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The Intersection of Climate Change, Water Security and Agricultural Innovation: Bangladesh Perspectives

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Abstract:
This study investigates the interconnected challenges of climate change, water security and agricultural innovation in rural Bangladesh. Using a mixed-method cross-sectional design, including interviews and case studies across five districts, the research reveals that while farmers demonstrate moderate awareness of climate change, they remain highly vulnerable to its consequences—particularly water scarcity, shifting weather patterns and declining agricultural productivity. Compared to many developing nations facing similar issues, Bangladesh presents a unique case where densely populated rural areas and dependence on traditional farming methods intensify the risks. Despite some awareness, farmers often lack the resources, institutional support and training needed to adopt adaptive practices. In contrast, countries with stronger policy frameworks and investment in rural education and technology have shown better outcomes in adopting climate-resilient agriculture. Water conservation techniques and climate-smart agricultural innovations remain underutilized in Bangladesh, largely due to financial constraints, limited market access and inadequate extension services. The study emphasizes that meaningful progress requires more than awareness, it demands structural changes, improved governance and international collaboration. By comparing Bangladesh's current strategies to more progressive models in similar agro-ecological zones, the study underscores the importance of integrating climate resilience into national agricultural policy. It recommends enhancing farmer access to technology, expanding training programs and encouraging public-private partnerships to scale innovation. Bridging the gap between knowledge and practice is essential to safeguarding food security and rural livelihoods in the face of accelerating climate threats.

Keywords: Climate change, water security, agriculture, Bangladesh, comparative policy, sustainable innovation

1. Introduction:

The convergence of climate change, water security and agricultural innovation represents one of the most pressing global challenges of the 21st century. As climate change intensifies, it brings about unpredictable weather patterns, more frequent and severe extreme events and rising global temperature factors that collectively undermine agricultural productivity and heighten water scarcity. Given that agriculture remains the largest consumer of freshwater resources, the sector

faces a dual imperative: to enhance food production while contending with diminishing water availability and increasing contamination of water sources.

This nexus of challenges not only endangers global food security but also exposes the livelihoods of billions who depend on agriculture for survival. In response, the adoption of innovative agricultural solutions that promote efficient water use and adapt to evolving environmental stresses has become significantly important. Innovations such as drought-tolerant crop varieties, precision irrigation technologies and integrated water resource management systems have gained prominence as potential pathways to mitigate these unified issues. However, the deployment and success of such technologies vary widely across regions, influenced by factors like economic capacity, institutional frameworks and access to technological resources.

The academic discourse on this subject reflects a wide range of perspectives. Some scholars argue that adaptive agricultural practices are fundamental to achieving long-term water security in the face of climatic variability, while others highlight the decisive role of water governance and policy in facilitating or constraining innovation in agriculture. Debates continue around the scalability and sustainability of these innovations, as well as their ability to address the root causes of water insecurity in a changing climate.

This study aims to explore the implied linkages between climate change, water security and agricultural innovation, with a particular focus on strategies that improve water-use efficiency in agriculture while enhancing resilience to climate impacts. It will examine global efforts to confront these challenges, the transformative role of agricultural technologies and the policy environments that enable or hinder their adoption. The urgency of addressing these interconnected issues is especially pronounced in developing nations such as Bangladesh, where geographic vulnerabilities, socio-economic constraints and a heavy dependence on agriculture compound the risks posed by climate change. Accordingly, this paper will provide both a global overview and a focused analysis of the Bangladesh context, exploring how integrated, context-specific strategies can drive sustainable agricultural and water management in the era of climate change.

2. Literature review:

While climate has always been instability, current changes and climate models predict a significant and rapid rise in temperatures, atmospheric CO2 levels, shifts in rainfall patterns and a higher frequency, duration and intensity of climate extremes (such as heat waves, droughts, heavy rainfall, floods and storm surges). Global climate change trends indicate rising temperatures, shifted precipitation patterns and more frequent extreme events, all which impact water resources[1]. Climate influences water availability, potential agricultural production and energy supply,

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especially in regions that rely on hydropower[2]. Climate-induced changes in precipitation patterns, rising temperatures, shifts in seasonal timing, increased pest infestations and water-related hazards are all affecting agricultural practices, productivity and sustainability[3]. Climate changes, particularly rising temperatures and altered rainfall patterns, have significant impacts on agriculture through extreme weather events, such as droughts and heat waves[4]. Droughts, which impact both smallholders and commercial farmers, have become a frequent occurrence. Over time, livestock production has decreased, with small livestock, as well as the beef and dairy industries, being particularly affected[5]. Global water usage has risen six-fold over the past century and continues to grow steadily at a rate of approximately 1% per year, driven by population growth, economic development and changing consumption patterns[6]. South Asia is especially affected by climate change, experiencing the largest harvest declines for nearly all crops. However, with CO2 fertilization, the crop reductions are less severe, and, in many areas, some harvest increases are observed compared to the year 2000[7]. The direct effect of climate factors, such as sunshine duration, on agricultural water use is statistically significant, though to a lesser degree. However, it has been demonstrated that agricultural water use reflects farmers' adaptive responses to climate change at the provincial level in China. Therefore, future studies could use agricultural water use as a proxy for human adaptation to climate change[8]. Methane is the second most significant greenhouse gas. Its high emissions primarily stem from agricultural activities, especially the management of manure and the decomposition of organic waste[9]. Climate change is manifested through its impact on water, influencing both its demand and supply. Water usage is primarily categorized into agricultural, industrial and domestic activities[10]. Climate change is driving a rapid

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rate of land degradation, leading to increased desertification and nutrient-deficient soils[11]. Climate change will have a profound effect on agriculture by raising water demand, reducing crop productivity and decreasing water availability in regions where irrigation is most essential or has a comparative advantage[12]. Agriculture is one of the sectors most impacted by climate change. With the growing occurrence of droughts and climate variability, crops and quality losses, along with reduced harvest stability, are expected to become common challenges in farming[13]. Agriculture is highly vulnerable to climate change. Rising temperatures ultimately lower the yields of desired crops while promoting the growth of weeds and the spread of pests[14]. Rainfall variability has detrimental impacts on agriculture, especially in developing countries. In addition to affecting livestock production and crop yields, it also plays a crucial role in influencing the extent of cropland[15]. Freshwater availability is crucial to nearly all socioeconomic and environmental impacts of climate and demographic changes, as well as their implications for sustainability[16]. Risks and opportunities were identified concerning the anticipated impacts on water availability and the water requirements for agriculture[17]. Climate change will impact agriculture through rising temperatures and more erratic rainfall, with significant reductions in precipitation expected in the mid-latitudes, where agriculture is already vulnerable and heavily reliant on irrigation[18]. Climate change and the rising demand for water will place further strain on the region's groundwater resources, which are already under significant pressure in certain areas due to the growing need for irrigation[19]. Climate change impacts agricultural water requirements, water availability, as well as both water quantity and quality. Agriculture is the most affected sector due to its heavy reliance on climatic variables such as rainfall and temperature, which are essential for crop and livestock

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systems[20]. Sound and effective guidance will be crucial in the development and management of water resources for agriculture, as well as in the creation and maintenance of climate-resilient food production systems[21]. As a result, agriculture and agro ecosystems are particularly susceptible and highly vulnerable to the impacts of these changes[22]. The impact of climate change on water and agriculture requires increased financing to transform farming systems in the region to be more water efficient. The region should prioritize investments in national agricultural investment plans that enhance the resilience of farming systems, while also boosting productivity and contributing to sustainable development[23]. Population growth and economic development are driving up demand for limited water resources across competing sectors. Meanwhile, increased climate variability introduces more uncertainty regarding water availability. The effects of intensified water scarcity and climate variability are expected to be unevenly distributed[24]. Water is regarded as the most vital resource for sustainable agricultural development globally. In the coming years, irrigated areas are expected to expand, while freshwater resources will be reallocated from agriculture to satisfy the growing demands of domestic use and industry. Additionally, irrigation efficiency remains low, with less than 65% of the water applied being effectively utilized by crops. Ensuring the sustainable use of irrigation water is a key priority for agriculture in arid regions[25]. Climate change is projected to exacerbate existing risks, especially in areas already facing water scarcity, while also creating new opportunities in certain regions. Developing effective adaptation strategies for agricultural water management can be enhanced by understanding the risks and adaptation measures that have been proposed so far[26]. Effective management of irrigation water necessitates a systematic approach that optimizes rainfall use, incorporates the treatment and reuse of non-conventional water sources, improves irrigation system efficiency and minimizes on-farm irrigation losses[27].

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3. Methodology:

This study adopted a mixed-method, cross-sectional research design, integrating both qualitative and quantitative approaches to explore the complex interrelationship between climate change, water scarcity and agricultural challenges, alongside potential adaptive solutions in rural regions of Bangladesh. The research was conducted across five strategically selected districts, representing the northern, riverine and southern coastal zones of the country, thereby capturing a diverse range of ecological and socio-economic contexts.

A total of 573 In-Depth Interviews (IDIs) were conducted with members of civil society organizations (CSOs), supplemented by five Key Informant Interviews (KIIs) with relevant project personnel and other stakeholders with expert knowledge of the study areas. Additionally, 15 detailed case studies were compiled to provide rich, contextual insights into lived experiences, localized challenges and innovative community-driven responses to climate and water-related stresses.

Data collection occurred in two phases—October 2023 to January 2024 and March 2025—and continued until thematic saturation was reached. All participants were informed about the study's objectives and provided both verbal and written consent prior to participation, ensuring ethical compliance throughout the research process.

Qualitative data, including field notes recorded during interviews and discussions, were analyzed thematically using IBM SPSS Version 24 to identify recurring patterns and correlations. Quantitative, household-level data were gathered using the KOBO Collect digital platform via smartphones. This digital data collection method was deliberately chosen to enhance operational efficiency by minimizing labor and time requirements, optimizing resource use and supporting environmental sustainability through the reduction of paper-based survey tools, thereby contributing to lower carbon emissions.

This methodological framework allowed for a comprehensive, context-sensitive exploration of how climate change impacts rural livelihoods and agricultural systems in Bangladesh, while also assessing the efficacy and scalability of localized innovations and adaptation strategies.

4. Findings:

Climate change impacts, intensity and community lead adaptation:

Climate change stands as one of the most significant threats to global agriculture, affecting everything from crop production to overall food security. Rising temperatures, unpredictable rainfall, extended droughts and severe weather events are all disrupting established agricultural practices. These changes endanger the livelihoods of countless farmers, particularly in regions already struggling with poverty and hunger. The growing intensity and frequency of climate-related disasters further increase the risks to agricultural output, highlighting the urgent need for innovative and adaptive strategies.

The effects of climate change on agriculture vary across regions. While some areas may benefit from longer growing seasons due to warmer temperatures, others may suffer from heat stress that makes crop cultivation more difficult. Increasingly erratic weather patterns add to the complexity

of farming, making it harder to plan planting and harvesting schedules. In response, the global agricultural sector must prioritize the development of scalable and sustainable solutions that address both food security and the challenges posed by a changing climate.

Effects, intensity and coping with flood/flash flood:

Flooding remains a common issue across the surveyed districts, with Lalmonirhat and Naogaon experiencing the most significant impacts. Most households in these regions report frequent flooding, while Satkhira and Nilphamari are also affected, though to a lesser degree. According to the data, 71.4% of affected households have observed an increase in flood intensity, with Lalmonirhat recording the highest escalation in conditions. Conversely, Satkhira shows signs of reduced flood intensity, indicating progress in flood resilience. Naogaon continues to face regular flooding, whereas Dinajpur reports a decline in intensity, possibly due to improved flood control measures.

Regarding coping mechanisms, Lalmonirhat stands out for its proactive strategies, with households engaging in adaptive agricultural practices, drawing on community support, and investing in home repairs. In contrast, residents of Nilphamari and Dinajpur lean more toward passive responses, such as cutting household expenses and fixing homes. Naogaon adopts a more balanced strategy, utilizing savings and loans while also growing vegetables to supplement food supply. Satkhira, however, has limited coping options, relying mainly on temporary shelters and external assistance. Overall, the findings suggest that communities with strong local support systems and adaptive farming practices, like those in Lalmonirhat, are better equipped to manage the effects of flooding than areas with fewer resources, such as Nilphamari and Dinajpur.

Effects, intensity and coping with temperature rise & drought:

A significant majority of households report rising temperatures, with Lalmonirhat and Satkhira being the most severely impacted. The intensity of temperature increase is highest in Naogaon, Lalmonirhat, and Satkhira, where over 70% of households are affected, highlighting substantial climate-related risks. Naogaon emerges as the most drought-vulnerable area, with about 77% of households (92 in total) reporting intensified drought conditions. Lalmonirhat and Satkhira also face considerable challenges from both heat and drought, affecting roughly 60–70% of households. In contrast, Dinajpur and Nilphamari report lower levels of concern, with only 20–40% of households experiencing drought-related impacts.

In terms of coping with rising temperatures, Satkhira leads with over 40% of households (123) adopting cost-cutting measures. Lalmonirhat follows, with around 24% (39 households) implementing health and agricultural adaptations. In Naogaon, approximately 20% (61 households) focus on saving money, while Dinajpur shows limited engagement, with only about 5% of households adopting coping strategies. Nilphamari's primary response centers on house repairs and preserving assets, involving about 20% of households.

Regarding drought responses, Satkhira again shows the most proactive stance, with more than 60% (101 households) reducing spending and practicing water conservation. Naogaon follows closely, with about 50% (60 households) relying on savings. Lalmonirhat demonstrates moderate adaptation, with 20–30% of households engaging in vegetable farming and water resource management. Dinajpur and Nilphamari exhibit minimal action, with only 10–15% of households implementing coping strategies.

Effects, intensity and community coping strategies for heavy rainfall:
Heavy rainfall affects most households (74.4%), with the most significant impacts reported in Lalmonirhat, Satkhira and Nilphamari. Of those affected, 66% report an increase in rainfall intensity, reflecting the growing influence of climate change. Lalmonirhat and Satkhira are particularly vulnerable to intensified rainfall, facing associated risks such as flooding and crop loss.

Coping mechanisms differ across the regions. Lalmonirhat demonstrates the most proactive approach, emphasizing adaptive agricultural practices and home repairs. In Satkhira, households tend to focus on financial adjustments to manage the impact. Nilphamari and Naogaon adopt strategies centered around repairing homes and managing household finances. Dinajpur, however, shows limited adaptive response, primarily through basic home repair efforts.

Effects, intensity and coping with sea level rise and tidal surges:
In Satkhira, 75.4% of households report being affected by rising sea levels or high tides, with 78.4% observing an increase in intensity—signaling growing risks of coastal flooding. While a smaller portion (18%) of household's experience sea tidal surges, 21.4% report that these surges have intensified over time. These trends underline Satkhira's heightened vulnerability to climate-related coastal hazards.

Despite the growing threat, most coping responses remain passive. Many households (100 responses) report taking no specific action, while only a few resort to house repairs or seeking temporary shelter. The data points to a lack of active adaptation efforts, highlighting the urgent need for enhanced coastal protection and robust disaster preparedness strategies in the region.

Effects, intensity and coping strategies for cyclones and nor'westers:
A large proportion of households (88.1%) across the surveyed districts report experiencing cyclones or nor'wester events, with Satkhira and Lalmonirhat being the most affected—largely due to their coastal proximity. An estimated 77.7% of households have observed an increase in storm intensity, suggesting that these weather events are becoming more frequent or severe, likely driven by climate change. While Naogaon and Dinajpur report fewer cyclone occurrences, Naogaon stands out with all affected households noting a rise in storm strength.

Coping responses vary by region. Satkhira and Lalmonirhat demonstrate the most diverse strategies, including sheltering, house repairs and vegetable cultivation. Naogaon focuses primarily on vegetable gardening and replanting trees, while households in Nilphamari and Dinajpur mainly engage in repairing homes. These findings highlight the urgent need for localized climate adaptation plans, especially in high-risk areas such as Satkhira and Lalmonirhat.

Effects, intensity and coping with salinity intrusion:
In Satkhira, 96.3% of households report experiencing salinity intrusion, with 96.2% observing an increase in its intensity. In terms of coping strategies, most households (85.7%) report taking no action, with 99 responses indicating passive responses. A small portion of households have adopted agricultural adaptations, such as vegetable cultivation (7.6%), hydroponic farming (5.1%), and seedling raising (2.5%). Additionally, a few households sought support from relatives or friends (1.7%) or utilized government shelters (0.8%). The data suggests that while most households are not engaging in active coping measures, a few are exploring agricultural alternatives. This emphasizes the urgent need for targeted interventions to improve water management, develop salt-tolerant crops and strengthen coastal protection measures.

Effects, intensity and coping with waterlogging:
In Satkhira, 77% of households reported taking no action in response to waterlogging. Among those who did take steps, 5.2% raised seedlings, 6.5% engaged in hydroponic or vegetable cultivation and 1.3% raised ducks. In Nilphamari, 15.6% of households reported no action, while a small number took actions such as raising seedlings (2.3%) and cultivating vegetables (1.6%). In Naogaon, a few households (2.4%) relied on government relief and one household (1.2%) focused on growing flood-resilient crops. Lalmonirhat saw 5.6% of households engaged in vegetable cultivation, and 1.1% received limited assistance. In Dinajpur, just 1% of households carried out house repairs.

Effects, intensity and coping with riverbank erosion:
Riverbank and land erosion are most prominent in Satkhira (74.2%) and Lalmonirhat (66.3%), with Naogaon experiencing minimal impact (3.6%). The intensity of erosion has increased for many households, particularly in Satkhira and Lalmonirhat, highlighting the growing severity of the issue. Coping responses in Satkhira were the most numerous, with 99 households providing feedback. A significant portion (about 67%) reported taking no action, while others sought shelter (4%) or received assistance from Union Parishad (UP) members (7%). Lalmonirhat showed more varied responses, with 10% of households repairing homes and 11% replanting tree saplings. In contrast, Naogaon and Nilphamari had fewer proactive strategies, with the most common actions being house repairs and replanting, indicating limited engagement in mitigation measures. These findings emphasize the need for focused erosion management, particularly in high-impact areas like Satkhira and Lalmonirhat.

Effects, intensity and coping with cold waves:
Cold waves and dense fog are most frequently reported in Lalmonirhat (37.3%) and Naogaon (28.6%), where households experience both regular and intense cold weather events. Nilphamari (15%) and Dinajpur (17.6%) report moderate exposure, while Satkhira (25.6%) shows a mixed pattern, with some households noting increased intensity and others reporting decreases. Coping strategies vary across districts. Lalmonirhat demonstrated the most proactive response, with 91.8% of households engaging in vegetable cultivation as a primary adaptation, alongside a few households involved in house repairs (0.6%) and health maintenance (0.6%). Naogaon also showed diverse responses, including support from Union Parishad (3.5%) and vegetable cultivation (2.6%). In contrast, Satkhira, Dinajpur, and Nilphamari relied more on passive strategies such as house repairs (36.5%) and the use of winter clothing (25%). Overall, Lalmonirhat

stood out for its active agricultural coping measures, while Satkhira and Dinajpur leaned more on basic household-level adaptations.

Action plan for disaster preparedness and risk reduction:
The data reflects a relatively strong level of awareness and planning for disaster preparedness and risk reduction across the surveyed districts. Lalmonirhat and Satkhira lead with the highest number of prepared households, each reporting 160 households with a disaster action plan—representing 27.9% of the total 573 households. Naogaon follows with 118 households, accounting for 20.6% of the total. In Dinajpur, 75 households (13.1%) have established preparedness plans, while Nilphamari reports the lowest proportion, with 60 households (10.5%) having a disaster preparedness strategy in place.

Types of measures to protect households from disaster risks and hazards:
Across the districts, households are adopting a range of measures to reduce disaster-related risks. In Lalmonirhat, 160 households (27.9%) are engaged in preparedness activities, with key efforts including raising homestead platforms, securing important documents and implementing other protective actions. Satkhira, with an equal number of prepared households (160, or 27.9%), focuses on safeguarding food supplies, ensuring access to clean drinking water, maintaining communication systems during emergencies and reinforcing homes. In Naogaon, 118 households (20.6%) report various preparedness measures such as reinforcing houses, storing dry food and medicine and staying informed about nearby shelters. Dinajpur sees 75 households (13.1%) act, mainly through food and water preservation and other vital precautions. In Nilphamari, 60 households (10.5%) are actively preparing, with emphasis on gathering reliable information and raising living platforms to prevent flood impacts.

Initiatives by government, NGOs and local communities for disaster risk reduction and hazard protection:
Lalmonirhat leads in disaster risk reduction efforts with 160 recorded initiatives (27.9%), focusing on community-driven actions such as tree planting, constructing bamboo bridges and building flood-resilient homes. Satkhira follows with 121 initiatives (21.1%), prioritizing embankment repairs, ensuring access to clean drinking water and disseminating information about available shelters. Naogaon contributes 118 initiatives (20.6%), adopting a diverse approach that includes cash savings, seed preservation and tree planting. In Dinajpur, 75 initiatives (13.1%) are reported, with a primary focus on preserving seeds and raising platforms to minimize flood risks. Nilphamari has 60 initiatives (10.5%), mainly centered around platform elevation and providing shelter-related information. Altogether, 573 initiatives (100%) were documented across the districts, reflecting a wide range of localized efforts by government bodies, NGOs and communities to enhance resilience and reduce disaster vulnerability.

Sources of disasters related warning messages:

The survey on disaster warning communication revealed that Lalmonirhat and Satkhira received the highest share of messages, accounting for 27.4% and 20.4% of the total, respectively. In both districts, the primary sources of these warnings were local disaster management committees (UDMC) and community volunteers. Naogaon contributed 16.1% of the total messages, with

information primarily shared via mobile communication (3.5%) and UDMC or disaster volunteers (16.0%). Nilphamari received 7.8% of messages, distributed through a mix of UDMC/volunteers (3.3%) and media sources such as radio and television (1.2%). Dinajpur had the fewest warnings, accounting for just 2.1%, mainly delivered by volunteers and UDMC members. Satkhira also showed a notable reliance on government announcements and traditional media (radio and TV), contributing an additional 6.9% to the total. Overall, 573 disaster-related warning messages were recorded, with the most common delivery channels being mobile phones and local disaster response networks involving UDMC and volunteers.

Protecting cultivated crops from disasters and hazards:
In disaster-responsive crop management, Lalmonirhat leads with 59% of households adopting sack or loft-based cultivation techniques and 52% focusing on growing saline-tolerant vegetables by elevating their homesteads. Naogaon and Satkhira also show strong adaptive strategies, with 8.5% and 7.5% of households respectively using quick-growing seeds, alongside significant efforts in selecting appropriate crops—37% in Naogaon and 28% in Satkhira. Dinajpur stands out with 49% of households emphasizing the harvesting of suitable vegetables, while both Satkhira (31%) and Naogaon (30%) combine strategies using flood-resistant and quick-growing seed varieties. In Nilphamari, 23% of households engage in sack/loft cultivation, and 9% use fast-growing seed options. These practices reflect a growing emphasis on agricultural resilience, focusing on adaptive techniques suited to saline-prone or waterlogged environments. Collectively, they demonstrate how communities are enhancing their crop management capacity in the face of increasing disaster risks.

Family decision-making on agricultural and livestock purchases during and after disasters:
Across all surveyed districts, joint decision-making between male and female household members is the most common approach, representing 64.6% of responses—323 out of 500. Female-only decision-making accounts for 17% (85 responses), while male-only decisions make up the smallest share at 18.4% (92 responses). These findings indicate that in most households, decisions regarding agricultural and livestock purchases during and after disaster events are made collectively, reflecting a balanced and inclusive approach to managing critical family resources under stress.

Family decision-making on adaptive varieties, technologies and crop patterns during and after disasters:
When it comes to selecting adaptive crop varieties, farming technologies and cultivation patterns in response to disasters, joint decision-making between male and female household members dominates—accounting for 58.1% of responses (209 out of 360). Female-only decision-making represents 18.3% (66 responses), while male-only decision-making contributes 23.6% (85 responses). This data highlights the serious role of shared household decision-making in shaping adaptive agricultural strategies, reflecting a collaborative approach in times of crisis.

Family decision-making on selling agricultural and livestock goods during and after disasters:

In matters concerning the sale of agricultural and livestock products during and after disasters, joint decision-making between male and female household members was most common, comprising 69.8% of the total responses (369 out of 529). Female-only decision-makers accounted for 21.2% (112 responses), while male-only decision-makers represented just 9.1% (48 responses). These findings highlight the strong presence of collaborative decision-making in households, alongside the notable and active role women play in managing agricultural and livestock sales during times of crisis.

Roles of disaster management committee (DMC) during the last disaster:
During the most recent disaster event, Disaster Management Committees (DMCs) were primarily involved in disseminating weather and climate-related information, with 52.71% of responses identifying this as their main role. An additional 29.67% of respondents indicated that DMCs provided a combination of services, including weather updates, rescue coordination, shelter assistance and the distribution of food, water and medicine. However, their direct involvement in emergency response activities was relatively limited—only 1.22% participated in rescue efforts, 2.09% in providing shelter and 0.87% in ensuring security. A smaller segment (6.63%) highlighted DMC roles in safeguarding women and children or managing livestock in open spaces. Meanwhile, 1.75% reported other unspecified roles and 4.71% gave unclear responses. These findings suggest that while DMCs were highly engaged in communication and coordination, their direct engagement in operational response activities remained minimal.

Sources of drinking and domestic water in the surveyed districts:
In the surveyed areas, shallow tubewells are the most common source of both drinking and domestic water. A significant 58.5% of households rely on shallow tubewells for drinking water, and 32.3% use them for domestic needs. This preference highlights the accessibility and affordability of shallow tubewells, which are particularly prevalent in districts like Nilphamari, Dinajpur, and Lalmonirhat. Although less common, deep tubewells play an important role, with 22.3% of households using them for drinking water and 12.0% for domestic purposes, especially in areas like Satkhira, where shallow groundwater may be insufficient or contaminated. Surface water, including ponds and ditches, is notably utilized in flood-prone regions like Satkhira, where 7.2% of households rely on them for domestic needs and 0.9% for drinking water. This indicates the vital role surface water plays, particularly during dry spells. River water is another key resource, especially in rural agricultural communities like Naogaon (14.8%) and Satkhira (7.3%), where it is used for both drinking and domestic needs. Despite the widespread reliance on groundwater and surface water, tap water remains scarce, serving only 2.4% of households for drinking and 0.7% for domestic use, pointing to the limited development of centralized water distribution systems. Some areas, like Naogaon and Dinajpur, have implemented measures to improve water quality, using Bio Sand Filters (PSF/BSF) and Rainwater Harvesting Systems (RWHS) to address water challenges.

Water security is a critical aspect of agricultural productivity, but it is increasingly threatened by climate change. Shifting rainfall patterns, diminishing freshwater resources and the overuse of groundwater are intensifying water scarcity. The United Nations predicts that by 2025, nearly two-thirds of the global population could face water stress, with agriculture being the largest consumer of water. To maintain agricultural resilience in the face of climate change, innovative water

management practices are vital. Solutions such as efficient irrigation systems like drip irrigation, automated watering technologies, watershed management and water recycling are essential to ensuring long-term agricultural sustainability and mitigating the impacts of climate-induced water stress.

Knowledge of climate change and its impact on agriculture:
The survey data indicates that most respondents possess a moderate level of understanding regarding climate change and its effects on agriculture. Approximately 43.64% of participants rated their knowledge as "Average," followed by 32.73% who considered their understanding "Good." A smaller segment, 14.55%, viewed their knowledge as "Poor," while 7.27% rated it as "Excellent," and just 1.82% described their understanding as "Very Poor." These findings suggest that while a considerable number of people are somewhat informed about climate change, there is room for enhancing awareness and deepening understanding of its agricultural impacts.

Observed climate change effects on agriculture (multiple response):
The data indicates that increased temperatures are the most observed impact of climate change on agriculture, with all respondents (100%) reporting this effect. Changes in rainfall patterns (94.55%) and cold waves/dense fog (74.55%) also play significant roles in affecting agricultural productivity. Extreme weather events, including heavy rainfall, floods and droughts were noted by 70.91% of respondents, while cyclones and nor'westers impacted 56.36% of the areas. Additional climate effects include riverbank erosion (49.09%), waterlogging (47.27%), salinity intrusion (23.64%) and sea-level rise/tidal surge (21.82%). These findings underline the diverse range of climate change impacts on agriculture, with varying levels of intensity across regions.

Impact of climate change on agricultural productivity:
The data reveals that climate change has notably affected agricultural productivity, with 45.45% of respondents reporting a significant impact. A moderate effect was observed by 27.27%, while 20% indicated a severe impact. Only 7.27% of respondents mentioned a slight effect. These findings suggest that, for most, climate change has had a substantial influence on agricultural output, though its severity varies across different areas.

Importance of climate change coping and adaptation for food security:
The data reveals that most respondents (60%) consider both climate change coping (short-term) and adaptation (long-term) strategies as "very important" for ensuring food security. Another 21.82% view these strategies as "moderately important," while 18.18% deem them "extremely important." These findings highlight the widespread acknowledgment of the essential role that both short-term coping and long-term adaptation measures play in securing food availability in the face of climate change.

Perception of water availability for agricultural purposes:
The data indicates that water availability for agricultural purposes is generally perceived as moderate in most areas. 34.55% of respondents rated it as "Average," while 27.27% considered it "Poor." A smaller portion, 18.18%, described it as "Good," 16.36% as "Very Poor," and only 3.64% rated it as "Excellent." These findings suggest that water access for farming remains a significant concern, with most respondents reporting either average or poor availability.

Primary water sources for agricultural activities:
The data shows that groundwater is the most widely used source for agricultural purposes, with 87.27% of respondents relying on it. Rainwater is also a key source, utilized by 72.73% of respondents. Irrigation systems, including canals and reservoirs, are used by 45.45%, while surface water sources such as rivers, ponds and ditches are mentioned by 32.73%. This indicates that groundwater and rainwater are the main sources of water for agriculture, with varying degrees of reliance on other methods like irrigation and surface water.

Water shortages during agricultural season:
The data reveals that water shortages or scarcity are common challenges during the agricultural season. Nearly half of the respondents (49.09%) report experiencing water scarcity frequently, while 34.55% face it occasionally. A smaller group, 9.09%, encounter water shortages rarely and 5.45% always experience them. Only 1.82% of respondents indicated that they never face water scarcity. This highlights that water availability remains a significant issue for many agricultural areas, with frequent shortages impacting a substantial number of respondents.

Impact of water scarcity on agricultural productivity and costs:
The data highlights the significant challenges water scarcity poses to agricultural productivity. Most of the respondent's report that water scarcity leads to reduced crop production, with 47.27% finding it "very impactful" and 30.91% considering it "moderately impactful." Additionally, water scarcity increases the costs of water supply, with 56.36% rating it as "very impactful" and 27.27% as "extremely impactful." The increased labor demand for water management is also seen as "very impactful" by 47.27%, while 34.55% view it as "moderately impactful." Crop failures due to water shortages are considered "very impactful" by 43.64% and "moderately impactful" by 23.64%. These results underscore the substantial negative effects of water scarcity, contributing to higher costs, labor demands and reduced agricultural productivity.

Adoption of water conservation techniques in agriculture:
The data reveals that most respondents (67.27%) have not adopted any water conservation techniques for agricultural use, while 32.73% have implemented such practices. This indicates that although a portion of farmers are actively managing water use more efficiently, a substantial number have yet to adopt conservation methods. This highlights a critical opportunity for promoting improved water management strategies in agriculture to address ongoing water scarcity challenges.

Types of adopted water conservation techniques:
The data shows that among those who have adopted water conservation methods, rainwater harvesting is the most widely used, reported by 12.73% of respondents. Water-efficient crop varieties are implemented by 10.91%, while 9.09% use mulching to retain soil moisture. Notably, no respondents reported using drip irrigation, indicating that while some conservation practices are in place, the adoption of advanced techniques like drip irrigation remains very limited. This points to the need for increased awareness and support for implementing more efficient water-saving technologies in agriculture.

Awareness of agricultural innovations to address climate change and water scarcity:
The data indicates that awareness of agricultural innovations designed to tackle climate change and water scarcity is generally low among respondents. The largest group (36.36%) reported being "slightly familiar" with such innovations, while 30.91% stated they are "not familiar at all." A smaller portion (21.82%) described themselves as "moderately familiar," with only 9.09% being "very familiar" and just 1.82% "extremely familiar." These findings point to a significant gap in knowledge, underscoring the need for improved outreach, education and promotion of climate-smart agricultural technologies and practices.

Adopted agricultural innovations and practices (multiple response):
The data highlights a range of innovative farming practices adopted to enhance resilience against climate change and water scarcity. The most common is ginger cultivation in sacks, practiced by 36.36% of respondents. Homestead vegetable gardening on lofts or water bodies is also widely adopted, with 29.09% participation. Integrated pest management (23.64%) and the use of saline-tolerant crop varieties (12.73%) are other notable strategies. Additionally, 16.36% of respondents have adopted climate-resilient farming techniques and drought-resistant crop varieties. Less commonly adopted practices include flood-tolerant crop varieties, smart irrigation systems and vertical farming or hydroponics, with adoption rates between 3.64% and 10.99%. Importantly, no respondents reported using precision agriculture technologies such as sensors or drones, highlighting a significant gap in the application of advanced farming technologies. This suggests a need for increased support and education to promote modern, tech-driven solutions in agriculture.

Perceived effectiveness of agricultural innovations under climate change:
The data indicates that most respondents view agricultural innovations as beneficial in enhancing productivity amid changing climatic conditions. Specifically, 41.82% consider these innovations "very effective," and 38.18% rate them as "moderately effective." A smaller group, 12.73%, believes they are "extremely effective," while 7.27% describe them as "slightly effective." These findings suggest that most respondents recognize the value of agricultural innovations, though there remains room to further improve their impact and accessibility.
Key barriers to adopting agricultural innovations:
The data highlights several major challenges that hinder the adoption of agricultural innovations in the surveyed areas. The two most cited barriers are a lack of knowledge or training and the high cost of technology, both reported by 81.82% of respondents. Additionally, 74.55% point to limited access to financing as a significant obstacle. Government policies are seen as a constraint by 69.09%, while 52.73% mention resistance to change as a barrier. Inadequate infrastructure is also a concern for 41.82% of respondents. These findings emphasize the need for targeted interventions—such as farmer education, financial support mechanisms and enabling policies—to support wider adoption of agricultural innovations.

Perception of government policies in promoting agricultural innovation for climate adaptation:
The data indicates that government policies are generally seen as only moderately helpful in encouraging agricultural innovation in response to climate change. The largest share of respondents (45.45%) views these policies as "slightly supportive," while 36.36% consider them "moderately supportive." A smaller percentage (16.36%) believe the policies are "very

supportive," and only 1.82% feel they are "extremely supportive." These responses suggest that although some support exists, there is significant scope for strengthening government initiatives to better promote innovation and resilience in the agricultural sector.

Perception of international collaboration in addressing climate, water and agricultural challenges:

The data reflects a strong consensus among respondents on the importance of international collaboration in tackling climate change, water security and agriculture-related issues. Over half (54.55%) consider such collaboration "extremely important," while the remaining 45.45% view it as "very important." This unanimous agreement underscores the recognition that global cooperation is essential for effectively addressing these interconnected and cross-border challenges.

Perceived importance of key strategies for tackling agricultural challenges:

The data reveals strong support for a range of strategies aimed at overcoming agricultural challenges. Most respondents (54.55%) regard improving water management infrastructure as "very important," followed closely by awareness programs for farmers (49.09%). Additionally, financial incentives for innovation and support for climate change mitigation and adaptation research are valued by 40% of respondents. Promoting sustainable agricultural practices is also recognized as "very important" by 34.55%. Although the majority view these strategies as essential, a smaller segment considers them only "slightly" or "moderately important," indicating some variation in prioritization. Overall, the findings suggest a clear consensus on the need for comprehensive, multi-pronged approaches—especially those focused on infrastructure, education, and innovation—to address the pressing issues facing agriculture under changing climate conditions.

Perception of Bangladesh's agricultural policy on climate change and water security:

The data reflects a prevailing sentiment that current agricultural policies in Bangladesh fall short in effectively addressing the challenges of climate change and water security. Nearly half of the respondents (47.27%) rated the policy as "poor," while 32.73% consider it "average." Only a small proportion view it positively, with 12.73% rated it as "good" and 7.27% as "very poor." These findings point to a clear need for policy enhancement. While some respondents acknowledge existing efforts, the majority believe that stronger, more targeted interventions are essential to build climate resilience and ensure sustainable water management within the agricultural sector.

5. Discussion:

Bangladesh: a nation balancing vulnerability and innovation

Bangladesh is one of the most vulnerable countries globally to the combined effects of climate change, water scarcity and agricultural instability. Situated in a low-lying delta, it faces heightened risks due to its geographic location, dense population and heavy reliance on agriculture. This makes the country particularly susceptible to climate-related disasters such as flooding, cyclones and rising sea levels. Furthermore, Bangladesh’s agriculture is highly dependent on the seasonal monsoon rains, which have become increasingly erratic due to

changing climate patterns. Consequently, the agricultural sector, which employs approximately 40% of the population, is frequently disrupted, threatening both crop yields and food security.

In terms of water security, Bangladesh grapples with significant challenges concerning both the availability and quality of freshwater. The country's vast network of rivers provides both benefits and challenges, as flooding often leads to crop losses and contamination of water supplies. Moreover, coastal regions are increasingly affected by salinity intrusion due to rising sea levels, further exacerbating the challenges for millions of farmers. Water management, therefore, becomes not just an issue of efficiency but also of fairness, as marginalized and vulnerable communities are often the most severely impacted by water-related crises.

Despite these challenges, Bangladesh offers a valuable example of resilience and agricultural innovation. Over recent decades, the country has introduced several creative solutions to address water scarcity and enhance agricultural productivity. These include the development of salt-tolerant rice varieties, the adoption of floating agricultural systems, and the promotion of rainwater harvesting techniques. Additionally, collaboration between the government, NGOs and local communities has led to the successful integration of modern technology with traditional knowledge, helping to build resilience in the face of climate uncertainty.

Agricultural innovation: a path to resilience

Agricultural innovation is vital for ensuring food systems are secure in an increasingly warming world. From genetically modified crops that can withstand extreme weather to the adoption of precision agriculture technologies, innovation has the potential to transform how food is produced, distributed and consumed. In the face of climate change and water scarcity, innovations like drought-resistant crop varieties, efficient irrigation systems and climate-resilient farming practices are essential to maintain food security.

In Bangladesh, the challenge goes beyond simply adopting new technologies. It's also about making these innovations accessible to small-holder farmers, who constitute most of the agricultural sector. Achieving this requires a comprehensive approach, including affordable financing, capacity-building programs and the integration of local knowledge into new agricultural practices. The government's role in promoting these innovations—through policy support, infrastructure improvements and research funding—is vital.
Furthermore, global cooperation and knowledge-sharing are key to advancing agricultural innovations that address specific regional needs. Climate change is a global issue and the solutions to water scarcity and agricultural challenges must be globally coordinated. By fostering international partnerships, governments and organizations can speed up the development and spread of climate-smart agricultural technologies, ensuring that vulnerable regions like Bangladesh are not left behind.

Essence from captured case stories in study areas:
The stories from the study areas reflect a broader global trend highlighting the serious role of local, grassroots efforts in addressing the challenges posed by climate change and water security.

Empowering women and rural communities are pivotal in driving sustainable development, fostering resilience and providing long-term solutions to environmental and social issues.

Women from diverse socio-economic backgrounds, each facing distinct challenges, found opportunities for growth and self-reliance through participation in development projects. These stories illuminate the intersection of social support, sustainable agricultural practices and gender empowerment in rural settings. By accessing resources, acquiring skills and developing small businesses, these women improved their financial stability and overall quality of life. Their experiences underscore the importance of targeted interventions, such as training in animal husbandry, climate-resilient farming and small business development, which enable individuals, particularly women, to break free from cycles of poverty, violence and social constraints. These narratives highlight how community-driven support fosters empowerment and paves the way for socio-economic prosperity.

This research emphasizes the transformative power of community-driven projects, especially in fostering resilience and self-reliance among rural women in the face of adversity and climate change. The stories demonstrate how access to training, resources and support networks can empower individuals to overcome significant socio-economic challenges. Women who embraced innovative approaches like vermicomposting, sustainable agriculture and small-scale businesses have secured financial stability, improved their livelihoods and inspired their communities. These experiences demonstrate the importance of integrating climate-resilient practices, sustainable farming and entrepreneurial skills in rural development programs. This approach not only mitigates the effects of climate change but also promotes poverty reduction and gender equality.

Ultimately, these case studies exemplify how well-targeted interventions can empower women to become agents of change, fostering both individual and collective progress amid environmental and socio-economic challenges.

Study overview and key findings:

This study provides a comprehensive analysis of the complex interplay between climate change, water scarcity and agricultural challenges in rural Bangladesh. It reveals that while most respondents have a moderate understanding of climate change and its impacts on agriculture, this awareness often does not translate into adaptive actions. Water scarcity emerged as a significant issue, with many respondents frequently facing shortages, which severely affected agricultural productivity. The reliance on groundwater and rainwater highlights the vulnerability of farming systems to climate-induced fluctuations in water availability.

Despite recognizing the potential of agricultural innovations and climate-smart practices, their adoption remains limited. Key barriers include high costs, insufficient training and inadequate infrastructure. While innovations like climate-resilient farming practices are seen as effective in improving productivity under changing climatic conditions, they are not widely implemented. Government policies, though somewhat supportive, are viewed as inadequate in addressing the full scope of challenges faced by farmers.

The study underscores the urgent need for enhanced government support, increased international collaboration and more comprehensive strategies to improve farmer education, access to technology and water management practices. Policies should focus on promoting sustainable agricultural practices, offering financial incentives for innovation and implementing robust climate adaptation measures to ensure long-term food security.

6. Conclusion:

The intersection of climate change, water security and agricultural innovation presents both significant challenges and opportunities. As the global community grapples with the realities of a shifting climate, the demand for innovative solutions to secure sustainable agricultural practices and reliable water resources becomes increasingly urgent. Bangladesh, with its unique vulnerabilities and innovative responses, provides valuable insights into resilience and adaptation. Through fostering collaboration, investing in research and embracing new technologies, both locally and globally, we can create pathways toward a future where agriculture continues to thrive despite the challenges posed by climate change and water scarcity. This approach not only protects food security but also enhances the livelihoods of millions of farmers worldwide.

This study highlights the critical challenges faced by rural Bangladesh in relation to climate change, water scarcity and agricultural productivity. While there is a moderate understanding of climate change among farmers, many continue to face inadequate resources, frequent water shortages and limited adoption of sustainable farming practices. Although government policies offer some support, they are widely regarded as insufficient to address the scale of the problem. The findings suggest that climate change is having a substantial impact on agricultural production and both immediate and long-term solutions are necessary to ensure food security and sustainability in these vulnerable regions.

Recommendations:

- Enhance training and awareness programs for farmers to improve knowledge on climate change impacts and water-efficient practices
- Government policies should focus on providing financial incentives, subsidies for climate-smart technologies and improving water management infrastructure
- Encourage the adoption of water conservation techniques like rainwater harvesting and the use of drought-resistant crop varieties through grants and technical support
- Support research on climate-resilient agricultural technologies and encourage the development of affordable innovations for farmers
- Strengthen international partnerships to share knowledge, technologies and resources for combating climate change and ensuring water security in agriculture.

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Competing Interests
The authors declare that they have no competing interests associated with this study.

Author Contributions:
Ashim Kumar Saha made significant contributions to this study. He conducted research, developed the manuscript and designed the study. Additionally, he formatted the manuscript according to the journal guidelines. The respective author collaborated on interpreting the results and ensuring the manuscript was written precisely.

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