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Perception of and adaption to climate change: the case of groundnut production of costal island in Bangladesh

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Introduction: Nut farming in the island regions of Bangladesh faces considerable challenges due to climate change. This research investigates the climate change perceptions and adaptive capacity of strategies of male and female groundnut farmers in island of Hatiya, Bangladesh where nut yields fall below the national average.
Methods: Data were gathered from 170 male and 130 female farmers on the island, with Chi-square tests used to analyze gender-based differences in perceptions of climate change and adaptive capacity. A probit regression model was applied to evaluate the factors driving the adoption of these strategies.
Results and discussion: The findings suggest that male and female farmers largely share similar perceptions of climate change impacts, such as changes in rainfall patterns, increased pest infestations, and a greater need for fertilizers. Consequently, a combined analysis of both genders was conducted to identify the factors influencing adaptive capacity of strategies. Additionally, the results indicated that older farmers are more likely to engage in off-farm activities as a strategy to cope with environmental uncertainties. Education and farming experience are key factors in driving crop diversification and climate-smart practices, with farmers adjusting planting dates, shifting crops, and using weather forecasts as the most common adaptive capacity. Less frequently adopted strategies include agroforestry and urban migration. Education and farming experience are positively associated with the adoption of proactive adaptive capacity, thereby improving farmers' ability to cope with climate change. This study exploring adaptive capacity of nut farmers in Bangladesh's island and suggests interventions to enhance resilience and encourage sustainable agricultural practices in response to climate change.

KEYWORDS

nut production, island, adaptive capacity, climate change, sustainable agriculture

1 Background

The landscape of Bangladesh is defined by numerous islands, estuaries, and riverine areas, where agricultural practices and land use are influenced by the dynamic interaction between land and water. The country's geographical features include many islands, particularly in the coastal regions (Mosa et al., 2023). These islands, often referred to as chars or sandbars, are constantly reshaped by river and tidal movements, making them both fertile and challenging for agriculture. Bangladesh's agrarian economy is highly dependent on its riverine and island ecosystems, where agriculture remains the mainstay for millions of rural households (Chowdhury, 2021).

Hatiya Island is one such significant island located in the southern part of Bangladesh, in the Noakhali District. The island is part of the Chattogram Division, situated in the Bay of Bengal's coastal belt. Hatiya is one of the largest islands in Bangladesh and is surrounded by the Bay of Bengal and other rivers (Uddin et al., 2022). The island is subject to the challenges of salinity, flooding, and soil erosion, which significantly affect the livelihood of its inhabitants (Roy et al., 2024). Despite these challenges, Hatiya continues to have significant agricultural potential, especially in crop cultivation and livestock farming. The people of Hatiya largely depend on agriculture for their livelihood, with nut farming especially the cultivation of coconut, betel nut, and date palm being a key component of the local economy (Shahidullah et al., 2006). These crops, which thrive in the tropical climate of the island, have become an integral part of the agricultural landscape, not only providing food and income to the farmers but also offering significant cultural and economic value (Dagar, 1995; Pawlak and Kołodziejczak, 2020). The island's agricultural productivity is threatened by climate change, particularly rising sea levels, increased salinity, and the frequent occurrence of natural disasters such as cyclones and floods (Roy et al., 2022). However, the farming communities on Hatiya Island face numerous socio-economic challenges. These include issues such as low income, poor infrastructure, and limited access to credit and markets, land erosion, which make it difficult for farmers to improve their living standards (Rahman and Rahman, 2015). These factors have intensified the vulnerability of farming communities, particularly in the production of crops that rely on favorable climatic conditions. Farmers' perceptions of these environmental challenges, as well as the perceived impacts on their agricultural productivity and socio-economic well-being, are critical for understanding how they respond to such challenges (Jha and Gupta, 2021). Thus, understanding the socio-economic conditions, perceptions of climate change impacts, and adaptive capacity of strategies of farmers in Hatiya Island is essential for developing sustainable agricultural policies and support programs. Climate change refers to long-term and persistent changes in climate patterns, particularly variations in temperature, rainfall, and the frequency of extreme weather events whereas adaptive capacity is the ability of farmers to adjust, mitigate, and recover from the adverse impacts of climate change through the utilization of available resources, knowledge, and skills.

Groundnut (peanut) is a key crop in Bangladesh, especially in the northern and central regions, where the climate and soil conditions favor its growth (Deb and Pramanik, 2015). It is valued for its nutritional content and versatility in food, oil production, and export markets. Peanut oil, rich in unsaturated fatty acids and oleic acid, offers health benefits, such as improved cardiovascular health, reduced LDL oxidation, and lower risk of type 2 diabetes. Groundnut and its products also help reduce the risk of colorectal cancer. Groundnut farming plays a crucial role in food security and income generation, particularly for smallholder farmers (Suchoszek-Łukaniuk et al., 2011). In this study, groundnut farmers are predominantly smallholders, cultivating from 0.1 to 2 hectares of land. They typically operate at a subsistence or semi-commercial level, with limited access to capital, agricultural technology, and extension services. On Hatiya Island, groundnut cultivation has grown due to favorable soil types and low input requirements, significantly contributing to the local economy (Melesse et al., 2023). Despite challenges such as climate related issues and market fluctuations, groundnut farming continues to thrive on the island, helping to enhance agricultural diversity and resilience in the region.

Over the period from the financial year 2013–2014 to 2022–2023, Smallholder nut farmer's in Bangladesh consistently outpaced that on Hatiya Island, though the gap between the two fluctuated. In the early years, such as 2013–2014, national production was significantly higher at 1.89 million metric tons, compared to 1.57 million metric tons on the island, resulting in a difference of 0.32 million metric tons. However, from 2018 to 2020, the gap narrowed considerably, with national and island production almost identical, differing by just 0.01 million metric tons. In the later years, such as 2020–2021 and 2021–2022 (Figure 1), the disparity remained small, with national production hovering between 1.85 and 1.91 million metric tons, and island production fluctuating between 1.80 and 1.85 million metric tons. While Hatiya Island has seen significant groundnut production, it remains notably lower than in previous years, largely due to the impact of climate change. Fluctuating environmental conditions have led to a decline in yields compared to earlier years. This decrease highlights the challenges island farmers face in maintaining stable production amid changing climate patterns. The disparity in production levels emphasizes the need for adaptive strategies to address the environmental impacts and sustain groundnut farming on the island.

Farmers' perceptions of climate change and their subsequent adaptation strategies are crucial to understand the broader impacts of climate variability on agriculture. Numerous studies have explored how farmers in different regions perceive climate change and the factors influencing their adaptive responses. Datta et al. (2022) conducted a systematic review of Indian farmers' perceptions and adaptation strategies, emphasizing the importance of localized approaches to coping with climate change. Similarly, Ricart et al. (2023) reviewed farmers' awareness of climate change and their behavioral adaptations, highlighting the role of experience in shaping responses. Jha and Gupta (2021) also examined the factors influencing adaptation decisions among Indian farmers, underlining socio-economic factors and institutional support as key determinants. Farmers' perceptions of climate change significantly influence their adaptation strategies, as highlighted in studies by Moniruzzaman et al. (2023) and Tasnim et al. (2023), which examine wheat farmers in Bangladesh. Studies in other countries have provided further insights, such as Yang et al. (2021), explored livestock farmers' perceptions in China, and Balasha et al. (2023), focused on adaptation practices in the marshlands of the Democratic Republic of Congo. Smallholder farmers' adaptation strategies were shaped by their perceptions of climate change, with significant differences observed between agro-ecological zones in Ghana (Aidoo et al., 2021; Adeboa and Anang, 2024). These findings highlight the importance of understanding farmers' perceptions and contextual factors to develop effective climate change strategies.

While much research has explored the broader impacts of climate change on agriculture in Bangladesh, most studies concentrate on major cereal crops in mainland areas and overlook cash crops like groundnut, which are vital for this coastal livelihood and highly sensitive to climatic changes due to distinct agro-ecological conditions like tidal flooding, soil salinity, land erosion, and isolation from extension services all of which uniquely influence farmers' adaptive behavior. Unlike previous studies, this research also explores gender

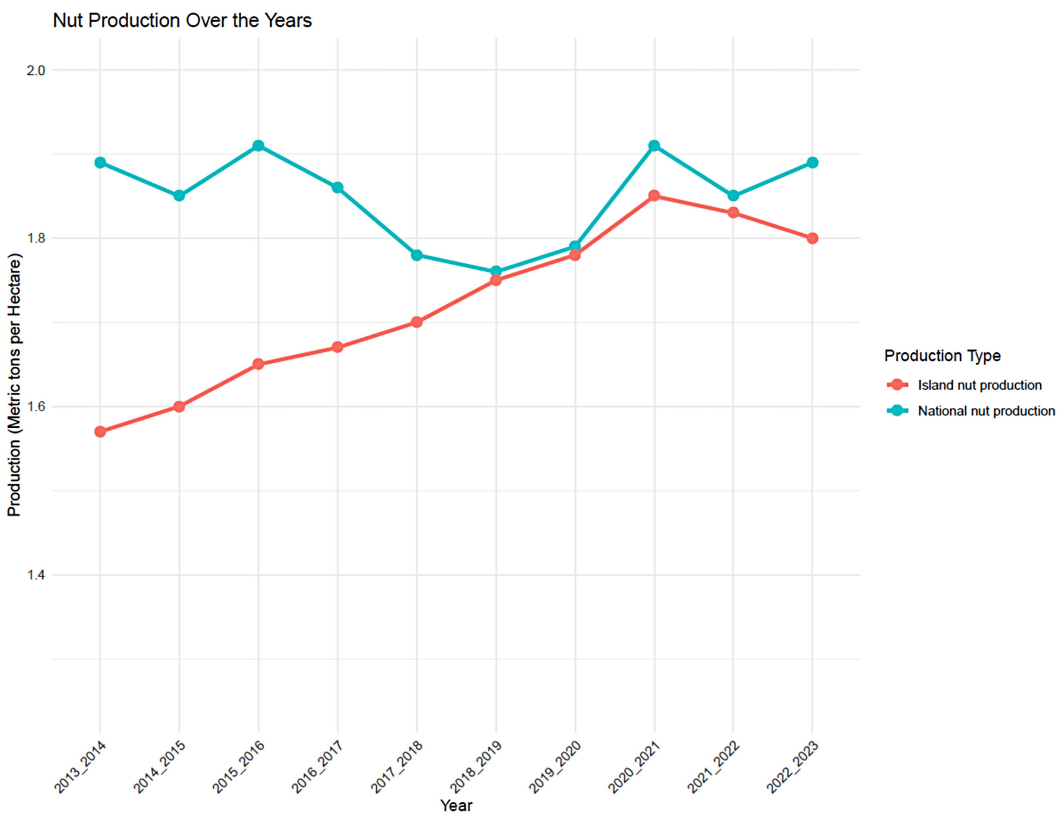

FIGURE 1
Production scenario of nut production in national and Hatiya island of Bangladesh.

differences in perceptions and adaptation behaviors, specifically how male and female farmers respond to climate change.

The main research gap addressed by this study lies in the lack of comprehensive understanding of the socioeconomic factors that influence the adaptive capacity of strategies of groundnut farmers. This research focuses on the production disparities between Hatiya Island and national levels, addressing a critical gap by examining how socioeconomic factors such as training, education, farming experience, and access to subsidies affect the adaptive capacity of groundnut farmers in an island context.

By focusing on groundnut farmers in the coastal island of Hatiya, this study provides new insights into the intersection of climate change, socioeconomics, and gender in a marginalized and under-researched geographic setting, offering both theoretical contributions and practical recommendations for climate-resilient agricultural planning.

2 Methodology

2.1 Study area and data

The study was conducted to explore groundnut farmers' perceptions and adaptations to climate change in Bangladesh's climate-vulnerable coastal island. It focused on Hatiya Island, which is frequently exposed to climatic hazards such as cyclones, tidal surges, saltwater intrusion, and erratic rainfall patterns that threaten agricultural productivity. The island's farming population is predominantly composed of smallholder farmers with limited access to education, extension services, and climate information, making them particularly vulnerable. Hatiya Island, is a key area for groundnut production and was purposively chosen for the study due to its significant role in local production (Figure 2). In the fiscal year 2022–2023, the total cultivated area for groundnut farming in Bangladesh was estimated at 97,875 acres, with the Noakhali region accounting for approximately 17,893 acres (18.28%) (Bangladesh Bureau of Statistics (BBS), 2024). A total of 300 groundnut farmers where 170 male and 130 female groundnut farmers were selected from the list provided by the Upazila Agriculture Offices through simple random sampling technique. Data collection occurred during the groundnut harvest season, from February to May (2022–2023), with face-to-face interviews conducted using a structured interview schedule in Tomoruddin, Burirchor, Jahajmara, Chorking, and Nijumdwip region. This schedule was designed after an extensive literature review and included questions on farmers' perceptions of climate variability, the causes and impacts of climate change, adaptive capacity of strategies, factors affecting adaptive capacity, and their socioeconomic characteristics. Prior to the main survey, a pilot test was conducted with a few farmers in the study area, and the interview schedule was adjusted based on the feedback to ensure it met the study objectives.

2.2 Analysis of data

Descriptive statistics were used to summarize the socioeconomic characteristics of the farmers in the study. Frequencies and percentages

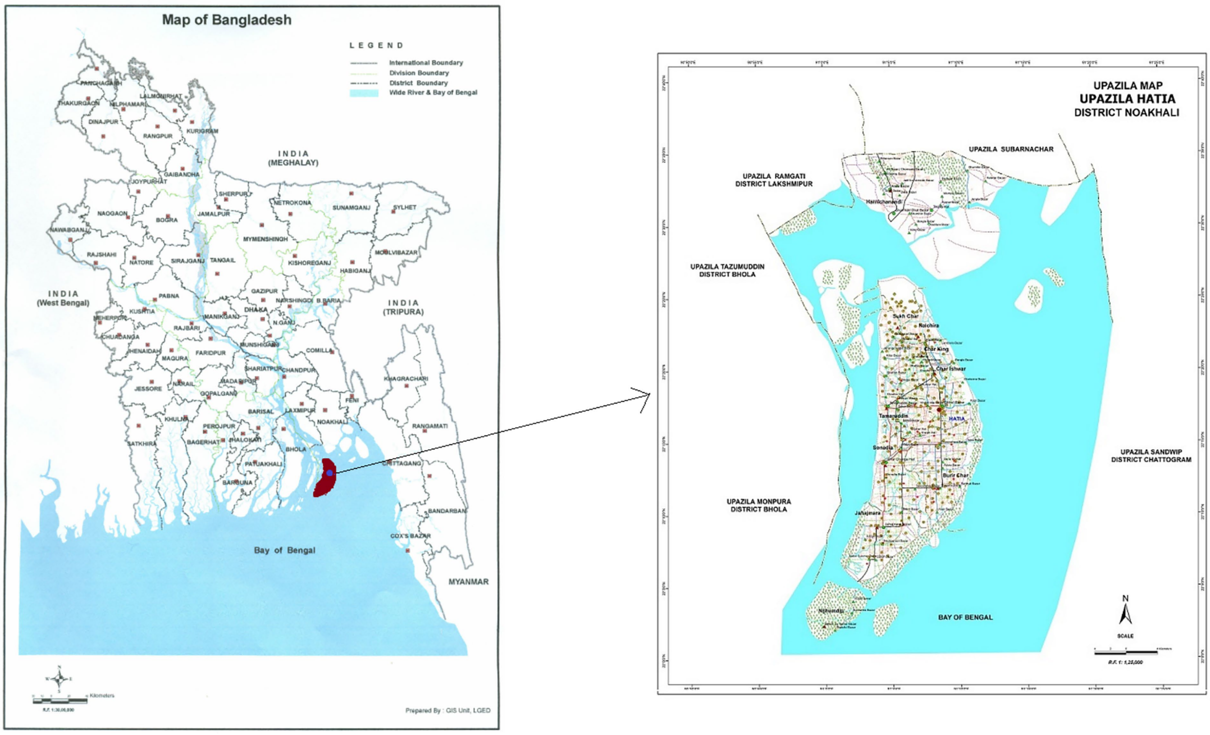

FIGURE 2
Selected study area.

were calculated for categorical variables, while the mean, standard deviation, minimum, and maximum values were computed for continuous variables, such as contact with extension agents, training days, farm size, and annual income. These analyses were performed using R software to provide a comprehensive overview of the study participants' profiles.

To examine the differences in perceptions, perceived impacts, and adaptive capacity between male and female farmers, a Chi-square test was conducted using R software. The Chi-square test was used to assess whether gender differences exist in the perceptions of climate change and the adoption of strategies. This test is particularly suitable for categorical data and allowed us to identify whether the observed gender differences were statistically significant.

2.2.1 Relationships between socio-economic factors and adaptive capacity of strategies

In this study, a multivariate probit regression model was employed to assess the relationships between adaptive capacity of strategies and socio-economic factors (Henningsen, 2021). The multivariate probit model was selected because it allows us to analyze the simultaneous adoption of multiple adaptation capacity (binary outcomes) and account for potential correlations between them. For instance, a farmer may adopt several strategies (e.g., adjusting planting dates and diversifying crops) in response to climate change. The model was specified using the mvProbit function in R, with the dependent variables representing different adaptive capacity, including changes in planting and harvesting dates, shifts to other crops, adoption of agroforestry and horticultural practices, migration to urban areas, use of weather forecasts, and shifts to other crop varieties. These strategies were modeled as binary outcomes, indicating whether a household had adopted each respective strategy. The independent variables included socio-economic factors such as sex, age, household size, access to credit, access to input subsidies, training received, contact with extension agents, farm size (in hectares), access to climate information, years of education, and years of farming experience. This approach allowed for the simultaneous analysis of multiple interrelated decisions made by households in response to environmental or socio-economic stressors, thus providing a more comprehensive understanding of the factors influencing adaptive capacity. Multicollinearity among predictors was checked using variance inflation factors (VIF), all within acceptable limits.

After running the multivariate probit regression model using the mvProbit function in R, we examined the estimated coefficients, standard errors, and *p*-values for each of the predictor variables. The estimated coefficients represent the change in the log-odds of adopting a particular adaptation strategy for a one-unit change in the respective independent variable, holding all other variables constant. A positive coefficient indicates that an increase in the predictor variable is associated with a higher likelihood of adopting the corresponding adaptation strategy, while a negative coefficient suggests the opposite. The standard errors reflect the precision of the coefficient estimates. Smaller standard errors indicate more precise estimates, while larger standard errors suggest greater uncertainty about the coefficient values. The *p*-values were used to assess the statistical significance of each predictor variable. A p-value less than 0.10 were considered evidence that the predictor variable significantly influences the likelihood of adopting a particular adaptation strategy.

2.2.2 Predicted probability and correlation analysis of key factors

After fitting the multivariate probit regression model, predicted probabilities for each adaptation strategy were calculated to assess the likelihood of households adopting specific strategies based on their socio-economic characteristics. Using the mvProbit function in R, we generated predicted probabilities for each binary adaptation strategy (e.g., changes in planting and harvesting dates, shifts to other crops, agroforestry adoption, migration, and use of weather forecasts). These probabilities were computed by applying the estimated coefficients from the probit model to the observed values of the independent variables (such as sex, age, household size, education, and farming experience) for each household. The predict () function with the type = "response" argument was used to obtain the predicted probabilities, which represent the likelihood of adopting each strategy, with values ranging from 0 to 1. These predicted probabilities were then examined for each adaptation strategy, providing insights into the factors that influence the likelihood of households engaging in various adaptive behaviors in response to environmental or socio-economic stressors.

To further explore the relationship between the predicted probabilities and key socio-economic factors, we visualized the correlation between predicted probabilities and key socio-economic factors using ggplot2. Scatter plots were created to examine how these socio-economic variables influence the likelihood of adopting each adaptation strategy. The geom_point() function was used to plot the predicted probabilities against education and farming experience, while geom_smooth() was applied to add trend lines that help visualize the strength and direction of the relationships.

3 Results and discussions

3.1 Socio-economic characteristics of nut farmers

The study sample consists of 170 males (56.67%) and 130 females (43.33%), with a predominant age group of 15–35 years (66%), followed by participants aged 36–50 years (22.33%) and those older than 50 years (11.67%). The average household size among the farmers was 5.67 members, which is slightly higher than the national average, indicating a relatively larger family structure compared to the general population (Bangladesh Bureau of Statistics (BBS), 2024). The majority of respondents are engaged in agriculture (89.33%). In terms of education, 45.33% have completed Junior High School (JHS) or middle school, followed by 38.33% with primary education, and 16.33% with Senior High School (SHS) or A-level education. The average educational level of nut farmers on coastal islands is lower compared to the national average (Bangladesh Bureau of Statistics (BBS), 2024), reflecting disparities in access to education between remote agricultural areas and urban regions. When it comes to farming experience, 41% of participants have 11 to 20 years of experience, with smaller groups having 0–10 years (34.33%) or 21–30 years (24.67%) of farming experience. The average contact with extension agents is limited, with a mean of 1.21 days, and participants have received an average of 1.08 days of training. Farm sizes are generally small, with the average farm size being 0.47 hectares (SD = 0.31), and annual incomes range from 75,000 to 200,000 TK (Bangladeshi currency). This data highlights a predominance of younger, male, and agriculture-based participants with relatively low levels of formal education, modest farm sizes, and limited engagement with extension services and training programs (Table 1).

3.2 Smallholder nut farmers' perception of climate change

Understanding the perceptions of climate changes is crucial for developing targeted adaptive capacity of adaption strategies. Table 2 presents smallholder nut farmers' perceptions of changes in rainfall timing and distribution over the past decade (2014–2023). On the topic of increased rainfall, 28% of males and 21.66% of females agreed, with a higher proportion of males being neutral (18%) compared to females (14.66%). Conversely, for decreased rainfall, 26% of males disagreed, compared to 18% of females, indicating a stronger perception of decreased rainfall among men. When asked about the late onset of rains, a similar trend emerged, with 24% of males and 20% of females disagreeing, suggesting a common perception across genders. Case of the early onset of rains, a significant gender difference was observed, with 30.33% of males and 23.33% of females agreeing to the statement, and this difference is statistically significant (p-value<0.0001). For the late end of rains, 25.66% of males and 21% of females agreed, but the chi-square test showed no significant difference (p-value = 0.4888). The perception of poor distribution of rainfall also revealed a noteworthy gender difference, with 32.33% of males and 21.66% of females agreeing, and this difference was statistically significant (p-value = 0.03339). Male farmers, in particular, were reported to perceive themselves as more vulnerable to changes in rainfall patterns and the growing season (Bessah et al., 2021). This aligns with the current findings, where gender-based variations in the perception of climate variability are evident. The gender differences in perceptions of rainfall changes on Hatiya Island can be attributed to factors such as differing access to resources and information, gender roles in farming, and varying responsibilities.

Overall, while there are some common perceptions between males and females regarding rainfall patterns, significant gender-based differences are particularly evident in the early onset and poor distribution of rainfall, where males tended to have stronger agreement.

The data presented in Table 3 reflects the perceptions of male and female respondents regarding various weather risks for a decade (2014–2023). Regarding increased temperature, 29.66% of males and 23.66% of females agreed that temperatures were rising, with almost similar proportion of both genders being neutral 13.66% of males and 11.66% of females although the difference was not statistically significant ($\chi^2 = 0.5525$). When asked about cold wave severity, 30.33% of males and 25.66% of females agreed that cold waves were becoming more severe, with males also showing slightly higher disagreement (15%) compared to females (9.33%). Again, this difference was not statistically significant ($\chi^2 = 0.5526$). For hot wave severity, a majority of both genders agreed, with 33.66% of males and 28.33% of females acknowledging the increased severity, though the difference was not statistically significant ($\chi^2 = 0.4644$). On the topic of climate change intensity, 27% of males and 23.33% of females considered the changes "intense." Overall, more males (18.33%) reported a perception of no change compared to females (11.33%), but again, the chi-square test showed no significant difference

TABLE 1 Socio-economic characteristics of the respondents.

Variable	Categories	Frequency	Percentage	Mean	SD	Min	Max
Gender	Male	170	56.67				
	Female	130	43.33				
Age (years)	15–35	198	66.00	28.37	5.57	15	35
	36–50	67	22.33	44.14	3.07	36	50
	>50	35	11.67	54.68	4.40	51	56
Household size	2 to 6	203	67.67	4.56	1.24	2	6
	7 to 10	97	32.33	7.97	1.02	7	10
Occupation	Agriculture	268	89.33				
	Fish farmer	17	5.67				
	Service	15	5.00				
Education (years)	Primary	115	38.33				
	JHS/Middle School	136	45.33				
	SHS/O/A Level	49	16.33				
Farming experience (years)	0–10	103	34.33	5.32	3.36	0	10
	11 to 20	123	41.00	15.60	2.68	11	20
	21–30	74	24.67	25.58	2.94	21	30
Contact with extension agents (days)				1.21	1.21	0	4
Training (days)				1.08	1.09	0	3
Farm size (hector)				0.47	0.31	0.1	2
Annual income (TK.)				164616.67	44636.43	75,000	200,000

($\chi^2 = 0.4684$). Bessah et al. (2021) demonstrated significant differences in how climate change is perceived and addressed by male and female farmers. For instance, male farmers were found to perceive themselves as more vulnerable to increased temperatures during the growing season. This aligns with the findings in the current study. These findings suggest that while there are slight differences in perception between males and females regarding various weather risks, the overall patterns are similar across both groups, and no significant gender-based differences were observed in the statistical analysis. Kumar et al. (2022) found that there is no significant difference in the knowledge and understanding of climate change between adult male and female respondents.

Table 4 outlines the perceptions of male and female nut farmers regarding the causes of climate change. The data reveals notable gender differences in the perceived drivers of climate change. Regarding environmental factors, 14% of male farmers and 8% of female farmers agreed that environmental factors contribute to climate change, with a statistically significant difference ($\chi^2 = 0.001938$), indicating that male farmers are more likely to perceive environmental factors as a primary cause. Denton highlights that gender can influence the understanding and attribution of climate change, with men often focusing more on environmental causes, while women may consider a broader range of factors (Denton, 2002). In contrast, supernatural factors were perceived by 15.33% of males and 20% of females, with females exhibiting a stronger belief in supernatural causes of climate change. Female farmers often expressed these views with statements such as Fatima, a smallholder nut farmer, who said, "Sometimes, the changes in weather feel like a punishment from unseen forces." Similarly, Rina shared, "Some say the gods are angry with the way we live now." Shahana added, "If the rain stops suddenly, it is because someone did not respect the sacred places nearby." These quotes illustrate how cultural and spiritual beliefs influence perceptions of climate variability among women farmers. For human activities, 10.66% of males and 5% of females attributed climate change to human actions, suggesting that males tend to emphasize human responsibility more than females. Both male and female farmers reported similar perceptions of political factors, with 6% of males and 6.33% of females agreeing, and no significant gender differences were observed. Lastly, 10.66% of males and 4% of females reported having no knowledge of climate change causes, with males more likely to express uncertainty.

Several studies have explored gender differences in the perception of environmental issues and climate change, which can help contextualize the finding that male farmers are more likely to perceive environmental factors as a primary cause of climate change. Agarwal (1992) discusses how men and women in rural and agricultural communities may prioritize different environmental factors due to their distinct roles in agricultural practices and land management. This supports the idea that male farmers, with greater involvement in direct environmental management, may be more attuned to environmental changes. Additionally, it was also suggest that perceptions of climate change and its environmental drivers are shaped by the roles individuals play in agriculture, which can vary by gender (Haque et al.,

TABLE 2 Perceived changes in rainfall timing and distribution among smallholder nut farmers (2014–2023).

Rainfall pattern	Perception	Male	Female	Total	χ^2 *p*-value
Increased rainfall	Agree	84 (28%)	65 (21.66%)	149 (49.66%)	0.8187
	Neutral	54 (18%)	44 (14.66%)	98 (32.66%)	
	Disagree	32 (10.66%)	21 (7%)	53 (17.66%)	
	Total	170 (56.67%)	130 (43.33%)	300 (100%)	
Decreased rainfall	Agree	35 (11.66%)	31 (10.33%)	66 (22%)	0.7058
	Disagree	78 (26%)	54 (18%)	132 (44%)	
	Neutral	57 (19%)	45 (15%)	102 (34%)	
	Total	170 (56.67%)	130 (43.33%)	300 (100%)	
Late onset of rains	Agree	48 (16%)	27 (9%)	75 (25%)	0.3323
	Disagree	72 (24%)	60 (20%)	132 (44%)	
	Neutral	50 (16.66%)	43 (14.33%)	93 (31%)	
	Total	170 (56.67%)	130 (43.33%)	300 (100%)	
Late end of rains	Agree	77 (25.66%)	63 (21%)	140 (46.66%)	0.4888
	Disagree	51 (17%)	31 (10.33%)	82 (27.33%)	
	Neutral	42 (14%)	36 (12%)	78 (26%)	
	Total	170 (56.67%)	130 (43.33%)	300 (100%)	
Early onset of rains	Agree	91 (30.33%)	70 (23.33%)	161 (53.66%)	0.00005
	Disagree	64 (21.33%)	27 (9%)	91 (30.33%)	
	Neutral	15 (5%)	33 (11%)	48 (16%)	
	Total	170 (56.67%)	130 (43.33%)	300 (100%)	
Early end of rains	Agree	39(%)	26 (8.66%)	65 (21.66%)	0.5111
	Disagree	71(%)	63 (21%)	134 (44.66%)	
	Neutral	60(%)	41 (13.66%)	101 (33.66%)	
	Total	170 (56.67%)	130 (43.33%)	300 (100%)	
Poor distribution of rainfall	Agree	97 (32.33%)	65 (21.66%)	162 (54%)	0.03339
	Disagree	52 (17.33%)	34 (11.33%)	86 (28.66%)	
	Neutral	21 (7%)	31 (10.33%)	52 (17.33%)	
	Total	170 (56.67%)	130 (43.33%)	300 (100%)	

2023). This notion is further supported by Maya Moore et al., who propose that gender influences the way farmers interpret and respond to climate change, with female farmers are significantly vulnerabilities to climate change (Moore and Niles, 2025). Furthermore, male farmers are more likely to attribute climate change to environmental factors, reflecting a deeper awareness of environmental degradation and its impact on agriculture (Food and Agriculture Organization of the United Nations, 2016; Sheikh et al., 2024). These findings suggest that male and female nut farmers have varying perceptions of the factors contributing to climate change, with significant differences observed in their views on environmental factors and supernatural factors, but no major gender-based differences in other categories.

3.3 Perceived impacts of climate change on nut farming

Table 5 presents the perceived impacts of climate change on nut farming, comparing the responses of male and female farmers. The data reveals that both male and female farmers perceive similar climate-related challenges, with only minor gender differences observed across various impacts.

Regarding changes in the timing of rain, 34.33% of male farmers and 23.66% of female farmers agreed that rainfall patterns have shifted, which is not significant indicates that there is no significant gender difference in this perception. Nnadi et al. (2019) found significant gender differences in the perception of rainfall variability in Anambra, Southeast Nigeria, with female farmers possibly perceiving rainfall changes differently than their male counterparts. Similarly, for increased plant diseases, 32.33% of males and 27% of females agreed which is insignificant. For increased pest infestations, 37% of male farmers and 26.33% of female farmers agreed that pests have become a bigger problem. One of the most important predictors of the magnitude of climate change effects may be the adaptive potential of plant and pathogen populations (Garrett et al., 2006). Gender perceptions regarding changes in the prevalence of pests can provide valuable insights that contribute to the sustainable development of smallholder irrigation farming systems. Understanding how different genders perceive pest-related challenges can help inform targeted strategies and policies that enhance resilience

TABLE 3 Perceptions of weather risks among smallholder nut farmers (2014–2023).

Weather risk	Perception	Male	Female	Total	χ^2 *p*-value
Increased temperature	Agree	89 (29.66%)	71 (23.66%)	160 (53.33%)	0.5525
	Disagree	40 (13.33%)	24 (8%)	64 (21.33%)	
	Neutral	41 (13.66%)	35 (11.66%)	76 (25.33%)	
	Total	170 (56.67%)	130 (43.33%)	300 (100%)	
Cold wave severity	Agree	91 (30.33%)	77 (25.66%)	168 (56%)	0.5526
	Disagree	45 (15%)	28 (9.33%)	73 (24.33%)	
	Neutral	34 (11.33%)	25 (8.33%)	59 (19.66%)	
	Total	170 (56.67%)	130 (43.33%)	300 (100%)	
Hot wave severity	Agree	101 (33.66%)	85 (28.33%)	186 (62%)	0.4644
	Disagree	35 (11.66%)	20 (6.66%)	55 (18.33%)	
	Neutral	34 (11.33%)	25 (8.33%)	59 (19.66%)	
	Total	170 (56.67%)	130 (43.33%)	300 (100%)	
Climate change intensity	Very Intense	55 (18.33%)	34 (11.33%)	89 (29.66%)	0.4684
	Intense	81 (27%)	70 (23.33%)	151 (50.33%)	
	No Change	34 (11.33%)	26 (8.66%)	60 (20%)	
	Total	170 (56.67%)	130 (43.33%)	300 (100%)	

TABLE 4 Smallholder nut farmers' perceptions of climate change causes (2014–2023).

Perception	Male	Female	Total	χ^2 *p*-value
Environmental factors	42 (14%)	24 (8%)	66 (22%)	0.0019
Supernatural factors	46 (15.33%)	60 (20%)	106 (35.33%)	
Human activities	32 (10.66%)	15 (5%)	47 (15.66%)	
Political factors	18 (6%)	19 (6.33%)	37 (12.33%)	
No knowledge	32 (10.66%)	12 (4%)	44 (14.66%)	
Total	170 (56.67%)	130 (43.33%)	300 (100%)	

and productivity within these agricultural systems (Mwadzingeni et al., 2022). The finding that 39% of male farmers and 27% of female farmers agreed on the increased requirement for fertilizers, which is consistent with study Islam et al. (2023) found that fertilizer use rates in women-headed households (WHHs) varied with crop type and cropping patterns, highlighting the gender-based differences in fertilizer application. This aligns with our result, where male farmers and female farmers agreed on the increased requirement for fertilizers. Regarding crop loss, 31% of male farmers and 26.33% of female farmers agreed that climate change has led to increased crop loss, accounting for a total of 57.33% of respondents. The chi-square test ($p = 0.3501$) indicates no statistically significant difference between male and female perceptions on this issue. In terms of the disturbance of the agricultural calendar, 43.66% of male farmers and 32.66% of female farmers agreed that climate change has disrupted their farming schedules. Finally, for decline of soil fertility, 33% of male farmers and 28.33% of female farmers agreed that soil fertility has declined. Balasha et al. observed that farmers consistently faced challenges related to declining soil fertility and crop loss (Balasha et al., 2023), which aligns with the impacts of climate change reported by farmers in our study. Overall, the findings suggest that male and female nut farmers share similar perceptions regarding the impacts of climate change on their farming practices, with no significant gender differences.

Moreover, the results indicated differences in the perceptions of agricultural changes between male and female participants (Figure 3). Both groups agreed on several issues, but males generally showed a higher level of agreement across most perceptions. For instance, a higher percentage of males (34.33%) agreed that the timing of rain has changed, compared to females (23.66%). Similarly, males reported greater concern about increased plant diseases (32.33% vs. 27%), pest infestations (37% vs. 26.33%), and the increased need for fertilizers (39% vs. 27%). Males also perceived greater crop loss (31% vs. 26.33%) and more disturbances in the agricultural calendar (43.66% vs. 32.66%). The decline in soil fertility was similarly perceived by more males (33%) than females (28.33%).

Overall, while both male and female participants shared similar concerns, males appeared to have a stronger perception of the agricultural challenges. The differences in agricultural perceptions between men and women are likely due to men's greater involvement in decision-making and large-scale farming, better access to climate information and extension services, education, and a stronger focus on economic impacts (Carnegie et al., 2020; Nchanji et al., 2025). Cultural norms and gender roles may also influence how concerns are expressed, with men more likely to report broader agricultural challenges (Holmelin, 2019; Mudege et al., 2017). These factors contribute to men's heightened perception of agricultural issues.

TABLE 5 Perceived impacts of climate change on nut farming (2014–2023): gender differences in farmers' perspectives.

Perceived impacts	Perception	Male	Female	Total	χ^2 *p*-value
Changes in the timing of rain	Agree	103 (34.33%)	71 (23.66%)	174 (58%)	0.3572
	Disagree	67 (22.33%)	59 (19.66%)	126 (42%)	
	Total	170 (56.66%)	130 (43.33%)	300 (100%)	
Increased plant diseases	Agree	97 (32.33%)	81 (27%)	178 (59.33%)	0.4246
	Disagree	73(%24.33)	49 (16.33%)	122 (40.66%)	
	Total	170 (56.66%)	130 (43.33%)	300 (100%)	
Increased pest infestations	Agree	111 (37%)	79 (26.33%)	190 (63.33%)	0.4933
	Disagree	59 (19.66%)	51 (17%)	110 (36.66%)	
	Total	170 (56.66%)	130 (43.33%)	300 (100%)	
Increased requirement of fertilizers	Agree	117 (39%)	81 (27%)	198 (66%)	0.2902
	Disagree	53 (17.66%)	49 (16.33%)	102 (34%)	
	Total	170 (56.66%)	130 (43.33%)	300 (100%)	
Crop Loss	Agree	93 (31%)	79 (26.33%)	172 (57.33%)	0.3501
	Disagree	77 (25.66%)	51 (17%)	128 (42.66%)	
	Total	170 (56.66%)	130 (43.33%)	300 (100%)	
Disturbance of agricultural calendar	Agree	131 (43.66%)	98 (32.66%)	229 (76.33%)	0.8407
	Disagree	39 (13%)	32 (10.66%)	71 (23.66%)	
	Total	170 (56.66%)	130 (43.33%)	300 (100%)	
Decline of soil fertility	Agree	99 (33%)	85 (28.33%)	184 (61.33%)	0.2541
	Disagree	71 (23.66%)	45 (15%)	116 (38.66%)	
	Total	170 (56.66%)	130 (43.33%)	300 (100%)	

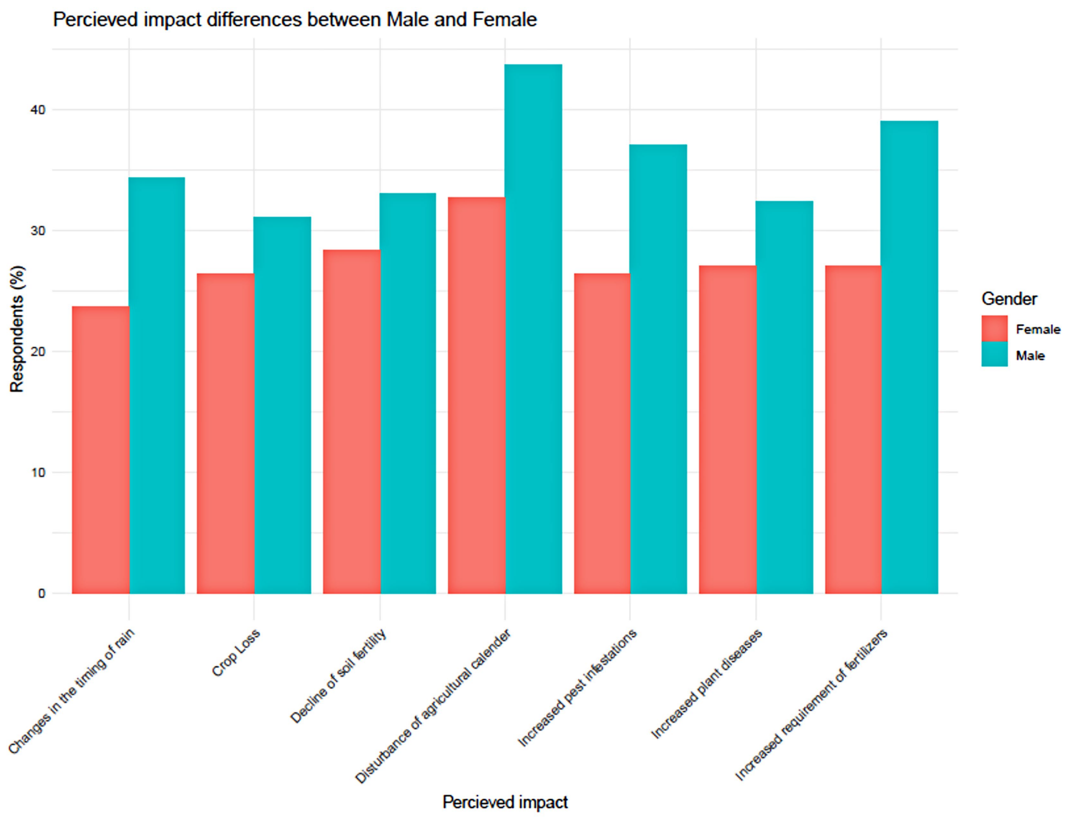

FIGURE 3
Gender-based comparison of perceived impacts on agricultural changes and challenges.

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3.4 Adaptive capacity of strategies taken by farmers

In response to the challenges posed by changing climate patterns and environmental variability, farmers have adapted a range of strategies to sustain their livelihoods and improve resilience. The results of the Pearson's Chi-squared tests on adaptive capacity of strategies showed a significant gender-based difference in only one response (Figure 4). Males (118 "Yes" responses) were more likely than females (75 "Yes" responses) to report changing planting and harvesting dates ($p < 0.05$). In contrast, no significant gender differences were observed for the other strategies.

To assess potential gender differences in response to climate change, the adoption of various strategies by farmers was analyzed. These strategies, which include changing agricultural practices, diversifying income sources, and utilizing climate-related information, reflect farmers' efforts to cope with the challenges posed by climate change (Figure 4). For changing planting and harvesting dates, Males (118 "Yes" responses) were more likely than females (75 "Yes" responses) to report changing their planting and harvesting dates (Figure 4), with a statistically significant difference observed ($p < 0.0479$). In contrast, for strategies such as shifting to other crops, Males (114 "Yes" responses) and females (80 "Yes" responses) showed no significant difference ($p > 0.05$) (Figure 4). Similarly, shifting to agroforestry and horticultural crops had nearly equal responses from males (76 "Yes") and females (58 "Yes"), with no significant gender difference ($p > 0.05$) (Figure 4). The adoption of off-farm income was also similar between males (96 "Yes") and females (80 "Yes"), with no significant difference ($p > 0.05$) (Figure 4). The responses for migration to urban areas (Males: 81 "Yes," Females: 67 "Yes") and the use of weather forecasts (Males: 114 "Yes," Females: 93 "Yes") did not reveal significant gender differences either ($p > 0.05$) (Figure 4). Finally, for shifting to other crop varieties, Males (94 "Yes") and females (80 "Yes") again exhibited no significant difference in adoption ($p > 0.05$) (Figure 4). Overall, the results indicate that while there is a significant gender difference in the adoption of changing planting and harvesting dates, other strategy were equally adopted by both male and female farmers. The gender difference in responses could reflect social and cultural factors, where men might be more active in making visible, larger-scale changes on the farm. However, the overall similarity in other responses suggests shared experiences and challenges across both genders. Several studies have explored the influence of gender on agricultural adaptive capacity, supporting the findings observed in our study. Doss and Morris explore how gender affects the adoption of agricultural innovations, highlighting that the adoption choices of men and women may vary based on their responsibilities in farming and decision-making power (Doss and Morris, 2000). Agarwal argues that while both men and women face similar environmental challenges, their strategies for adapting to climate change differ due to socio-cultural factors, resource access, and decision-making power (Agarwal, 2010). The FAO report also highlights how gender roles in agriculture influence the adoption of climate change with specific practices more commonly reported by one gender, such as altering planting schedules (FAO, 2011). Bryan et al. demonstrate in their study of Ethiopian and South African farmers that gender differences play a crucial role in adaptation

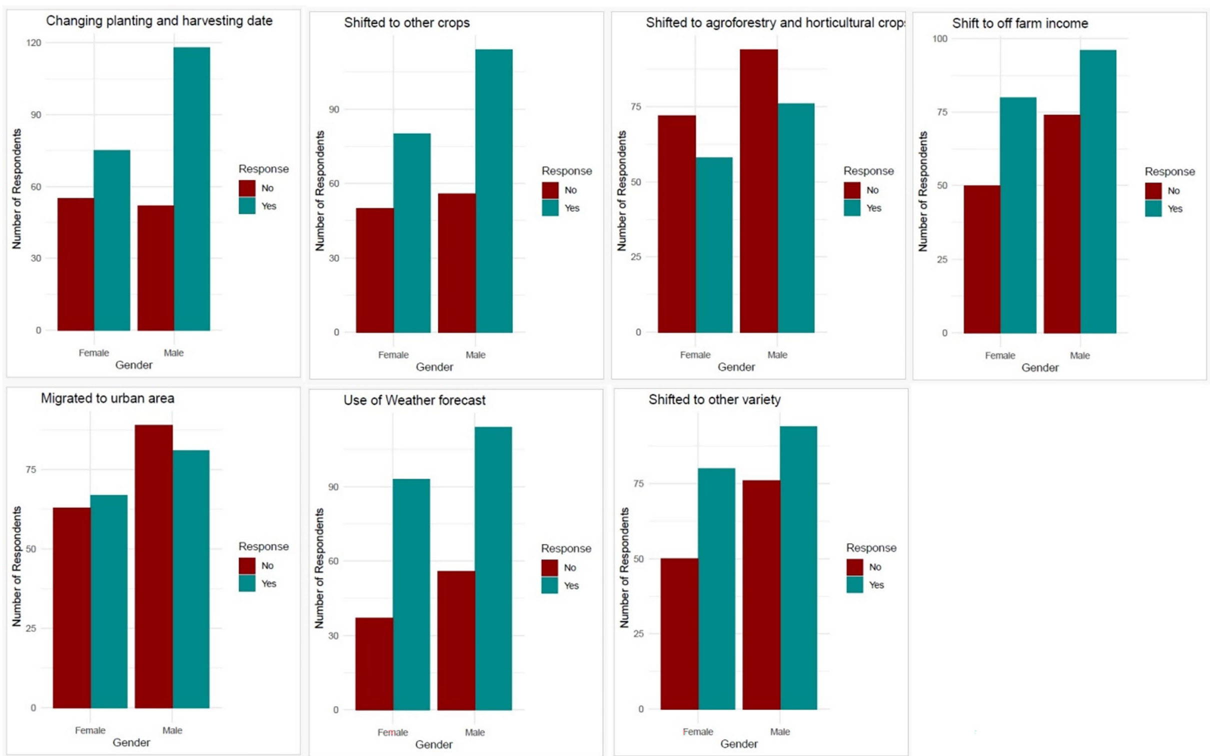

FIGURE 4
Gender-based comparison of adaptive capacity of strategies in response to agricultural changes.

decisions, shaped by access to resources, information, and control over farming activities (Bryan et al., 2009). These studies collectively provide a comprehensive context for understanding the gender-based variations in adaptive capacity, suggesting that while some practices, such as shifting planting and harvesting dates, may show gender differences, other strategies are more universally adopted across genders.

3.5 Factors influencing adaptive capacity of strategies

To explore the relationship between socio-economic characteristics and the adoption of various strategies, we applied a multivariate probit model. The probit model used in this study is suitable for analyzing binary decision outcomes, such as whether or not farmers adopt specific adaptation strategies. Given its flexibility and robustness, the model can be transferred to similar rural contexts in developing countries where smallholder farmers operate under comparable socio-economic and agro-ecological conditions (Aidoo et al., 2021; Mankhin et al., 2024). The model's structure allows for integration of localized variables, making it a useful analytical tool for exploring climate adaptation behavior among diverse farming communities facing climate-induced risks. This model aims to identify how factors such as sex, age, household size, access to credit, access to input subsidy, training received, contact with extension agents, farm size, access to climate information, years of education, and years of farming experience influence farmers' decisions to adopt strategies for coping with climate change. Model fit was assessed using the log-likelihood of the Multinomial Probit Regression model. The log-likelihood value was −1245.649, based on 105 degrees of freedom. Given the similar adoption strategies, the decision was made to combine male and female farmers for analyzing the factors influencing the adaptive capacity. The Probit regression model indicates a positive association between age and the probability of transitioning to off-farm income (0.015) (Table 6). This suggests that older farmers are more inclined to engage in off-farm income-generating activities. With increasing of age, farmers may experience a need for additional financial resources or seek to supplement farm income due to reduced physical capacity for farming or lower agricultural productivity. Moreover, older farmers tend to possess more extensive networks, skills, and life experience, which can facilitate their participation in non-agricultural employment or entrepreneurial ventures. Barrett et al. (2001) also find that in rural Africa, older farmers engage more in non-farm income-generating activities, often due to a decline in physical capacity and the desire for additional financial security.

Access to input subsidies significantly influences farmers' decisions to adapt their agricultural practices, particularly in relation to changing planting and harvesting dates (0.336) and negative effect on adoption of agroforestry and horticultural practices (−0.50). Farmers with access to input subsidies are more likely to adjust their schedules, as the financial support provided subsidies which enables

TABLE 6 Estimating parameters of a multinomial probit regression model to identify factors influencing farmers' adaptive capacity.

Variable	Adaptation strategies						
	Changing planting and harvesting date	Shifted to other crops	Shifted to agroforestry and horticultural crops	Shift to off farm income	Migrated to urban area	Use of Weather forecast	Shifted to other variety
Sex	−0.5415031	−0.0673493	0.093053	0.1234912	0.101595	0.2297441	−0.2181531
Age	−0.3201869	−0.0673493	−0.0057562	0.0151345*	0.0123233	−0.0074983	0.0002629
Household size	−0.0011873	0.0028426	−0.0247481	−0.0138465	0.0123233	−0.0401145	−0.0225677
Access to credit	0.0242314	−0.0838633	0.146709	−0.1670546	0.1572792	0.1021655	−0.1083665
Access to input subsidy	0.3368118*	−0.1278691	−0.5059917**	−0.0175173	−0.1276659	0.0180899	0.016075
Training	0.1363499	−0.2453737	−0.1404106	0.3002538	0.3600111*	0.0534315	0.10853
Contact with extension agents	0.0747852	0.0321234	0.0457678	−0.0462052	0.0717314	−0.0945384	−0.1616592
Farm size hector	−0.0152231	0.3009449	−0.0080561	−0.1080686	−0.5037405	0.1214363	−0.2546553
Access to climate information	0.2501471	0.1080739	−0.0796313	0.0132957	0.3583575*	0.1693507	0.1088093
Years of education	0.0639968*	0.0740778**	0.0682314**	0.0585332**	0.0879987***	0.0350286	0.0051894
Years of farming	0.0420025****	0.0446608****	0.0526515****	−0.0126256	0.0545526****	0.0474866****	0.009861
Constant	−0.5415031	−0.395053	−0.874348	−0.6082407	−2.2397511****	−0.4133739	0.4396178

Multinomial probit regression model; Wald test, log-likelihood: −1245.649 on 105 Df; *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$, ****$p < 0.001$.

them to invest in essential inputs such as seeds and fertilizers. This financial assistance allows farmers to better respond to seasonal variability and climate fluctuations by ensuring timely and effective adjustments in planting and harvesting and encourage the continuation of farming activities rather than diversifying into alternative agricultural practices. Input subsidies for seeds and fertilizers supported the adoption of improved agricultural practices, including changes in planting schedules to cope with climate variability in Ethiopia (Belay et al., 2022).

Training and access to climate information both play a significant role in influencing farmers' adaptive capacity, particularly in relation to migration (0.36) indicating that farmers who receive training and have access to climate information are more likely to migrate in urban areas. Training equips farmers with the tools necessary to adapt to environmental and economic challenges, making migration an attractive and viable option. Agricultural training exposes farmers to modern techniques and climate-smart practices, which may not be fully applicable in rural settings. In essence, training not only enhances farmers' skill sets but also encourages them to seek migration to cities, where they can apply their knowledge in more diverse and lucrative ways. Consequently, farmers with access to reliable climate data may be drawn to urban areas where better infrastructure, higher income opportunities, and alternative agricultural-related jobs are available. By gaining a better understanding of climate patterns, farmers may recognize the limitations of rural farming and the potential for improved economic stability in urban areas. Research by Gray and Mueller (2012) suggests that farmers who have access to climate data are more likely to migrate, as it helps them assess agricultural risks, such as droughts or extreme weather, and realize the limited economic opportunities in rural areas. Similarly, it was suggested that when farmers are trained in new agricultural techniques or exposed to alternative livelihood strategies, they are more likely to migrate (Migration, Agriculture and Rural Development, 2025; FAO, 2018).

In addition, Education plays a crucial role in shaping farmers' responses to changing agricultural conditions, as demonstrated by the Probit regression model, which reveals that years of education positively influence adaptive capacity of all five strategies. Educated farmers are more likely to adjust their planting and harvesting dates (0.063) as they have a better understanding of climate patterns and seasonal variations (Table 6). Educated farmers possess the knowledge and skills necessary to interpret climate information and apply it to their agricultural decisions (Deressa et al., 2009). In addition, they shifted to other crops and agroforestry and horticultural practices (0.07), as educated farmers are more likely to switch to alternative crops as a risk management strategy and are more aware of sustainable land management techniques (FAO Knowledge Repository, 2015). Educated farmers also migrated to urban areas (0.08), and engage in off-farm income activities (0.06), as education provides the skills and qualifications for non-farm job opportunities in urban areas. Education shapes migration patterns by enhancing individuals' ability to take advantage of better-paying non-farm economic opportunities such as salaried jobs, small businesses, or trade in cities (Aydemir et al., 2022; Boccanfuso et al., 2015; Sen et al., 2021). Overall, education empowers farmers to make informed decisions, adopt innovative practices, diversify their income sources, and better adapt to environmental and economic challenges, highlighting its critical role in enhancing resilience to climate change and promoting sustainable farming practices.

The Probit regression model reveals significant relationships between years of farming experience and various strategy's adaptive capacity employed by farmers. Firstly, years of farming experience positively influence farmers' decisions to change their planting and harvesting dates and they shifted to other crops (0.04) as well as agroforestry and horticultural practices (0.05) (Table 6). Experienced farmers are more adept at recognizing climate variations and adjusting their schedules accordingly, ensuring better adaptation to seasonal changes. They are more likely to adjust planting and harvesting schedules to ensure better synchronization with seasonal changes, as they are familiar with local climate patterns and more proactive in adopting strategies and select more resilient and diversification crops with changing weather conditions (Fosu-Mensah et al., 2012; Cano and Castro Campos, 2024; Yeleliere et al., 2023; Berhanu et al., 2024). Experienced farmers, through their knowledge of ecosystem dynamics, are better equipped to integrate trees into their farming systems and adopt horticultural practices that enhance resilience to climate change (Jovanelly et al., 2025). Lastly, we found years of farming experience significantly influence both the migration to urban areas and the use of weather forecasts with coefficient of (0.05). Their accumulated knowledge of farming also by utilizing weather forecasts allowing them to seek alternative opportunities in cities where they can secure stable income sources for improving their quality of (Bangladesh Bureau of Statistics (BBS), 2024; Wang and Cai, 2009).

3.6 Predicted probabilities for adaptive capacity of strategies

The predicted probabilities for adaption capacity of each strategy in this dataset highlight varying degrees of response to environmental, economic, and socio-demographic factors. The higher probabilities (Figure 5) for changing planting and harvesting dates (63.76%), shifting to other crops (64.50%), and using weather forecasts (68.85%) suggest that these are the most commonly adopted strategies, likely driven by immediate needs for climate adaptation and resource optimization in agriculture. These behaviors indicate a high level of awareness and responsiveness to climatic variability, with farmers increasingly using weather information to inform their decisions, adjusting planting schedules and crop choices to optimize yields. On the other hand, strategies such as shifting to agroforestry and horticultural crops (44.41%) and migrating to urban areas (48.88%) show less widespread adoption but remain significant. These behaviors reflect a growing trend towards diversification in land use and livelihoods, influenced by factors like changing land availability, government incentives for agroforestry, or the economic pull of urban centers. The shift to off-farm income (58.53%) further illustrates a crucial adaptation strategy, particularly in rural areas, where individuals are increasingly seeking financial stability outside agriculture due to economic challenges or limited access to resources. The relatively balanced probability for shifting to other crop varieties (51.34%) highlights a middle-ground adaptation strategy, where a large portion of individuals are experimenting with new varieties to

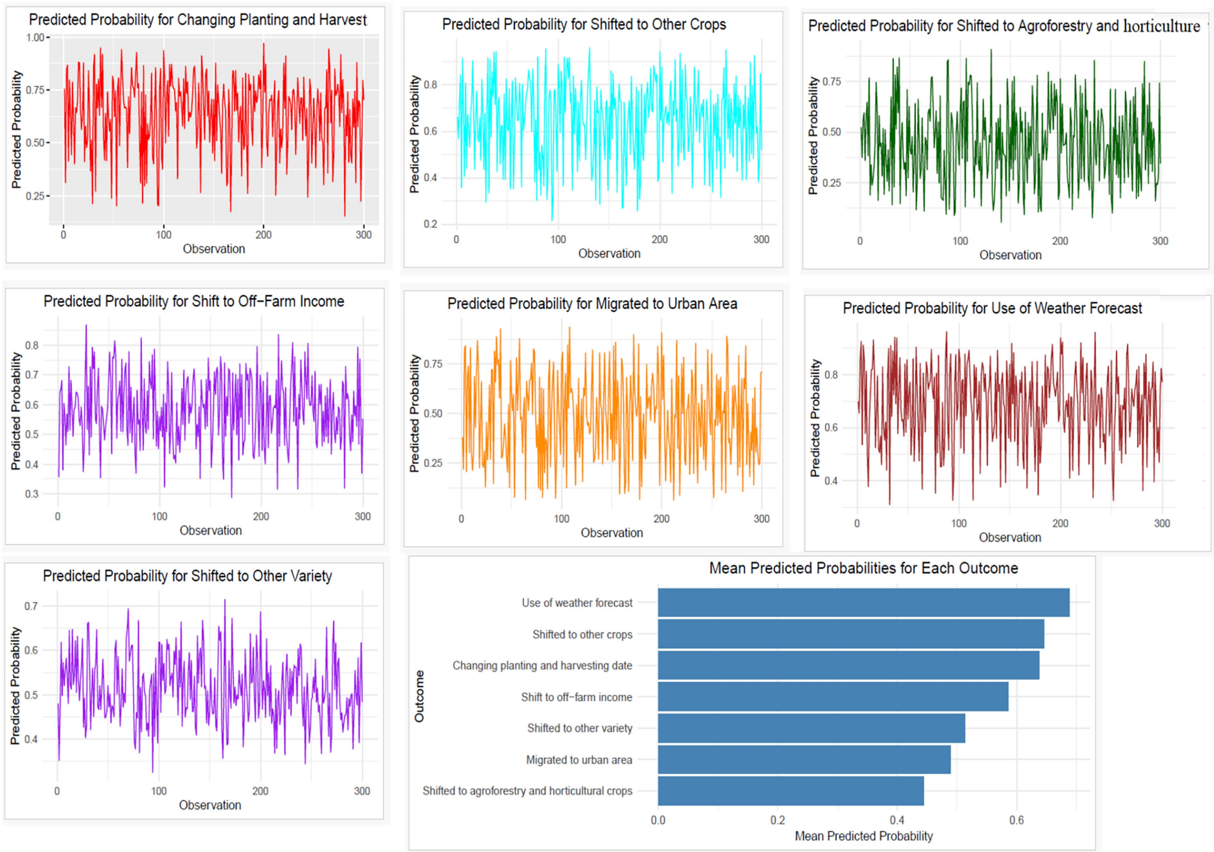

FIGURE 5
Predicted probabilities of different strategy's adaption capacity and mean predicted probabilities of different strategies.

respond to evolving climate conditions or market demand. Recent studies highlight the diverse adaptive capacity employed by smallholder farmers in response to climate change, for instance altering planting dates and crop varieties (Tessema et al., 2019), switching to off-farm income (Fonjong et al., 2024) and migration (Quarshie et al., 2023) particularly in regions vulnerable to environmental stressors. These findings emphasize that adaptation to climate change and other external pressures is multifaceted, with individuals employing a mix of short-term and long-term strategies depending on their immediate circumstances, economic motivations, and available resources. This variability underscores the need for targeted interventions that address the diverse challenges faced by different segments of the population.

3.7 The relationship between education, experience and adaption strategies

Since education and experience are key to adaptation, the correlation between these factors and the likelihood of adopting strategies is significant, suggesting that more education and experience improve farmers' ability to adapt to climate change. The correlation between the predicted probability of various stratagy's adaption capacity and education reveals important insights into how education influences farmers' decisions (Figure 6A). For example, higher levels of education are positively correlated with an increased likelihood of farmers adopting strategies such as changing planting and harvesting dates, shifting to other crops, engaging in agroforestry, seeking off-farm income, or migrating to urban areas. The correlation coefficient indicates a moderate positive relationship ($R > 0.50$, $p < 0.0001$) between education and the predicted probabilities of these strategies (Figure 6A). Education has been shown to play a crucial role in enhancing farmers' adaptive capacity to climate change. Studies have demonstrated that higher education levels are positively correlated with the adoption of a variety of strategies. For instance, farmers with higher education levels were more likely to adopt innovative agricultural practices such as changing planting schedules, experimenting with new crop varieties (Hu et al., 2024) and engage in practices like agroforestry. This suggests that education equips farmers with the knowledge and decision-making skills necessary to respond to climate change challenges and economic pressures, thus enhancing their adaptive capacity.

The positive correlation (Figure 6B) between farming experience and the predicted probabilities of changing planting and harvesting dates, shifting to other crops, shifting to agroforestry and horticultural crops, migrating to urban areas, and using weather forecasts suggests that as farmers gain more experience, they are more likely to adopt these adaptive strategies. The correlation coefficient between 0.70 and

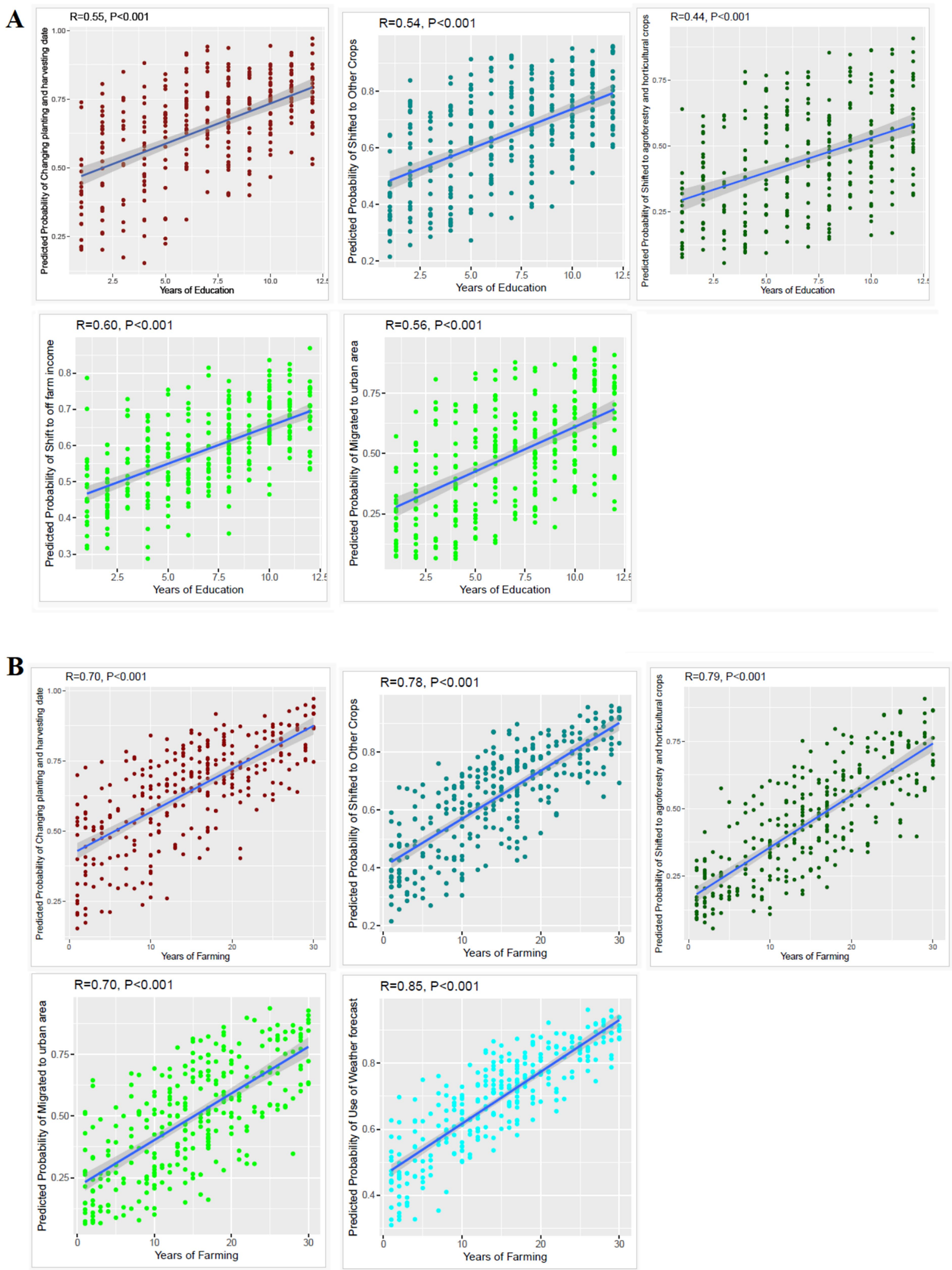

FIGURE 6
Correlation of predicted probability with education **(A)** and farming experience **(B)**.

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0.85 indicates a strong to very strong positive relationship (Figure 6B), meaning that the more years of farming experience a farmer has, the more likely they are to engage in behaviors that reflect adaptation to climate variability or changing agricultural conditions. Studies have consistently shown that farming experience enhances the ability to make informed decisions regarding the timing of planting, crop diversification (Yahaya et al., 2023) and adopting of agroforestry. Furthermore, Adger et al. (2005) emphasized that farmers with longer agricultural careers often possess greater adaptive capacity because they can more easily incorporate climate information into their decision-making processes. In summary, farming experience appears to play a crucial role in shaping adaptive behaviors, with more experienced farmers demonstrating a higher likelihood of adopting strategies that reflect both practical knowledge and the need for resilience in the face of changing conditions.

The correlation analysis reveals strong positive associations between farming experience, education, and the predicted probabilities of adopting strategies. These results align closely with the Probit regression model, which identifies both variables as significant predictors of adaptive behavior. The consistency between the correlation findings and model outputs affirms the model's validity and suggests it effectively captures real-world decision-making patterns. Specifically, the results indicate that more experienced and better-educated farmers are significantly more likely to adopt strategies. This reinforces the critical influence of farming experience and education on adaptive capacity. The strong correlations further confirm that the model's predicted probabilities reflect actual trends in the data, enhancing confidence in its predictive reliability and utility for forecasting agricultural adaptation behavior.

4 Concluding remarks

This study underscores the distinct climate related challenges confronting smallholder nut farmers on Hatiya Island, Bangladesh, where rising sea levels, salinity intrusion, and erratic weather patterns continue to undermine agricultural productivity. While both male and female farmers share comparable perceptions of climate risks, notable gender differences emerge in the attribution of causes and the adaptive capacity of strategies. Key factors education, farming experience, and access to subsidies play a significant role in enabling farmers to adopt measures like adjusting planting schedules, diversifying crops, and utilizing weather forecasts.

To enhance resilience, policy interventions must prioritize gender-sensitive approaches, expand access to climate information, and promote sustainable subsidy mechanisms. Investments in education, digital tools, and rural infrastructure are also essential. Additionally, supporting off-farm income and addressing rural-to-urban migration can contribute to long-term livelihood stability.

Despite observed progress, barriers such as limited resource access and inadequate extension services remain. These findings point to the need for targeted, evidence-based interventions and further research to evaluate the long-term effectiveness of adaptation strategies. Strengthening the adaptive capacity of island-based nut farmers through inclusive, collaborative, and sustainable approaches is critical to ensuring agricultural sustainability and protecting rural livelihoods in the face of escalating climate threats.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

RB: Funding acquisition, Software, Formal analysis, Conceptualization, Writing – review & editing, Supervision, Methodology, Writing – original draft, Investigation, Visualization, Data curation. AA: Writing – review & editing, Supervision, Formal analysis, Project administration, Writing – original draft, Methodology, Resources, Investigation, Data curation, Visualization, Validation. DE: Data curation, Methodology, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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