informing locally relevant adaptation planning.

7 Data Availability

The household-level survey data used for this study are not publicly available to protect respondents' privacy and confidentiality. However, the data processing procedure, statistical analysis scripts, and reproducible workflow used to develop and assess the Household Heat Vulnerability Index are publicly available in the following GitHub repository: https://github.com/Muhammad1085069/Household-Heat-Vulnerability-Index-HHVI-.git

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9 References

Adger, W. N. (2006). Vulnerability. Global Environmental Change, Resilience, Vulnerability, and Adaptation: A Cross-Cutting Theme of the International Human Dimensions Programme on Global Environmental Change, 16(3), 268–281. https://doi.org/10.1016/j.gloenvcha.2006.02.006

Aggarwal, P. K., & Sivakumar, M. V. K. (2011). Global Climate Change and Food Security in South Asia: An Adaptation and Mitigation Framework. In R. Lal, M. V. K. Sivakumar, S. M. A. Faiz, A. H. M. Mustafizur Rahman, & K. R. Islam (Eds.), Climate Change and Food Security in South Asia (pp. 253–275). Springer Netherlands. https://doi.org/10.1007/978-90-481-9516-9_16

Ahmed, A., Hasan, M. K., & Uddin, M. E. (2026). Climate vulnerability of rural households in the central exposed coastal areas of Bangladesh. Journal of Environmental Management, 408, 129914. https://doi.org/10.1016/j.jenvman.2026.129914

Ahmed, B., & Kelman, I. (2018). Measuring Community Vulnerability to Environmental Hazards: A Method for Combining Quantitative and Qualitative Data. Natural Hazards Review, 19. https://doi.org/10.1061/(asce)nh.1527-6996.0000290

Ahmed, Md. R. (2024). Climate shocks' impact on agricultural income and household food security in Bangladesh: An implication of the food insecurity experience scale. Heliyon, 10(4), e25687. https://doi.org/10.1016/j.heliyon.2024.e25687

Ahsan, Md. N., & Warner, J. (2014). The socioeconomic vulnerability index: A pragmatic approach for assessing climate change led risks–A case study in the south-western coastal Bangladesh. International Journal of Disaster Risk Reduction, 8, 32–49. https://doi.org/10.1016/j.ijdrr.2013.12.009

Al Mamun, A., Islam, A. R. Md. T., Alam, G. M. M., Sarker, M. N. I., Erdiaw-Kwasie, M. O., Bhandari, H., & Mallick, J. (2023). Livelihood vulnerability of char land communities to climate change and natural hazards in Bangladesh: An application of livelihood vulnerability index. Natural Hazards, 115(2), 1411–1437. https://doi.org/10.1007/s11069-022-05599-y

Al Mamun, Md. A., Sarkar, Md. A. R., Sarker, M. R., McKenzie, A. M., Nihad, S. A. I., Hossain, Md. A., & Hossain, A. (2025). Temperature variability and its effect on seasonal yield of rice in Bangladesh: A long-term trend assessment. Cogent Food & Agriculture, 11(1), 2447903. https://doi.org/10.1080/23311932.2024.2447903

Alam, K. (2015). Farmers' adaptation to water scarcity in drought-prone environments: A case study of Rajshahi District, Bangladesh. Agricultural Water Management, 148, 196–206. https://doi.org/10.1016/j.agwat.2014.10.011

Amin, M. R., Zhang, J., & Yang, M. (2015). Effects of Climate Change on the Yield and Cropping Area of Major Food Crops: A Case of Bangladesh. Sustainability, 7(1), 898–915. https://doi.org/10.3390/su7010898

Ashrafuzzaman, M., Gomes, C., Cerdà, A., Schmidt, L., & Guerra, J. (2022). Agricultural vulnerability and adaptation strategies by farmers to climate change in south-western coastal Bangladesh. 125–158. https://doi.org/10.1007/978-3-030-98617-9_8

Bakhtiar, M. M., & Karim, R. (2025). Threshold effects of extreme heat on schooling and child labor in rural Bangladesh. https://hdl.handle.net/10568/180558

Bhowmik, B. C., Rima, N. N., Gosh, K., Hossain, M. A., Murray, F. J., Little, D. C., & Mamun, A.-A. (2023). Salinity extrusion and resilience of coastal aquaculture to the climatic changes in the southwest region of Bangladesh. Heliyon, 9(3), e13935. https://doi.org/10.1016/j.heliyon.2023.e13935

Bhuyan, M. I., Supit, I., Mia, S., Mulder, M., & Ludwig, F. (2023). Effect of soil and water salinity on dry season boro rice production in the south-central coastal area of Bangladesh. Heliyon, 9(8), e19180. https://doi.org/10.1016/j.heliyon.2023.e19180

Budhathoki, N. K., & Zander, K. K. (2019). Socio-Economic Impact of and Adaptation to Extreme Heat and Cold of Farmers in the Food Bowl of Nepal. International Journal of Environmental Research and Public Health, 16(9), 1578. https://doi.org/10.3390/ijerph16091578

Chowdhury, Md. A., Zzaman, R. U., Tarin, N. J., & Hossain, M. J. (2022). Spatial variability of climatic hazards in Bangladesh. Natural Hazards, 110(3), 2329–2351. https://doi.org/10.1007/s11069-021-05039-3

Cutter, S., Emrich, C., Haney (Webb), J., & Morath, D. (2009). Social Vulnerability to Climate Variability Hazards: A Review of the Literature. Final Report to Oxfam America, 1–44.

Dasgupta, S., Robinson, E. J. Z., Shayegh, S., Bosello, F., Park, R. J., & Gosling, S. N. (2024). Heat stress and the labour force. Nature Reviews Earth & Environment, 5(12), 859–872. https://doi.org/10.1038/s43017-024-00606-1

de Lima, C. Z., Buzan, J. R., Moore, F. C., Baldos, U. L. C., Huber, M., & Hertel, T. W. (2021). Heat stress on agricultural workers exacerbates crop impacts of climate change. Environmental Research Letters, 16(4), 044020. https://doi.org/10.1088/1748-9326/abeb9f

Dintwa, K. F., Letamo, G., & Navaneetham, K. (2019). Quantifying social vulnerability to natural hazards in Botswana: An application of cutter model. International Journal of Disaster Risk Reduction, 37, 101189. https://doi.org/10.1016/j.ijdrr.2019.101189

Dokuru, D. R., Horwitz, T. B., Freis, S. M., Stallings, M. C., & Ehringer, M. A. (2024). South Asia: The Missing Diverse in Diversity. Behavior Genetics, 54(1), 51–62. https://doi.org/10.1007/s10519-023-10161-y

Ebi, K. L., Capon, A., Berry, P., Broderick, C., Dear, R. de, Havenith, G., Honda, Y., Kovats, R. S., Ma, W., Malik, A., Morris, N. B., Nybo, L., Seneviratne, S. I., Vanos, J., & Jay, O. (2021).

Hot weather and heat extremes: Health risks. The Lancet, 398(10301), 698–708. https://doi.org/10.1016/S0140-6736(21)01208-3

Emran, S.-A., Krupnik, T. J., Aravindakshan, S., Kumar, V., & Pittelkow, C. M. (2021). Factors contributing to farm-level productivity and household income generation in coastal Bangladesh's rice-based farming systems. PLoS ONE, 16(9), e0256694. https://doi.org/10.1371/journal.pone.0256694

Estoque, R. C., Ishtiaque, A., Parajuli, J., Athukorala, D., Rabby, Y. W., & Ooba, M. (2023). Has the IPCC's revised vulnerability concept been well adopted? Ambio, 52(2), 376–389. https://doi.org/10.1007/s13280-022-01806-z

Farukh, M. A., Brahma, P. P., Hossain, Md. S., Hoque, Md. J., Sejuti, S. I., Shammy, U. S., & Arefin, K. S. (2025). Climatological assessment of pre-monsoon heatwave days in Bangladesh and their relationship to Indo Pacific circulation anomalies. Natural Hazards, 122(1), 32. https://doi.org/10.1007/s11069-025-07746-7

Ghosh, S., Das, P., Zhang, Z., Lu, J., Ayugi, B. O., & Gao, Z. (2025). Unraveling extreme high-temperature events in South Asia: Insights from ensemble learning models and geophysical drivers. Climatic Change, 178(8), 149. https://doi.org/10.1007/s10584-025-03993-6

Gibb, K., Beckman, S., Vergara, X. P., Heinzerling, A., & Harrison, R. (2024). Extreme Heat and Occupational Health Risks. Annual Review of Public Health, 45(1), 315–335. https://doi.org/10.1146/annurev-publhealth-060222-034715

Habiba, U., Shaw, R., & Takeuchi, Y. (2014). Farmers' adaptive practices for drought risk reduction in the northwest region of Bangladesh. Natural Hazards, 72(2), 337–359. https://doi.org/10.1007/s11069-013-1011-5

Harvey, C. A., Rakotobe, Z. L., Rao, N. S., Dave, R., Razafimahatratra, H., Rabarijohn, R. H., Rajaofara, H., & MacKinnon, J. L. (2014). Extreme vulnerability of smallholder farmers to agricultural risks and climate change in Madagascar. Philosophical Transactions of the Royal Society B: Biological Sciences, 369(1639), 20130089. https://doi.org/10.1098/rstb.2013.0089

Hasan, M. K., & Kumar, L. (2019). Comparison between meteorological data and farmer perceptions of climate change and vulnerability in relation to adaptation. Journal of Environmental Management, 237, 54–62. https://doi.org/10.1016/j.jenvman.2019.02.028

Hondula, D. M., Balling, R. C., Vanos, J. K., & Georgescu, M. (2015). Rising Temperatures, Human Health, and the Role of Adaptation. Current Climate Change Reports, 1(3), 144–154. https://doi.org/10.1007/s40641-015-0016-4

Hondula, D. M., Kuras, E. R., Betzel, S., Drake, L., Eneboe, J., Kaml, M., Munoz, M., Sevig, M., Singh, M., Ruddell, B. L., & Harlan, S. L. (2021). Novel metrics for relating personal heat exposure to social risk factors and outdoor ambient temperature. Environment International, 146, 106271. https://doi.org/10.1016/j.envint.2020.106271

Im, E.-S., Pal, J. S., & Eltahir, E. A. B. (2017). Deadly heat waves projected in the densely populated agricultural regions of South Asia. Science Advances, 3(8), e1603322. https://doi.org/10.1126/sciadv.1603322

Ishtiaque, A., Estoque, R. C., Eakin, H., Parajuli, J., & Rabby, Y. W. (2022). IPCC's current conceptualization of 'vulnerability' needs more clarification for climate change vulnerability assessments. Journal of Environmental Management, 303, 114246. https://doi.org/10.1016/j.jenvman.2021.114246

Islam, M. A., Pariyar, S., Krupnik, T. J., & Becker, M. (2024). Changing trends in crop management practices and performance attributes of rice-based systems of coastal Bangladesh. Frontiers in Agronomy, 6. https://doi.org/10.3389/fagro.2024.1397474

Jahura, S., Islam, M. S., & Mostafa, M. G. (2024). Impact of water scarcity on rural livelihood in the drought-prone region: A review of global perspectives. Indonesian Journal of Social Sciences, 16(1), Article 1. https://doi.org/10.20473/ijss.v16i1.49143

Jamal, Md. R., Kristiansen, P., Kabir, Md. J., & Lobry de Bruyn, L. (2022). Cropping systems intensification and diversification: Risk, vulnerability and adaptation in southwest coastal Bangladesh. International Journal of Sustainable Development & World Ecology, 29(8), 677–694. https://doi.org/10.1080/13504509.2022.2073615

Kamal, A. S. M. M., Fahim, A. K. F., & Shahid, S. (2024). Changes in wet bulb globe temperature and risk to heat-related hazards in Bangladesh. Scientific Reports, 14(1), 10417. https://doi.org/10.1038/s41598-024-61138-8

Karim, M. F., & Mimura, N. (2008). Impacts of climate change and sea-level rise on cyclonic storm surge floods in Bangladesh. Global Environmental Change, Globalisation and Environmental Governance: Is Another World Possible?, 18(3), 490–500. https://doi.org/10.1016/j.gloenvcha.2008.05.002

Liu, X., Song, Z., Xu, J., Feng, W., & Liu, W. (2024). Impact of Linking Livelihood Resilience of Smallholder Households and the Risk Management Strategies: The Case of China from Socioeconomic Perspectives. Agriculture, 14(9), Article 9. https://doi.org/10.3390/agriculture14091599

Mamun, M. A. A., Nihad, S. A. I., Sarker, M. R., Sarkar, M. A. R., Hossain, M. I., & Kabir, M. S. (2024). Spatiotemporal mapping of rice acreage and productivity growth in Bangladesh. PLOS ONE, 19(3), e0300648. https://doi.org/10.1371/journal.pone.0300648

Mehrin, M., Tuz Zuhra, F., & Rahman, M. M. (2025). Heatwave induced health vulnerability assessment in Bangladesh. Environmental Research: Health, 3(1), 015007. https://doi.org/10.1088/2752-5309/ada17d

Mertz, O., Halsnæs, K., Olesen, J. E., & Rasmussen, K. (2009). Adaptation to Climate Change in Developing Countries. Environmental Management, 43(5), 743–752. https://doi.org/10.1007/s00267-008-9259-3

Mudasser, M., Hossain, M. Z., Rahaman, K. R., & Ha-Mim, N. M. (2020). Investigating the Climate-Induced Livelihood Vulnerability Index in Coastal Areas of Bangladesh. World, 1(2), 149–170. https://doi.org/10.3390/world1020012

Naylor, A., Ford, J., Pearce, T., & Alstine, J. V. (2020). Conceptualizing Climate Vulnerability in Complex Adaptive Systems. One Earth, 2(5), 444–454. https://doi.org/10.1016/j.oneear.2020.04.011

Osberghaus, D., & Abeling, T. (2022). Heat vulnerability and adaptation of low-income households in Germany. Global Environmental Change, 72, 102446. https://doi.org/10.1016/j.gloenvcha.2021.102446

Pettigrew, K. A., & McCauley, D. (2026). Coastal salinity challenges in Bangladesh: Impacts on health, agriculture, and livelihoods. Groundwater for Sustainable Development, 33, 101603. https://doi.org/10.1016/j.gsd.2026.101603

Quandt, A. (2018). Measuring livelihood resilience: The Household Livelihood Resilience Approach (HLRA). World Development, 107, 253–263. https://doi.org/10.1016/j.worlddev.2018.02.024

Quandt, A., Neufeldt, H., & McCabe, J. T. (2019). Building livelihood resilience: What role does agroforestry play? Climate and Development, 11(6), 485–500. https://doi.org/10.1080/17565529.2018.1447903

Rahman, M. A., Afridi, S., Hossain, M. B., Rana, M., Al Masum, A., Rahman, M. M., & Al-Maruf, A. (2024). Nexus between heat wave, food security and human health (HFH): Developing a framework for livelihood resilience in Bangladesh. Environmental Challenges, 14, 100802. https://doi.org/10.1016/j.envc.2023.100802

Rahman, M. M., Mannan, M. A., Sarkar, M. S. K., Mallik, M. A. K., Sultana, A., Islam, M. K., Akter, M. Y., Alam, E., & Islam, A. R. M. T. (2024). Are hotspots and frequencies of heat waves changing over time? Exploring causes of heat waves in a tropical country. PLOS ONE, 19(5), e0300070. https://doi.org/10.1371/journal.pone.0300070

Rahman, M. M., Tasnim, F., Uddin, A., Chayan, M. S. I., Arif, M. S. I., Asikunnaby, & Hossain, M. T. (2023). Assessing vulnerability in ethnic Munda community: A study on a cyclone-prone area of Bangladesh. International Journal of Disaster Risk Reduction, 95, 103884. https://doi.org/10.1016/j.ijdrr.2023.103884

Rahman, N. M. F., Haque, N., Asadullah, M., Hossain, A. B. M. Z., Hossain, M. S., Uddin, M. J., Hassan, S. M. Q., & Baten, M. A. (2026). Machine learning-based temperature prediction across diverse ecosystems for the Boro Season in Bangladesh. Scientific Reports, 16(1), 15437. https://doi.org/10.1038/s41598-026-46341-z

Sainath, B., Asadullah, M., Kumar, U., & Mukherjee, A. (2025). Socioeconomic Implications of Heat and Drought Stress on Indian Agriculture. In R. Dubey, K. Shubha, A. Rakshit, S. Kumar, & A. Das (Eds.), Drought and Heat Stress in Agriculture: Implications, Mitigation and Policy Approaches (pp. 483–500). Springer Nature. https://doi.org/10.1007/978-981-96-5735-3_20

Salam, M. A., Sarker, M. N. I., & Sharmin, S. (2021). Do organic fertilizer impact on yield and efficiency of rice farms? Empirical evidence from Bangladesh. Heliyon, 7(8), e07731. https://doi.org/10.1016/j.heliyon.2021.e07731

Salman Chowdhury, J. M. A., Khalek, Md. A., & Kamruzzaman, Md. (2025). Farmers' climate change perception, impacts and adaptation strategies in response to drought in the Northwest area of Bangladesh. Climate Services, 38, 100540. https://doi.org/10.1016/j.cliser.2025.100540

Shampa, Mosa. T. A., Shimu, N. J., Chowdhury, K. M. A., Islam, Md. M., & Ahmed, Md. K. (2023). A comprehensive review on sustainable coastal zone management in Bangladesh: Present status and the way forward. Heliyon, 9(8), e18190. https://doi.org/10.1016/j.heliyon.2023.e18190

Sharma, A., Andhikaputra, G., & Wang, Y.-C. (2022). Heatwaves in South Asia: Characterization, Consequences on Human Health, and Adaptation Strategies. Atmosphere, 13(5), 734. https://doi.org/10.3390/atmos13050734

Simpson, N. P., Williams, P. A., Mach, K. J., Berrang-Ford, L., Biesbroek, R., Haasnoot, M., Segnon, A. C., Campbell, D., Musah-Surugu, J. I., Joe, E. T., Nunbogu, A. M., Sabour, S., Meyer, A. L. S., Andrews, T. M., Singh, C., Siders, A. R., Lawrence, J., van Aalst, M., & Trisos, C. H. (2023). Adaptation to compound climate risks: A systematic global stocktake. iScience, 26(2), 105926. https://doi.org/10.1016/j.isci.2023.105926

Singh, J., Singh, D., Sippel, S., & Fischer, E. (2026). Emergence of strong trends in humid heat intensity and duration in recent decades over South Asia. Environmental Research: Climate, 5(1), 015010. https://doi.org/10.1088/2752-5295/ae2c14

Southard, E. M. L., & Randell, H. (2022). Climate Change, Agrarian Distress, and the Feminization of Agriculture in South Asia. Rural Sociology, 87(3), 873–900. https://doi.org/10.1111/ruso.12439

Tran, P. T., Vu, B. T., Ngo, S. T., Tran, V. D., & Ho, T. D. N. (2022). Climate change and livelihood vulnerability of the rice farmers in the North Central Region of Vietnam: A case study in Nghe An province, Vietnam. Environmental Challenges, 7, 100460. https://doi.org/10.1016/j.envc.2022.100460

Watkins, L. E., Wright, M. K., Kurtz, L. C., Chakalian, P. M., Mallen, E. S., Harlan, S. L., & Hondula, D. M. (2021). Extreme heat vulnerability in Phoenix, Arizona: A comparison of all-hazard and hazard-specific indices with household experiences. Applied Geography, 131, 102430. https://doi.org/10.1016/j.apgeog.2021.102430

693 Wilhelmi, O. V., & Hayden, M. H. (2010). Connecting people and place: A new framework for
694 reducing urban vulnerability to extreme heat. Environmental Research Letters, 5(1), 014021.
695 https://doi.org/10.1088/1748-9326/5/1/014021
696 Wisner, B. (2016). Vulnerability as Concept, Model, Metric, and Tool.
697 https://doi.org/10.1093/acrefore/9780199389407.013.25
698 Wisner, B., Blaikie, P., Cannon, T., & Davis, I. (2010). At Risk: Natural Hazards, People's
699 Vulnerability and Disasters. Routledge.
700 Wisner, B., Gaillard, J. C., & Kelman, I. (2012). Framing Disaster: Theories and Stories Seeking to
701 Understand Hazards, Vulnerability and Risk. In Handbook of Hazards and Disaster Risk
702 Reduction. Routledge.

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