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RESEARCH

The role of farm production diversity in enhancing dietary diversity and food security in Southern Bangladesh

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Abstract

Farm production diversification is widely recognized as a promising pathway to enhance household dietary diversity and food security, though its effectiveness varies across ecological and socioeconomic contexts. This study investigates the relationship between farm production diversity and household dietary diversity and food security in five climate-vulnerable districts of southern Bangladesh. Data were collected from 768 households between April and June 2023 using structured surveys stratified by salinity zones. Dietary diversity was measured through household dietary diversity scores and food variety scores, while food insecurity was assessed using the Household Food Insecurity Access Scale. Farm production diversity was quantified by the number of food groups produced, the Shannon diversity index, and food crop diversity. Poisson and ordered probit regression models were applied to estimate associations, controlling for market access, off-farm household income, household demographics, and environmental factors. The results reveal that greater production diversity is modestly but significantly associated with improved dietary diversity and reduced food insecurity, particularly in low and medium salinity zones. In high salinity areas, these associations were weaker or statistically insignificant, likely reflecting environmental constraints limiting production options. Market access, off-farm household income, education, and household size also played significant roles. These findings underscore the need for context-specific strategies that integrate production diversification with climate-resilient technologies, livelihood diversification, and improved market access to strengthen food security in climate-vulnerable rural communities.

Keywords Farm production diversity · Household dietary diversity · Food security · Salinity · Bangladesh

1 Introduction

Food security and dietary diversity remain critical challenges in Bangladesh, where a large share of the rural population depends on smallholder agriculture for both food and income (Ali et al., 2019; Roy et al., 2022). Despite notable improvements in agricultural productivity, malnutrition persists, particularly among women and children, with high prevalence of undernutrition and micronutrient deficiencies (Ahmed et al., 2016; Hasan et al., 2017; Alam et al., 2023a, b). The dominance of rice cultivation has contributed to caloric adequacy but has also resulted in dietary imbalances, with limited intake of essential nutrients found in vegetables, pulses, fish, and animal-source foods (Rahman & Islam, 2014; Pingali & Sunder, 2017; Ruel et al., 2018). Consequently, Bangladesh continues to face multiple forms of malnutrition among vulnerable groups. Among children under five, 24% are stunted, 11% are wasted, and 22% are underweight, while 31% suffer from vitamin A deficiency (NIPPORT & ICF, 2024). Among women of reproductive age, 36.7% are anemic, 9% are underweight, and 38% are overweight or obese (NIPPORT & ICF, 2024), reflecting a rising burden of both undernutrition and overnutrition. This double burden persists even as Bangladesh moves toward self-sufficiency in staple grain production (Ahmed et al., 2012; Bishwajit et al., 2013; Rahman et al., 2017, 2021; Mahfuz et al., 2019).

One key driver of this nutritional shortfall is the limited diversification of agricultural production (FAO, 2013a, b; Headey & Hoddinott, 2017). Agricultural diversification, a central element of structural transformation in rural

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economies, involves a shift from subsistence-based farming to more market-oriented systems that include a wider range of nutrient-dense crops, livestock, and aquatic foods (Rosegrant & Hazell, 1999; Saikia & Gogoi, 2017). Such transitions are often enabled by technological advancements, improved rural infrastructure, and evolving consumer preferences. Diversified farming systems can enhance household income, increase food availability, and strengthen resilience against climatic and market-related shocks (Powell et al., 2015; Herforth & Ahmed, 2015). These systems also improve nutrition by expanding the variety of foods available for household consumption and by generating income that can be used to purchase diverse foods and essential services such as education and healthcare (Gillespie et al., 2012).

Farm production diversity has attracted growing interest for its potential to enhance dietary diversity and food security (Jones et al., 2014; Sibhatu et al., 2015; Islam et al., 2018). Empirical studies suggest that households cultivating a broader mix of crops, livestock, and aquatic species are more likely to consume diverse food and experience better nutrition outcomes (Sekaran et al., 2021; Atapattu et al., 2024). In Bangladesh, integrated farming systems that combine fish, livestock, and crop production have demonstrated positive effects on food security and climate resilience (Ahmed & Garnett, 2011; Hasan et al., 2018; Akber et al., 2021; Lam et al., 2022; Rahman et al., 2024). For example, small indigenous fish species such as mola (*Amblypharyngodon mola*), punti (*Puntius spp.*) and tengra (*Mystus tengara*), which are rich in micronutrients, have been found to address nutritional deficiencies effectively when incorporated into homestead aquaculture systems (Ignowski et al., 2023). Similarly, homestead vegetable gardens integrated with small-scale poultry or dairy farming have shown promising impacts on dietary diversity and maternal and child nutrition (Galhena et al., 2013).

However, the relationship between production diversity and dietary diversity is not always direct or consistent. Factors such as market access, household preferences, and household income can strongly influence the extent to which diversified production translates into improved diets (Haggblade et al., 2007; Jones et al., 2014). While some households benefit from consuming a diverse mix of self-produced foods, others rely on farm income to purchase varied diets from markets. This dual pathway complicates the link between production diversity, dietary diversity, and food security. Excessive diversification may also reduce household income by limiting the gains from specialization (Chege et al., 2015). In many contexts, off-farm household income plays an important role in shaping household food access, adding further complexity (Haggblade et al., 2007). Where markets are the main source of food, nutrition outcomes depend heavily on market functionality and intra-household dynamics, including control over income from both farm and off-farm sources (von Braun & Kennedy, 1994; Fischer & Qaim, 2012). Effective food access through markets is influenced by infrastructure, value chain efficiency, and household decision-making structures. Additionally, trade-offs between specialization and diversification may arise. Beyond a certain threshold, further diversification can reduce farm efficiency and limit nutritional gains (Sibhatu et al., 2015). Gender roles, access to productive resources, and decision-making power within households are also critical determinants of how production diversity affects dietary and food security outcomes (Sraboni et al., 2014). As a result, the relationship between production and consumption diversity is highly context-specific.

In the climate-vulnerable southern areas of Bangladesh, smallholder farmers face significant environmental constraints that limit opportunities for agricultural diversification (Toufique & Islam, 2014; Alam et al., 2017; Kabir et al., 2017; Sarker et al., 2020). These regions are increasingly affected by climate-induced stressors such as floods, cyclones, and salinity intrusion, which degrade soil and water quality, reduce crop options, and heighten the risks associated with monoculture practices (Gopalakrishnan et al., 2019). In high-salinity zones, many farmers have adopted saline-tolerant aquaculture systems, focusing primarily on shrimp and finfish species like tilapia and mullet (Rahman et al., 2013; Islam et al., 2014). These systems are often export-oriented and less diversified, which can reduce the cultivation of rice, vegetables, and livestock, potentially limiting household access to diverse and nutritious foods. Conversely, low-salinity areas support more integrated and diversified farming practices, including rice and vegetable cultivation, livestock rearing, and freshwater aquaculture (Akber et al., 2021). Such practices tend to enhance food self-sufficiency, dietary diversity, and resilience to environmental shocks (de Roos et al., 2019). Environmental variability across the salinity gradient also influences market access and reliance on off-farm household income. High salinity areas are often more remote or have limited infrastructure, which can reduce farmers' ability to participate in markets and access diverse foods (Hossen et al., 2022; Alam et al., 2025). In contrast, low salinity areas generally have better connectivity, facilitating market participation and supporting both income generation and dietary diversity (Dasgupta et al., 2015). This highlights the need for adaptive, context-specific strategies to promote food and nutritional security. Sustainable aquaculture practices, such as the use of native fish species and integrated rice-fish systems, have also shown promise for improving both environmental sustainability and nutritional outcomes (Ahmed & Garnett, 2011; Freed et al., 2020; Ignowski et al., 2023).

Despite growing recognition of the value of diversified farming systems, limited attention has been given to how environmental factors, particularly salinity, shape the relationship between farm production diversity, dietary diversity, and food security in Bangladesh. Although a substantial body of literature addresses shrimp aquaculture, salinity, and food security in southernl regions (Islam et al., 2014; Jahan et al., 2015; Belton, 2016; Lam et al., 2022; Akber et al., 2021; Bernzen et al., 2022), few studies explicitly examine how these relationships vary across different agroecological contexts. This represents a critical knowledge gap, especially as climate change is projected to intensify salinity intrusion in coastal regions, with far-reaching consequences for agriculture and nutrition (Dasgupta et al., 2015; Sultan et al., 2023).

This study aims to address this gap by examining the impact of farm production diversity on household dietary diversity and food security in southern Bangladesh. Drawing on data from 768 smallholder households across low-, moderate-, and high-salinity zones, the analysis explores how environmental variation influences production choices, access to diverse foods, and nutrition outcomes. It also assesses how locally adapted farming strategies contribute to food security in climate-exposed settings. By incorporating environmental heterogeneity into the analysis, this research provides a more nuanced and context-specific understanding of the pathways through which farm production diversity supports improved household dietary diversity and food security in areas increasingly affected by climate change.

2 Materials and methods

2.1 Study area

This study was conducted in five climate-vulnerable districts of southern Bangladesh: Khulna, Bagerhat, Jashore, Satkhira, and Barguna. These districts span a distinct salinity gradient that significantly shapes local agricultural systems, food access, and livelihood strategies.

2.2 Sampling frame and data collection

To capture the agroecological and livelihood diversity across salinity zones, a multistage cluster sampling approach was employed. The sampling frame was stratified by salinity zone: low (LSZ), medium (MSZ), and high (HSZ), reflecting the key environmental gradient that influences agricultural practices in the study region. The five study districts were purposively selected due to their exposure to climate stressors and the prevalence of smallholder farming systems. Within each salinity zone, villages served as primary sampling units (PSUs). A household listing was conducted in each selected village to establish a comprehensive sampling frame, from which households were randomly selected using proportional allocation: 167 from LSZ, 311 from MSZ, and 290 from HSZ. This yielded a total sample of 768 households.

The sample size was determined using the standard formula for estimating proportions, adjusted for design effect in multistage cluster sampling (Alimohamadi & Sepandi, 2019):

$$n = 2 \times \frac{\mathrm{Z2.p.q}}{d2}$$

where $p=0.5$ (assumed proportion for maximum variability), $q=1 - p$, $Z=1.964$ (standard normal deviate at 95% confidence level), $d=0.05$ (margin of error), and the factor 2 accounts for the design effect due to the multistage sampling. This approach ensures an adequate sample size to capture variation in household characteristics such as dietary diversity, production diversity, and food security.

Data were collected between April and June 2023 using a structured household questionnaire. The instrument was developed in English, pilot-tested for clarity and contextual relevance, translated into Bengali, and digitized using the KoBo Toolbox platform to ensure efficient mobile-based data collection. Enumerators received seven days of intensive training, covering ethical protocols, interview techniques, and digital survey administration, including mock interviews and pretesting in non-sample areas. Data were collected through face-to-face interviews using tablets, which enabled real-time validation, skip logic, geotagging, and minimized data loss or entry errors. Supervisors conducted daily checks and field verifications to maintain quality control and data integrity throughout the survey period.

2.3 Measurement of key variables

2.3.1 Dietary diversity

Dietary diversity is the primary outcome variable in this study. We used two measures of dietary diversity: the household dietary diversity score (HDDS) and food variety score (FVS) (Swindale & Bilinsky, 2006; FAO, 2013a, b). The dietary diversity score is a widely used indicator that counts the number of food groups consumed over a specified recall period, typically 7 days or 24 h (Keding et al., 2012; Sibhatu et al., 2015). Most existing literature has employed HDDS based on a 7-day food consumption recall to examine the relationship between farm diversity and dietary diversity (Jones et al., 2014; Sibhatu et al., 2015). HDDS was measured by counting the number of food groups consumed by the household over the preceding seven days, using a standard 12-group classification. These food groups include: Cereals; White tubers and roots; Legumes, nuts, and seeds; Vegetables; Fruits; Fish and other seafood; Meat; Eggs; Milk and dairy products; Oils and fats; Sweets; and Spices, condiments, and beverages (FAO, 2013a, b; Sibhatu et al., 2015; Islam et al., 2018; Khandoker et al., 2022). A household earns one point for each food group consumed by any member within the household during the recall period, yielding an HDDS range of 0 to 12. This includes foods produced at home or purchased outside but consumed within the household, and excludes foods consumed outside the household. However, research has shown that the last three food groups contribute minimally to the micronutrient density of the diet, leading some studies to calculate dietary diversity scores based solely on the nine more nutritionally significant food groups, often referred to as the "healthy" food groups (Sibhatu et al., 2015; Islam et al., 2018). In our sensitivity analysis, we also computed dietary diversity scores using only these nine food groups. The second measure of dietary diversity, food variety score (FVS), counts the number of distinct food items consumed during the recall period. This measure is particularly useful when dietary data include highly disaggregated food groups (Sibhatu et al., 2015). To further test the robustness of our results, we also used FVS as an alternative dietary diversity indicator, counting the number of distinct food items consumed by the household in the seven days prior to the survey.

2.3.2 Food security

Food security is another key outcome variable in this study. We assessed food security using the household food insecurity access scale (HFIAS), a widely recognized tool developed by USAID's Food and Nutrition Technical Assistance (FANTA) project (Coates et al., 2007). The HFIAS evaluates food access at the household level by capturing experiences of food insecurity over the preceding four weeks. Households were categorized into four levels of food insecurity: food secure, mildly food insecure, moderately food insecure, and severely food insecure, following the classification guidelines of Swindale and Bilinsky (2006). The assessment involved a standardized set of nine food insecurity-related questions, which capture household concerns regarding food availability, dietary compromises, and coping strategies. Responses to these questions were classified into three frequency categories: Rarely, Sometimes, and Often. The HFIAS was constructed by summing responses to these nine questions, generating a continuous score ranging from 0 to 27, where higher scores indicate greater food insecurity. Based on the score, households were categorized into one of the four food insecurity levels. This methodology has been extensively validated in diverse settings, particularly in low-income and agrarian communities, making it a robust tool for assessing the impact of farm production diversification on household food security (Jones et al., 2014).

2.3.3 Production diversity

The main explanatory variable in our analysis is farm production diversity (FPD), which measures farm diversification by counting the number of crops, fish, and livestock species produced by the household over the past 12 months (Sibhatu et al., 2015). This is a simple, unweighted count measure that has been used in several recent studies (Jones et al., 2014; Powell et al., 2015; Sibhatu et al., 2015; Islam et al., 2018; Khandoker et al., 2022). FPD classifies farm-produced species into 12 major food groups following the HDDS framework (Sibhatu & Qaim, 2017). Each distinct food group produced contributes one point to the FPD, highlighting the dietary diversity of production.

To ensure the robustness of our results, we also employed two alternative measures of production diversity. First, the Shannon diversification index (SDI), a widely recognized metric in ecological and agricultural studies for assessing farm production diversity (Shannon, 1948), incorporates both the richness and evenness, making it a strong tool for evaluating farm diversification (Magurran, 2004). Second, to focus on crop related diversity, we estimated a food crop diversity score, a simple unweighted measure that counts only the number of food crop species produced by the household (Sibhatu et al., 2015).

2.3.4 Control variables

A range of factors beyond farm diversification may have influenced dietary diversity and food security, shaping the observed relationship between them. To account for this, we included several control variables such as household distance to the nearest subdistrict market, food access, market orientation, income from off-farm activities, and socioeconomic and demographic characteristics, including farm size, and the age, sex, and educational attainment of the household head. The selection of these covariates was guided by established theoretical frameworks, such as the non-separable household model, and by a thorough review of relevant literature (Pellegrini & Tasciotti, 2014; Jones et al., 2014; Sibhatu et al., 2015; Shively & Sununtnasuk, 2015; Kumar et al., 2015; Dillon et al., 2015; Jodlowski et al., 2016; Romeo et al., 2016; Koppmair et al., 2017; Carletto et al., 2017; Hirvonen & Hoddinott, 2017; Islam et al., 2018; Khandoker et al., 2022).

2.3.5 Econometric model

To investigate the relationship between farm production diversity and household dietary diversity and food security outcomes, we applied regression models that incorporate household food access (proxied by HDDS) and farm production diversity as a source of potential dietary variety.

Dietary diversity model To explore the association between farm production diversity and household dietary diversity, we estimated the following baseline model:

$$DD_i = b + b_1 PD_i + \epsilon_i \tag{1}$$

where DD_i denoted the dietary diversity score for household i, PD_i was the farm production diversity score. A positive and statistically significant b_1 would suggest that greater production diversity was associated with higher dietary diversity, as commonly hypothesized. The error term ϵ_i captures unobserved factors.

Given that DD_i was a non-negative count variable bounded between 1 and 12, and the distribution was slightly left-skewed, we applied a Poisson regression model using maximum likelihood estimation (Greene, 2012). The coefficients from the Poisson model were interpreted as semi-elasticities—indicating the percentage change in dietary diversity for a one-unit change in the explanatory variable.

To expand the analysis, we included additional covariates reflecting market access related indicators, income sources, and environmental stressors, resulting in the following extended specification:

$$\begin{aligned} DD_i &= b + b_1 PD_i + b_2 MD_i + b_3 FA_i \\ &+ b_4 MO_i + b_5 OFI_i + b_6 F_i + \epsilon_i \end{aligned} \tag{2}$$

where MD_i represented distance to the nearest subdistrict market (km); FA_i denoted a categorical variable capturing household food access through purchasing behavior; MO_i was market orientation, measured as the ratio of the value of farm produce sold to the total value produced; OFI_i captured off-farm income from employment or self-employment and F_i was a dummy variable indicating whether the household experienced flooding in the past 12 months.

Market access was theorized to improve dietary diversity by expanding income opportunities and broadening access to diverse foods. Following Koppmair et al. (2017), we categorized food access into four levels based on purchasing behavior: (1) no food purchase (self-sufficient), (2) purchases only within village markets, (3) only outside village markets, and (4) both within and outside village markets. Households accessing markets beyond their villages were expected to attain higher dietary diversity due to greater exposure to nutrient-rich foods (Herforth et al., 2019).

To assess robustness, we further included household demographic and socioeconomic characteristics—age, gender, and education of the household head; household size; and land area operated. All regressions were estimated with robust standard errors to correct for potential heteroskedasticity (Greene, 2012). Additionally, subgroup analyses by salinity level (low, medium, and high) were conducted to explore environmental heterogeneity in dietary outcomes.

Food security model To assess the relationship between farm production diversity and household food security, we employed an ordered probit model, appropriate for the ordinal nature of the Household Food Insecurity Access Scale (HFIAS) (McKelvey & Zavoina, 1975). The HFIAS classified households into four ordered levels of food insecurity, ranging from 1 (food secure) to 4 (severely food insecure). The model was based on the following latent variable specification:

$$\begin{aligned} & HFIAS_i* = b + b_1 PD_i + b_2 DD_i \\ & + b_3 MD_i + b_4 FA_i + b_5 MO_i + b_6 FI_i \\ & + b_7 OFI_i + b_8 F_i + b_8 X_i + \epsilon_i \end{aligned} \tag{3}$$

where $HFIAS_i^*$ was the unobserved latent variable determining observed food insecurity category $HFIAS_i$, and Xi was a vector of household characteristics including age, gender, and education of the household head; household size; and land area. The remaining explanatory variables were defined as in the dietary diversity model.

The observed household food insecurity outcome (HFIAS) is modeled as an ordered categorical variable based on an unobserved continuous latent variable $HFIAS_i^*$, such that:

- HFIAS = 1 if $HFIAS_i^* \le \mu_1$.
- HFIAS = 2 if $\mu_1 < HFIAS_i^* \le \mu_2$.
- HFIAS = 3 if $\mu_2 < HFIAS_i^* \le \mu_3$.
- HFIAS = 4 if $HFIAS_i^* > \mu_3$.

where μ1, μ2, and μ3 are threshold parameters that divide the latent variable into four ordered levels of food insecurity. These thresholds are estimated from the data and determine the cutoffs between different severity levels of food insecurity.

The inclusion of both farm production diversity and dietary diversity enables a comprehensive analysis of the pathways through which agricultural diversification may influence food security. Additional covariates capturing market access, income diversification, and vulnerability to climatic shocks were included to provide a more nuanced understanding of food security dynamics. To test the robustness of our findings, we re-estimated the model using the Shannon Diversity Index (SDI) as an alternative measure of farm production diversity. The model also allows us to examine the role of market engagement and environmental stressors such as flooding and cyclones. Similar to the dietary model, we conducted subgroup analyses by salinity zone and applied robust standard errors in all estimations.

3 Results and discussion

3.1 Descriptive statistics

Descriptive statistics for the explanatory variables across the salinity zones are presented in Table 1. Farm production diversity (FPD) differed significantly ($p \leq 0.05$), with the highest levels observed in LSZ, followed by MSZ and HSZ. A similar pattern was found for food crop production diversity, where LSZ households cultivated an average of 3.7 ± 1.3 food crop groups, compared to only 2.8 ± 1.4 groups in HSZ. This decline in production diversity in high salinity areas likely reflects the adverse impacts of saline soil and water, which restrict the cultivation of many food crops and limit traditional aquaculture practices (Hamed, 2008; Rahman et al., 2013; de Roos et al., 2019). Such limitations in on-farm food diversity can reduce access to self-produced foods and decrease the resilience of farming systems to climatic shocks (FAO, 2018). Interestingly, the Shannon Diversity Index (SDI), which captures both species richness and evenness, was slightly higher in HSZ (2.8 ± 0.8) than in the other zones. This may suggest a more even distribution among fewer species, possibly due to a shift toward saline-tolerant monocultures such as shrimp or specific fish species that dominate production in high salinity areas (Rahman et al., 2013).

Table 1 Farm production diversity, household food access, and socio-economic characteristics across salinity zones

Explanatory variables	Pooled	LSZ	MSZ	HSZ
Farm production diversity (no. of crop, fish, or livestock groups produced)	5.4 (2.1)	6.0 (2.0)^a	5.4 (2.2)^b	5.0 (2.0)^c
Food crop production diversity (no. of food crop groups produced)	3.1 (1.4)	3.7 (1.3)^a	3.2 (1.3)^b	2.8 (1.4)^c
Shannon diversity index (SDI)	2.7 (0.7)	2.7 (0.5)^a	2.7 (0.7)^a	2.8 (0.8)^a
Distance to subdistrict market (km)	10.0 (4.4)	8.4 (2.0)^a	9.0 (4.5)^a	12.0 (4.5)^b
Household food access (%)				
No purchase	0.0	0.0	0.0	0.0
Purchased within village only	38.5	65.3	41.2	20.3
Purchased outside village only	24.1	10.8	20.3	35.9
Purchased both within and outside village	37.4	24.0	38.6	43.8
Market orientation (share of output sold to markets, %)	40.6 (32.6)	33.0 (29.1)^a	37.0 (30.8)^a	48.8 (34.8)^b
Off-farm household income (log of household off-farm income in the past 12 months, USD)	6.2 (2.2)	6.1 (2.4)^a	5.8 (2.5)^a	6.7 (1.6)^b
Household experienced flooding in past 12 months (dummy)	0.2 (0.4)	0.2 (0.4)^a	0.1 (0.3)^b	0.2 (0.4)^a
Age of household head (years)	49.5 (13.1)	48.8 (12.2)^a	49.7 (13.4)^a	49.7 (13.2)^a
Sex of household head (dummy)	1.0 (0.1)	1.0 (0.0)^a	1.0 (0.0)^a	1.0 (0.1)^a
Education of household head (years of schooling)	5.8 (4.6)	5.2 (4.2)^a	5.9 (4.9)^a	6.1 (4.4)^a
Household size (number of people)	4.3 (1.6)	4.3 (1.4)^a	4.1 (1.5)^a	4.4 (1.7)^a
Farm size (ha)	0.7 (0.9)	0.6 (0.6)^a	0.7 (0.8)^a	0.7 (1.1)^a

Note: Mean values are shown with standard deviations in parentheses. Different superscript letters within a row (a, b,c) indicate significant differences across salinity zones at $p \leq 0.05$. LSZ is low salinity zone, MSZ is medium salinity zone and HSZ is high salinity zone

Market access also varied across zones. The average distance to the subdistrict city market was shortest in LSZ (8.4 ± 2.0 km) and longest in HSZ (12.0 ± 4.5 km), indicating that households in saline-prone areas face greater geographic constraints in accessing urban markets. However, market orientation was significantly higher ($p \leq 0.05$) in HSZ (48.8%) compared to LSZ (33.0%), likely due to the concentration of production in a few commercially viable aquaculture commodities. Household off-farm income was also highest in HSZ, reflecting limited opportunities for subsistence rice cultivation and a greater reliance on non-agricultural income sources. This aligns with previous findings that off-farm employment serves as an important adaptation strategy in environmentally stressed areas (Barrett et al., 2001; Lam et al., 2022). Food access patterns differed by zone as well. In LSZ, 65.3% of households purchased food only within the village, whereas in HSZ, 43.8% purchased food both within and outside the village. These variations reflect differences in food environments and market dependencies. There were no substantial differences in household demographic characteristics across salinity zones. Variables such as the age, sex, and education level of the household head, household size, and total farm size remained relatively stable. This indicates that the observed patterns are shaped more by biophysical and market-related factors than by household composition.

Table 2 presents the descriptive statistics for the key outcome variables used in this study across the salinity zones. The average household dietary diversity score (HDDS) was 10.0 ± 1.4, indicating that households consumed nearly 10 out of 12 possible food groups during the seven-day recall period. This reflects relatively better household food access to diverse foods. However, HDDS was significantly lower ($p \leq 0.05$) in HSZ compared to LSZ and MSZ, suggesting that higher salinity may be associated with reduced household access to a diverse range of foods. This may result from

Table 2 Household dietary diversity and food insecurity levels across salinity zones

Outcome variables	Pooled	LSZ	MSZ	HSZ
Household dietary diversity score (number of food groups consumed by any household member at home)	10.0 (1.4)	10.2 (1.3)^a	10.2 (1.3)^a	9.7 (1.3)^b
Household dietary diversity score of purchased foods (number of purchased food groups consumed at home)	7.8 (1.6)	7.8 (1.6)^a	7.8 (1.7)^a	7.8 (1.5)^a
Food variety score (number of individual food items consumed at home by any household member)	30.1 (7.9)	30.0 (8.2)^a	30.0 (7.5)^a	31.0 (8.1)^a
Household food insecurity (%)				
Food secure	37.8	35.3	37.6	39.3
Mildly food insecure	34.2	34.7	32.5	35.9
Moderately food insecure	24.7	29.3	26.1	20.7
Severely food insecure	3.3	0.6	3.9	4.1

Mean values are shown with standard deviations in parentheses. Different superscript letters within a row (a, b) indicate significant differences across salinity zones at $p \leq 0.05$. LSZ is low salinity zone, MSZ is medium salinity zone and HSZ is high salinity zone

constraints in local production systems, limited income, and restricted market access, which are commonly intensified in saline-prone coastal areas (de Roos et al., 2019; Lam et al., 2022). In contrast, dietary diversity of purchased foods and overall food variety scores remained relatively consistent across the salinity zones.

Household food insecurity patterns also reflected these challenges. Although HSZ had the highest proportion of food-secure households (39.3%), it also showed the highest rate of severe food insecurity (4.1%), compared to only 0.6% in LSZ. This dual trend suggests greater inequality in food access, possibly due to differences in livelihood resilience and integration with markets in saline-affected regions (Islam et al., 2014).

3.2 Dietary diversity

3.2.1 Association between farm production diversity and household dietary diversity

Table 3 presents the Poisson regression results, where household dietary diversity score (HDDS) is the dependent variable, and farm production diversity is the key explanatory variable. The analysis was conducted for the full sample as well as separately for three salinity zones: the low salinity zone (LSZ), the medium salinity zone (MSZ), and the high salinity zone (HSZ).

Across all models, a statistically significant and positive association was found between farm production diversity and dietary diversity, although the effect sizes were relatively modest. For the pooled sample, each additional species produced on the farm (including crops, fish, or livestock) was associated with a 1.4% increase in dietary diversity (coefficient: 0.014, $p < 0.01$). The relationship remained statistically significant across all salinity zones, with estimated coefficients of 0.011 in LSZ ($p < 0.05$), 0.011 in MSZ ($p < 0.01$), and 0.014 in HSZ ($p < 0.01$). These findings suggest that increasing the diversity of farm production is positively linked to household dietary diversity, even under different environmental stress levels caused by salinity. The relatively stronger association in HSZ may reflect a greater reliance on production diversification as a risk management strategy or as a means of compensating for poor market access. In contrast, the smaller effect sizes in LSZ and MSZ could be due to better market connectivity or higher income from commercial aquaculture activities, such as fish and crustacean farming. In such cases, households may be less dependent on production diversity for improving their diets (Jones et al., 2014; Sibhatu et al., 2015). These results are consistent with prior research that highlights the role of diversified farming systems in enhancing dietary diversity and food security. Previous studies have shown that production diversity can improve dietary diversity either by increasing the availability of diverse food groups for household consumption or by generating income that enables food purchases (Pellegrini & Tasciotti, 2014; Jones et al., 2014; Sibhatu et al., 2015; Koppmair et al., 2017; Romeo et al., 2016; Islam et al., 2018; Khandoker et al., 2022). This relationship is particularly relevant in ecologically fragile regions such as coastal Bangladesh, where salinity intrusion and climate-related stress frequently disrupt food production and access (Lam et al., 2022).

Table 3 Association between farm production diversity and household dietary diversity across salinity zones

Explanatory variables	Pooled	LSZ	MSZ	HSZ
Farm production diversity no. of crop, fish, or livestock groups produced)	0.014 (0.002)***	0.011 (0.005)**	0.011 (0.003)***	0.014 (0.004)***
Constant	2.225 (0.013)***	2.249 (0.032)***	2.258 (0.020)***	2.195 (0.022)***
Log likelihood	−1662.34	−361.29	−676.35	−622.99
Wald χ2	37.77***	5.73**	11.61***	13.00***
Number of observations	768	167	311	290

Note: The dependent variable is household dietary diversity score (HDDS); *Significant at 10%, **Significant at 5%, ***Significant at 1%; figures in parentheses are standard errors; LSZ is low salinity zone, MSZ is medium salinity zone and HSZ is high salinity zone

Although the estimated effects in this study are relatively small, they align with patterns observed in subsistence-oriented farming systems, where a large portion of the farm output is retained for household use (World Bank, 2007;

Sibhatu et al., 2015). It is important to note that the strength of the relationship between production diversity and dietary diversity can be influenced by other factors, including household income, market access, and socioeconomic characteristics (Sibhatu et al., 2015; Koppmair et al., 2017). To address possible endogeneity, since farm production diversity may be influenced by household choices and environmental conditions, the next section includes models that control for market access indicators and household-level characteristics.

3.2.2 Role of market access on the relationship between farm production diversity and household dietary diversity

Table 4 showed results from extended models that included market access indicators such as distance to subdistrict city markets, market orientation, food access, and off-farm income. In these models, the positive and statistically significant relationship between production diversity and dietary diversity persisted. For the pooled sample, the coefficient for production diversity increased slightly to 0.015 ($p < 0.01$), indicating that controlling for market and income factors strengthened the observed relationship.

Distance to the subdistrict market was negatively and significantly associated with dietary diversity in the pooled, MSZ, and HSZ models, indicating that households located farther from markets tended to have lower dietary diversity, likely due to reduced access to food and agricultural inputs (Jones et al., 2014). These findings underscore the important role of market proximity in enhancing the dietary benefits of on-farm production diversification. Household food access was positively and significantly associated with dietary diversity in MSZ and HSZ, with the strongest effect found in HSZ (coefficient: 0.027, $p < 0.01$). This emphasizes that in areas with greater environmental constraints, improved access to food through markets plays a more critical role in supporting household access to a diverse diet. These findings are aligned with broader food systems literature, which stressed both physical and economic access to nutritious food (HLPE, 2017). Market orientation had a small but significant effect only in LSZ, suggesting that commercialization might improve dietary diversity in more favorable zones but had limited relevance under ecological stress. Off-farm household income showed a positive and significant association with dietary diversity across all zones, with the largest effect observed in LSZ (coefficient: 0.021, $p < 0.01$), indicating that households with higher non-agricultural income were better able to use this income to access a wider variety of foods. This finding is especially relevant for vulnerable coastal regions, where reliance on subsistence production alone may not ensure adequate dietary outcomes (Romeo et al., 2016). These patterns reinforce evidence from earlier studies highlighting the complementary roles of off-farm household income, market access, and commercialization in enhancing household access to a diverse diet (Sibhatu et al., 2015; Koppmair et al., 2017; Romeo et al., 2016). The result shows that while market-related factors significantly contribute to dietary diversity, their effects are complementary to, rather than a substitute for, the contribution from production diversity. This finding aligns with Islam et al. (2018) and Khandoker et al. (2022), who found that although market access is an important determinant of dietary diversity, it does not outweigh the nutritional benefits derived from diversified farming systems.

Table 4 Association between farm production diversity, market access, and household dietary diversity across salinity zones

Explanatory variables	Pooled	LSZ	MSZ	HSZ
Farm production diversity (no. of crop, fish, or livestock groups produced)	0.015 (0.003)***	0.010 (0.006)*	0.016 (0.004)***	0.005 (0.006)
Distance to subdistrict market (km)	−0.005 (0.001)***	0.008 (0.006)	−0.005 (0.002)***	−0.003 (0.003)
Household food access (%)	0.008 (0.005)	−0.006 (0.009)	0.011 (0.009)	0.027 (0.011)***
Market orientation (share of output sold to markets, %)	0.000 (0.000)	0.001 (0.000)*	0.000 (0.000)	0.000 (0.000)
Off-farm household income (log of household off-farm income in the past 12 months, USD)	0.007 (0.002)***	0.021 (0.004)***	0.003 (0.003)	0.008 (0.004)*
Household experienced flooding in past 12 months (dummy)	−0.009 (0.015)	0.030 (0.023)	−0.017 (0.031)	0.016 (0.025)
Constant	2.192 (0.031)***	2.031 (0.067)***	2.214 (0.050)***	2.111 (0.067)***
Log likelihood	−1659.01	−358.86	−675.00	−621.63
Wald $\chi 2$	84.77***	65.08***	33.45***	32.87***
Number of observations	768	167	311	290

The dependent variable is household dietary diversity score (HDDS); *Significant at 10%, **Significant at 5%, ***Significant at 1%; figures in parentheses are standard errors; LSZ is low salinity zone, MSZ is medium salinity zone and HSZ is high salinity zone

3.2.3 Robustness checks

To validate the consistency of the findings, robustness checks were conducted by incorporating additional household socioeconomic and demographic variables. These included household size, farm size, and the age, sex, and education of the household head (Zezza & Tasciotti, 2010; Sibhatu et al., 2015; Islam et al., 2018). The inclusion of these variables did not significantly change the estimated coefficients for production diversity or market access, suggesting that omitted variable bias was not a significant concern (Table 5).

Some of the additional covariates showed statistically significant associations with dietary diversity. Age of the household head was weakly and negatively associated with household dietary diversity, suggesting that older household heads may have a reduced capacity to produce or access diverse foods for their households. Education level of the household head had a positive and statistically significant effect, suggesting that more educated individuals may have better income and economic access to food, enabling improved household dietary diversity, consistent with the findings of Dillon et al. (2015) and Headey et al. (2018). Household size was positively and significantly associated with dietary diversity, possibly reflecting that larger households may have more productive members contributing income, which can be used to purchase a greater variety of food, similar to the findings of Khandoker et al. (2022). Farm size was also positively related to dietary diversity, indicating that households with larger landholdings were better able to produce a variety of foods for home consumption and sale, consistent with Dillon et al. (2015). These robustness checks provided further support for the positive and stable relationship between farm production diversity and dietary diversity, even when accounting for key demographic and contextual factors.

Next, we tested the robustness of our findings by using two alternative measures of household dietary diversity. First, when household dietary diversity was restricted to include only purchased food groups (Table 7), the sign of the coefficient for farm production diversity turned negative and significant across all models, including the pooled sample (–0.019, $p<0.01$). This suggests a substitution effect: households with more diverse on-farm production rely less on market purchases for dietary diversity. This result aligns with previous studies (Sibhatu et al., 2015; Bellon et al., 2016; Islam et al., 2018; Khandoker et al., 2022), which suggest that farm production diversity enhances own-consumption pathways, especially in rural or remote contexts where market access is limited or food prices are high. However, the magnitude of the coefficients, although

Table 5 Association between farm production diversity, market access, other confounding factors, and dietary diversity across salinity zones

Explanatory variables	Pooled	LSZ	MSZ	HSZ
Farm production diversity (no. of crop, fish, or livestock groups produced)	0.013 (0.003)***	0.010 (0.006)*	0.013 (0.004)***	0.000 (0.000)
Distance to subdistrict market (km)	−0.005 (0.001)***	0.006 (0.006)	−0.005 (0.002)**	0.005 (0.006)
Household food access (%)	0.006 (0.005)	−0.004 (0.008)	0.010 (0.009)	0.003 (0.003)**
Market orientation (share of output sold to markets, %)	0.000 (0.000)	0.001 (0.000)*	0.000 (0.000)	0.025 (0.011)*
Off-farm household income (log of household off-farm income in the past 12 months, USD)	0.006 (0.002)***	0.021 (0.004)***	0.001 (0.003)	0.001 (0.004)
Household experienced flooding in past 12 months (dummy)	−0.009 (0.015)	0.032 (0.022)	−0.011 (0.030)	0.006 (0.004)
Age of household head (years)	−0.001 (0.000)***	0.000 (0.001)	−0.001 (0.001)***	0.007 (0.024)
Sex of household head (dummy)	0.172 (0.132)	0.000 (0.000)	0.000 (0.000)	−0.001 (0.001)
Education of household head (years of schooling)	0.002 (0.001)**	0.006 (0.002)**	0.001 (0.002)	0.118 (0.151)**
Household size (number of people)	0.007 (0.003)**	0.004 (0.007)	0.010 (0.005)**	0.004 (0.002)***
Farm size (ha)	0.015 (0.005)***	−0.001 (0.019)	0.021 (0.010)**	0.011 (0.004)***
Constant	2.051 (0.136)***	2.006 (0.088)***	2.259 (0.062)***	0.015 (0.005)***
Log likelihood	−1656.10	−358.38	−673.73	−620.00
Wald χ2	131.27***	73.58***	54.82***	69.88***
Number of observations	768	167	311	290

The dependent variable is household dietary diversity score (HDDS); *Significant at 10%, **Significant at 5%, ***Significant at 1%; figures in parentheses are standard errors; LSZ is low salinity zone, MSZ is medium salinity zone and HSZ is high salinity zone significant, indicates that own production can only partially offset the need for market-based food acquisition as approximately three-quarters of household food consumption still originates from markets (Table 2). Second, we used the household food variety score (FVS), which captures the total number of different food items consumed, as another alternative dietary diversity measure (Table 8). The relationship between farm production diversity and household dietary diversity remained positive and statistically significant in all models except HSZ. In the pooled model, the coefficient was relatively strong (0.036, $p<0.01$), and was even higher in LSZ (0.049) and MSZ (0.037). This reinforces the conclusion that diversified production systems not only increase food group diversity but also the number of unique food items available for household consumption, particularly in regions with lower or moderate salinity.

Finally, we tested two alternative measures of farm production diversity: the Shannon Diversity Index (SDI) and the food crop production diversity, instead of using a simple count of crops, fish, and livestock. Results from these alternative specifications were largely consistent with our primary findings. As shown in Table 9, the SDI was positively and significantly associated with household dietary diversity in the pooled sample and in both LSZ and MSZ. Similarly, Table 10 presents results using food crop production diversity, which also exhibited a positive and statistically significant association with household dietary diversity in the pooled sample and most salinity zones. These models indicate that the coefficients for production diversity indicators, while modest in magnitude, were consistently larger than or comparable to those of other significant variables. These findings reinforce the central conclusion that diversified farm production contributes significantly to improving household dietary diversity, although its influence may vary across agroecological zones.

3.3 Food security

The results of the ordered probit model, shown in Table 6, revealed a statistically significant model fit across all salinity zones, evidenced by the Wald χ^2 statistics ($p<0.01$) and consistent improvements in log-likelihood values. These findings confirm that the models are well-specified and suitable for assessing the relationships between production diversity, dietary diversity, market access, and other household characteristics with food insecurity across different agroecological contexts.

Farm production diversity was found to have a statistically significant negative association with household food insecurity in the pooled model ($\beta = -0.049$, $p<0.05$). This indicates that households practicing diversified farming

Table 6 Association between farm production diversity, household dietary diversity, market access, other confounding factors, and household food insecurity across salinity zones

Explanatory variables	Pooled	LSZ	MSZ	HSZ
Farm production diversity (no. of crop, fish, or livestock groups produced)	−0.049 (0.025)**	0.059 (0.055)	−0.134 (0.045)***	−0.124 (0.051)**
Household dietary diversity score (number of food groups consumed by any household member at home)	−0.123 (0.036)***	−0.156 (0.081)**	−0.101 (0.072)	−0.202 (0.056)***
Distance to subdistrict market (km)	−0.033 (0.010)***	−0.142 (0.055)***	−0.033 (0.018)*	−0.075 (0.020)***
Household food access (%)	−0.113 (0.047)**	−0.082 (0.111)	−0.073 (0.077)	0.014 (0.087)
Market orientation (share of output sold to markets, %)	−0.001 (0.001)	0.011 (0.004)***	−0.001 (0.002)	−0.005 (0.002)**
Off-farm household income (log of household off-farm income in the past 12 months, USD)	0.008 (0.019)	0.077 (0.042)*	−0.026 (0.028)	−0.032 (0.042)
Household experienced flooding in past 12 months (dummy)	0.382 (0.114)***	−0.287 (0.243)	0.418 (0.228)*	0.685 (0.210)***
Age of household head (years)	0.002 (0.003)	0.006 (0.008)	−0.003 (0.005)	0.003 (0.005)
Sex of household head (dummy)	0.089 (1.160)	0.000 (0.000)	0.000 (0.000)	0.255 (0.964)
Education of household head (years of schooling)	−0.013 (0.010)	0.034 (0.028)	−0.021 (0.015)	−0.035 (0.018)**
Household size (number of people)	−0.050 (0.030)*	−0.021 (0.067)	−0.055 (0.047)	0.005 (0.052)
Farm size (ha)	−0.239 (0.076)***	−0.602 (0.277)**	−0.320 (0.145)**	−0.228 (0.100)**
μ_1	−3.428 (1.227)	−3.961 (1.017)	−3.533 (0.828)	−4.505 (1.202)
μ_2	−2.403 (1.225)	−2.902 (1.009)	−2.514 (0.807)	−3.336 (1.188)
μ_3	−0.908 (1.220)	−0.499 (1.100)	−0.931 (0.784)	−2.040 (1.162)
Log likelihood	−838.13	−166.65	−325.41	−297.34
Wald $\chi2$	141.90***	46.55***	62.72***	77.77***
Number of observations	768	167	311	290

The dependent variable is household food insecurity access scale (HFIAS); *Significant at 10%, **Significant at 5%, ***Significant at 1%; figures in parentheses are standard errors; LSZ is low salinity zone, MSZ is medium salinity zone and HSZ is high salinity zone systems are less likely to experience food insecurity. The literature supports this finding, noting that production diversity offers multiple income and food sources, which buffers households against market volatility and climatic shocks (Mango et al., 2018; Adjimoti & Kwadzo, 2018; Mengistu et al., 2021; Alam et al., 2023a, b; Nahar et al., 2024). The association between farm production diversity and household food security was particularly strong in the medium (MSZ: $\beta = -0.134$, $p < 0.01$) and high saline zone (HSZ: $\beta = -0.124$, $p < 0.05$), but not significant in the low saline zone (LSZ). In saline environments, where reliance on a single crop or a specialized aquaculture systems such as predominately shrimp or prawn farming can be risky due to environmental uncertainties, diversified farming systems including multiple species of fish and shrimp as well as vegetables and cereal crops serve as a key strategy to strengthen household resilience and reduce vulnerability to food insecurity (Akber et al., 2021). Household dietary diversity showed a strong negative association with food insecurity in the pooled model ($\beta = -0.123$, $p < 0.01$), indicating that greater household dietary diversity is linked to reduced food insecurity. This relationship was most pronounced in the HSZ ($\beta = -0.202$, $p < 0.01$) and LSZ ($\beta = -0.156$, $p < 0.05$), highlighting that improved household dietary diversity supports better food access and reduced vulnerability to food insecurity. In regions where environmental constraints limit both agricultural production and market access, household dietary diversity plays a critical role in enhancing household resilience and overall food security (Hoddinott & Yohannes, 2002; Jones et al., 2014; Alam et al., 2023a, b).

Market access, as measured by various explanatory variables discussed above, was found to have a significant impact on food insecurity. The distance to the nearest subdistrict city market showed a significant negative relationship with food insecurity. The pooled sample analysis revealed that a greater distance to markets was significantly associated with higher food insecurity ($\beta = -0.033$, $p < 0.01$). The effect was most pronounced in the LSZ ($\beta = -0.142$, $p < 0.01$) and HSZ ($\beta = -0.075$, $p < 0.01$), suggesting that physical proximity to markets is crucial for enhancing food access, particularly in remote and saline areas where infrastructure and transportation are limited. These results are consistent with findings by Moroda et al. (2018), Mitu et al. (2022), Usman and Haile (2022), and Kolog et al. 2023), who emphasized the critical role of market access in improving food security. Market orientation had a modest effect in the pooled model, being significant only in the LSZ ($\beta = 0.011$, $p < 0.01$) and HSZ ($\beta = -0.005$, $p < 0.05$). The positive coefficient in the LSZ may reflect the economic benefits derived from market sales, while the negative relationship in the HSZ suggests that greater market integration may help households better cope with environmental stresses. This aligns with the findings of Abebe (2025), who argued that market orientation enhances food availability and household resilience. Off-farm income had mixed effects. It was not significant in most zones, except for the LSZ, where it had a positive and significant effect ($\beta = 0.077$, $p < 0.10$). This suggests that off-farm income may serve as a financial buffer during agricultural shortfalls in the LSZ, aligning with previous research that highlighted the importance of off-farm employment in mitigating food insecurity (Kehinde & Ogundeji, 2023). The lack of significance in the MSZ and HSZ may reflect limited off-farm opportunities or lower returns in saline regions, possibly due to their remoteness or constrained labor markets.

Household experienced flooding emerged as a significant driver of food insecurity in the pooled sample ($\beta = 0.382$, $p < 0.01$) and particularly in the HSZ ($\beta = 0.685$, $p < 0.01$) and MSZ ($\beta = 0.418$, $p < 0.10$). This underscores the compounded impact of environmental stress in coastal and flood-prone regions, where flooding caused by heavy monsoon rainfall, river overflows, tidal surges, and cyclones disrupts food production, damage assets, and displace populations, thereby exacerbating household food insecurity in southern Bangladesh (Hossain et al., 2020; Parven et al., 2022).

Among household-level characteristics, farm size was negatively and significantly associated with food insecurity across all zones, including the pooled sample ($\beta = -0.239$, $p < 0.01$), suggesting that larger landholdings contribute to improved food availability and economic resilience. This supports earlier studies indicating that larger farms are better able to meet household consumption needs and generate marketable surpluses, likely due to their greater total output and the flexibility to cultivate both food and cash crops (Okezie et al., 2012; Goshu et al., 2012; Osmani & Hossain, 2015; Martey et al., 2012). The education of the household head was significantly associated with reduced food insecurity in the high salinity zone (HSZ) ($\beta = -0.035$, $p < 0.05$), highlighting the role of education in enhancing adaptive capacity and informed decision-making under more challenging environmental conditions. This finding is consistent with those of Idrisa et al. (2008) and Fisher & Lewin (2013), who found that educated households are better equipped to access, interpret, and apply agricultural information to improve food security and dietary diversity year-round. Household size was positively associated with food insecurity in the pooled model ($\beta = 0.050$, $p < 0.10$), indicating that larger households may face greater pressure on available food resources and income. This finding aligns with Babatunde et al. (2007), who reported that increased household size often exacerbates food insecurity due to higher dependency ratios and consumption demands. By contrast, the age and sex of the household head were not significantly associated with food insecurity in any zone, suggesting that these characteristics have limited influence in deltaic southern Bangladesh.

To test the robustness of our findings, we employed the Shannon Diversity Index (SDI) as an alternative measure of farm production diversity. The results (Table 11) remained consistent with the primary analysis, showing a significant negative association between SDI and household food insecurity. The SDI-based models, particularly in the MSZ and HSZ, revealed stronger effects, suggesting that both the balance and composition of farm activities—not just their number—are critical for enhancing food security. These findings reinforce the robustness of our results and underscore the importance of diverse and well-balanced production systems, especially in vulnerable regions.

The estimated cutpoints from the ordered probit model (Table 6) indicate the thresholds between different levels of food insecurity (e.g., food secure, mildly food insecure, moderately food insecure, and severely food insecure). Showing how households transition from one category to another. The estimated cutpoints for the HSZ were consistently lower ($\mu 1 = -4.51$, $\mu 2 = -3.34$, $\mu 3 = -2.04$), indicating that households in the HSZ reach higher levels of food insecurity at lower thresholds of underlying vulnerability. This suggests a heightened susceptibility to food insecurity in saline-affected coastal areas. This aligns with findings by Lam et al. (2022), who highlighted how salinity intrusion, driven both by climate factors and shrimp farming, exacerbates food insecurity in deltaic southern Bangladesh. Thus, even marginal deteriorations in socioeconomic or environmental conditions in HSZ significantly increase the likelihood of households falling into more severe food insecurity categories. The positioning of the cutpoints thus supports the hypothesis that geographic and ecological stressors, such as salinity, structurally predispose certain regions to chronic food insecurity and highlight the need for context-specific, resilience-building interventions (Hoque et al., 2019).

4 Conclusion and policy recommendations

This study provides robust empirical evidence that farm production diversity contributes to improved household dietary diversity and reduced food insecurity among climate-vulnerable rural households in southern Bangladesh. The relationship is strongest in low and medium salinity zones, where agroecological conditions are more favorable for diversification across crops, aquaculture, and livestock. In these areas, households engaging in more diverse food production systems, integrating nutrient-rich small indigenous fish species (SIS), vegetables, and cereal crops, achieved improved dietary outcomes. In contrast, the benefits of production diversity were more limited in high salinity zones due to significant environmental constraints, including degraded soils, saline water intrusion, frequent flooding, and limited access to climate-adaptive technologies. The analysis also highlights the importance of market access, off-farm household income, education, and household composition in shaping dietary diversity.

To enhance the contribution of farm production diversity to food security, a set of integrated and context-specific interventions is essential. In low and medium salinity zones, nutrition-sensitive and climate-smart farming systems should be promoted by expanding access to genetically improved fish fingerlings, small indigenous fish species (e.g., mola, punti, tengra etc.), and nutrient-rich, locally adapted crop varieties. Strengthening decentralized seed distribution systems is critical to ensure equitable and timely access to quality inputs.

In high salinity zones, where production opportunities are severely constrained, diversification alone may not be sufficient. Greater emphasis should be placed on promoting climate-resilient innovations such as salt-tolerant rice and vegetable varieties, salinity-adapted fish species including improved strains, and short-cycle crop and fish production systems that align with seasonal salinity dynamics. Integrated aquaculture-agriculture (IAA) models, such as rice-SIS polyculture adapted to post-monsoon conditions, can offer viable solutions in these settings. These models must be complemented by investments in water management systems, reliable access to agricultural inputs (such as quality seed, feed, and fertilizer) through efficient distribution networks, and efforts to improve physical market infrastructure as well as institutional support mechanisms (such as cooperatives, producer groups, and market information systems) to strengthen household resilience and food availability.

In conclusion, while farm production diversity offers a promising pathway to improve household dietary diversity and food security, its success depends on ecological suitability and the availability of enabling institutional, technological, and market support. A systems-based approach that integrates agronomic innovations with nutrition objectives, climate adaptation strategies, and socioeconomic support mechanisms is crucial to delivering sustainable improvements in dietary diversity and food security in vulnerable rural contexts.

Appendix

Table 7 Association between farm production diversity, market access, and household dietary diversity of purchased foods only across salinity zones

Explanatory variables	Pooled	LSZ	MSZ	HSZ
Farm production diversity (no. of crop, fish, or livestock groups produced)	−0.019 (0.004)***	−0.016 (0.009)*	−0.008 (0.007)**	−0.027 (0.008)***
Distance to sub-district market (km)	−0.006 (0.002)***	0.002 (0.009)	−0.009 (0.003)***	−0.006 (0.004)
Household food access (%)	0.011 (0.008)	0.014 (0.017)	0.024 (0.014)*	0.004 (0.014)
Market orientation (share of output sold to markets, %)	0.000 (0.000)	0.001 (0.001)*	0.000 (0.000)	0.001 (0.000)**
Off-farm household income (log of household off-farm income in the past 12 months, USD)	0.013 (0.003)***	0.019 (0.007)***	0.018 (0.005)***	0.008 (0.006)
Household experienced flooding in past 12 months (dummy)	0.021 (0.022)	0.097 (0.037)***	0.010 (0.043)	−0.008 (0.040)
Constant	2.119 (0.048)***	1.944 (0.098)***	2.018 (0.078)***	2.236 (0.090)***
Log likelihood	−1609.74	−348.73	−656.20	−601.14
Wald χ2	93.23***	32.14***	45.76***	50.71***
Number of observations	768	167	311	290

The dependent variable is household dietary diversity score for purchased foods only; *Significant at 10%, **Significant at 5%, ***Significant at 1%; figures in parentheses are standard errors

Table 8 Association between farm production diversity, market access, and household dietary diversity as measured by food variety score (FVS) across salinity zones

Explanatory variables	Pooled	LSZ	MSZ	HSZ
Farm production diversity (no. of crop, fish, or livestock groups produced)	0.036 (0.005)***	0.049 (0.011)***	0.037 (0.007)***	0.004 (0.012)
Distance to subdistrict market (km)	−0.001 (0.002)*	0.029 (0.009)**	−0.005 (0.004)	−0.008 (0.005)*
Household food access (%)	0.019 (0.010)*	0.054 (0.019)***	0.016 (0.015)	0.014 (0.020)
Market orientation (share of output sold to markets, %)	0.001 (0.000)***	0.001 (0.001)	0.001 (0.000)	0.000 (0.001)
Off-farm household income (log of household off-farm income in the past 12 months, USD)	0.021 (0.005)***	0.031 (0.008)***	0.017 (0.006)***	0.013 (0.010)*
Household experienced flooding in past 12 months (dummy)	0.040 (0.026)	−0.043 (0.042)	0.025 (0.043)	0.084 (0.049)*
Constant	3.002 (0.060)***	2.714 (0.122)***	2.924 (0.080)***	3.238 (0.134)***
Log likelihood	−2700.51	−556.04	−1054.18	−1030.03
Wald χ2	84.46***	100.36***	70.06***	36.60***
Number of observations	768	167	311	290

The dependent variable is the household food variety score (FVS) including all food items; *Significant at 10%, **Significant at 5%, ***Significant at 1%; figures in parentheses are standard errors

Table 9 Association between farm production diversity measured with Shannon diversity index, market access, and household dietary diversity across salinity zones

Explanatory variables	Pooled	LSZ	MSZ	HSZ
Shannon diversity index	0.032 (0.007)***	0.047 (0.018)***	0.045 (0.013)***	0.009 (0.013)
Distance to subdistrict market (km)	−0.005 (0.001)***	0.005 (0.005)	−0.005 (0.002)**	−0.003 (0.003)
Household food access (%)	0.007 (0.005)	−0.002 (0.009)	0.011 (0.009)	0.028 (0.011)***
Market orientation (share of output sold to markets, %)	0.000 (0.000)	0.001 (0.000)*	0.000 (0.000)	0.000 (0.000)
Off-farm household income (log of household off-farm income in the past 12 months, USD)	0.006 (0.002)***	0.020 (0.004)***	0.002 (0.003)	0.008 (0.004)*
Household experienced flooding in past 12 months (dummy)	−0.012 (0.015)	0.028 (0.023)	−0.020 (0.031)	0.016 (0.025)
Constant	2.183 (0.032)***	1.988 (0.074)***	2.180 (0.052)***	2.108 (0.066)***
Log likelihood	−1660.06	−358.73	−675.28	−621.66
Wald χ2	71.01***	67.30***	27.02***	33.35***
Number of observations	768	167	311	290

The dependent variable is household dietary diversity (HDDS); *Significant at 10%, **Significant at 5%, ***Significant at 1%; figures in parentheses are standard errors

Table 10 Association between farm production diversity measured with food crop production diversity, market access, and household dietary diversity across salinity zones

Explanatory variables	Pooled	LSZ	MSZ	HSZ
Food crop production diversity (no. of food crop groups produced)	0.015 (0.004)***	0.010 (0.008)*	0.017 (0.006)***	0.001 (0.007)
Distance to subdistrict market (km)	−0.005 (0.001)***	0.011 (0.005)**	−0.004 (0.002)*	−0.004 (0.003)
Household food access (%)	0.008 (0.005)	−0.007 (0.009)	0.010 (0.009)	0.029 (0.011)***
Market orientation (share of output sold to markets, %)	0.000 (0.000)	0.001 (0.000)*	0.000 (0.000)	0.000 (0.000)
Off-farm household income (log of household off-farm income in the past 12 months, USD)	0.007 (0.002)***	0.021 (0.004)***	0.002 (0.003)	0.008 (0.004)*
Household experienced flooding in past 12 months (dummy)	−0.005 (0.015)	0.030 (0.023)	−0.017 (0.031)	0.016 (0.025)
Constant	2.201 (0.031)***	2.021 (0.067)***	2.221 (0.049)***	2.116 (0.066)***
Log likelihood	−1660.19	−358.96	−675.63	−621.69
Wald χ2	74.43***	59.55***	25.49***	32.66***
Number of observations	768	167	311	290

The dependent variable is household dietary diversity (HDDS); *Significant at 10%, **Significant at 5%, ***Significant at 1%; figures in parentheses are standard errors

Table 11 Association between farm production diversity measured with Shannon diversity index, household dietary diversity, market access, other confounding factors, and household food insecurity across salinity zones

Explanatory variables	Pooled	LSZ	MSZ	HSZ
Shannon diversity index	−0.178 (0.079)**	0.089 (0.207)	−0.319 (0.133)**	−0.366 (0.159)**
Household dietary diversity score (number of food groups consumed by any household member at home)	−0.126 (0.036)**	−0.148 (0.080)*	−0.111 (0.072)	−0.203 (0.057)***
Distance to subdistrict market (km)	−0.030 (0.010)***	−0.136 (0.059)**	−0.028 (0.017)*	−0.073 (0.020)***
Household food access (%)	−0.106 (0.047)**	−0.080 (0.114)	−0.068 (0.077)	0.011 (0.088)
Market orientation (share of output sold to markets, %)	0.000 (0.001)	0.011 (0.004)***	0.000 (0.002)	−0.004 (0.002)*
Off-farm household income (log of household off-farm income in the past 12 months, USD)	0.011 (0.019)	0.071 (0.041)*	−0.019 (0.028)	−0.031 (0.041)
Household experienced flooding in past 12 months (dummy)	0.400 (0.114)***	−0.303 (0.241)	0.426 (0.222)*	0.691 (0.208)***
Age of household head (years)	0.003 (0.003)	0.006 (0.008)	−0.003 (0.005)	0.004 (0.005)
Sex of household head (dummy)	0.015 (1.198)	0.000 (0.000)	0.000 (0.000)	0.120 (1.055)
Education of household head (years of schooling)	−0.010 (0.010)	0.030 (0.028)	−0.021 (0.015)	−0.032 (0.018)*
Household size (number of people)	−0.047 (0.030)*	−0.017 (0.067)	−0.059 (0.048)	0.007 (0.052)
Farm size (ha)	−0.235 (0.077)***	−0.558 (0.271)**	−0.344 (0.151)**	−0.233 (0.102)**
μ_1	−3.593 (1.266)	−3.835 (1.029)	−3.853 (0.843)	−4.729 (1.287)
μ_2	−2.567 (1.263)	−2.780 (1.021)	−2.844 (0.821)	−3.555 (1.271)
μ_3	−1.067 (1.258)	−0.385 (1.113)	−1.270 (0.797)	−2.248 (1.244)
Log likelihood	−824.83***	−167.06***	−327.67***	−296.43***
Wald $\chi2$	142.20	46.99	58.78	78.87
PseudoR^2	0.10	0.11	0.13	0.14
Number of observations	768	167	311	290

The dependent variable is household food insecurity access scale (HFIAS); *Significant at 10%, **Significant at 5%, ***Significant at 1%; figures in parentheses are standard errors; LSZ is low salinity zone, MSZ is medium salinity zone and HSZ is high salinity zone

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics Statement The research design was reviewed and approved by the Ethical Standard of Research Committee of the Bangladesh Agricultural University Research System (BAURES), under approval number BAURES/FISH/25, at Bangladesh Agricultural University (BAU), Mymensingh, Bangladesh.

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References

Abebe, M. G. (2025). Strengthening household resilience for enhanced food security in Northwestern Ethiopia: Insights from resilience pillars. *Frontiers in Sustainable Food Systems, 9*, Article 1528346. https://doi.org/10.3389/fsufs.2025.1528346

Adjimoti, G. O., & Kwadzo, G. T. M. (2018). Crop diversification and household food security status: Evidence from rural Benin. *Agriculture & Food Security*, *7*(82). https://doi.org/10.1186/s40066-018-0233-x

Ahmed, F., Prendiville, N., & Narayan, A. (2016). Micronutrient deficiencies among children and women in Bangladesh: Progress and challenges. *Journal of Nutritional Science, 5*, Article e46. https://doi.org/10.1017/jns.2016.39

Ahmed, N., & Garnett, S. T. (2011). Integrated rice–fish farming in Bangladesh: Meeting the challenges of food security. *Food Security, 3*(1), 81–92. https://doi.org/10.1007/s12571-011-0113-8

Ahmed, T., Mahfuz, M., Ireen, S., Ahmed, A. M. S., Rahman, S., Islam, M. M., Alam, N., Hossain, M. I., Rahman, S. M. M., Ali, M. M., Choudhury, F. P., & Cravioto, A. (2012). Nutrition of children and women in bangladesh: Trends and directions for the future. *Journal of Health Population and Nutrition*, *30*(1), 1–11. https://doi.org/10.3329/jhpn.v30i1.11268

Akber, M. A., Islam, M. A., Rahman, M. M., & Rahman, M. R. (2021). Crop diversification in Southwest coastal Bangladesh: Insights into farming adaptation. *Agroecology and Sustainable Food Systems, 46*(2), 316–324. https://doi.org/10.1080/21683565.2021.1989105

Alam, G. M. M., Alam, K., & Mushtaq, S. (2017). Climate change perceptions and local adaptation strategies of hazard-prone rural households in Bangladesh. *Climate Risk Management, 17*, 52–63. https://doi.org/10.1016/j.crm.2017.06.006

Alam, M. J., Begum, I. A., Mastura, T., Kishore, A., Woodhill, J., Chatterjee, K., & Jackson, T. (2023a). Agricultural diversification and intra-household dietary diversity: Panel data analysis of farm households in Bangladesh. *PLoS One, 18*(6), Article e0287321. https://doi.org/10.1371/journal.pone.0287321

Alam, M. J., Begum, I. A., Mastura, T., Kishore, A., Woodhill, J., Chatterjee, K., et al. (2023b). Agricultural diversification and intra-household dietary diversity: Panel data analysis of farm households in Bangladesh. *PLoS One, 18*(6), Article e0287321. https://doi.org/10.1371/journal.pone.0287321

Alam, M., Ahmad, M. M., Tsusaka, T. W., & Pramanik, M. (2025). Awareness of impacts of salinity intrusion on livelihoods: Evidence from Southern coastal rural areas of Bangladesh. *Current Research in Environmental Sustainability*, *9*, 100293. https://doi.org/10.1016/j.crsust.2025.100293

Ali, N. B., Tahsina, T., Hoque, D. M. E., Hasan, M. M., Iqbal, A., Huda, T. M., & Arifeen, E., S (2019). Association of food security and other socio-economic factors with dietary diversity and nutritional statuses of children aged 6–59 months in rural Bangladesh. *Plos One*, *14*(8), e0221929. https://doi.org/10.1371/journal.pone.0221929

Alimohamadi, Y., & Sepandi, M. (2019). Considering the design effect in cluster sampling. *Journal of Cardiovascular and Thoracic Research, 11*(1), 78. https://doi.org/10.15171/jcvtr.2019.14

Atapattu, A. J., Nuwarapaksha, T. D., Udumann, S. S., & Dissanayaka, N. S. (2024). Integrated farming systems: A holistic approach to sustainable agriculture. In S. Babu, R. Singh, S. S. Rathore, A. Das, & V. K. Singh (Eds.), *Agricultural diversification for sustainable food Production. Sustainability sciences in Asia and Africa ()*. Springer. https://doi.org/10.1007/978-981-97-7517-0_4

Babatunde, R. O., Omotesho, O. A., & Sholotan, O. S. (2007). Socio-economic characteristics and food security status of farming households in Kwara State, North-Central Nigeria. *Pakistan Journal of Nutrition*, *6*(1), 49–58. https://doi.org/10.3923/pjn.2007.49.58

Barrett, C. B., Reardon, T., & Webb, P. (2001). Nonfarm income diversification and household livelihood strategies in rural Africa: Concepts, dynamics, and policy implications. *Food Policy, 26*(4), 315–331. https://doi.org/10.1016/S0306-9192(01)00014-8

Bellon, M.R., Ntandou-Bouzitou, G.D., Caracciolo, F. (2016) On-Farm Diversity and Market Participation Are Positively Associated with Dietary Diversity of Rural Mothers in Southern Benin, West Africa. PLoS ONE 11(9): e0162535. https://doi.org/10.1371/journal.pone.0162535

Belton, B. (2016). Shrimp, prawn and the political economy of social wellbeing in rural Bangladesh. *Journal of Rural Studies, 45*, 230–242. https://doi.org/10.1016/j.jrurstud.2016.03.014

Bernzen, A., Mangnus, E., & Sohns, F. (2022). Diversify, produce or buy? An analysis of factors contributing to household dietary diversity among shrimp and non-shrimp farmers in coastal Bangladesh. *Food Security, 14*(3), 741–761. https://doi.org/10.1007/s12571-021-01245-w

Bishwajit, G., Sarker, S., Kpoghomou, M. A., Gao, H., Jun, L., Yaya, S., & Feng, Z. (2013). Self-sufficiency in rice and food security: A South Asian perspective. *Agriculture & Food Security*, *2*, 10. https://doi.org/10.1186/2048-7010-2-10

Carletto, C., Corral, P., & Guelfi, A. (2017). Agricultural commercialization and nutrition revisited: Empirical evidence from three African countries. *Food Policy, 67*, 106–118.

Chege, C. G. K., Andersson, C. I. M., & Qaim, M. (2015). Impacts of supermarkets on farm household nutrition in Kenya. *World Development, 72*, 394–407. https://doi.org/10.1016/j.worlddev.2015.03.016

Coates, J., Swindale, A., & Bilinsky, P. (2007). *Household food insecurity access scale (HFIAS) for measurement of food access: Indicator guide*. Food and Nutrition Technical Assistance Project, Academy for Educational Development.

Dasgupta, S., Hossain, M. M., Huq, M., & Wheeler, D. (2015). Climate change and soil salinity: The case of coastal Bangladesh. *Ambio, 44*(8), 815–826. https://doi.org/10.1007/s13280-015-0681-5

de Roos, B., Roos, N., Mamun, A. A., Ahmed, T., Sneddon, A. A., Murray, F., Grieve, E., & Little, D. C. (2019). Linking agroecosystems producing farmed seafood with food security and health status to better address the nutritional challenges in Bangladesh. *Public Health Nutrition, 22*(16), 2941–2949. https://doi.org/10.1017/S1368980019002295

Dillon, A., McGee, K., & Oseni, G. (2015). Agricultural production, dietary diversity and climate variability. *The Journal of Development Studies, 51*(8), 976–995.

FAO (2018). *The State of Food Security and Nutrition in the World 2018*. Rome. https://www.fao.org/3/I9553EN/i9553en.pdf

FAO. (2013a). *Guidelines for measuring household and individual dietary diversity*. Mimeo.

FAO. (2013b). *The state of food and agriculture 2013: Food systems for better nutrition*. FAO.

Fisher, M., & Lewin, P. A. (2013). Household, community, and policy determinants of food insecurity in rural Malawi. Development Southern Africa, 30(4–05), 451–467. https://doi.org/10.1080/0376835X.2013.830966

Fischer, E., & Qaim, M. (2012). Gender, agricultural commercialization, and collective action in Kenya. *Food Security, 4*(3), 441–453. https://doi.org/10.1007/s12571-012-0199-7

Freed, S., Barman, B., Dubois, M., Flor, R. J., Funge-Smith, S., Gregory, R., Hadi, B. A. R., Halwart, M., Haque, M., Jagadish, S. V. K., Joffre, O. M., Karim, M., Kura, Y., McCartney, M., Mondal, M., Nguyen, V. K., Sinclair, F., Stuart, A. M., Tezzo, X., … Cohen, P. J. (2020). Maintaining diversity of integrated rice and fish production confers adaptability of food systems to global change. *Frontiers in Sustainable Food Systems, 4*, Article 576179. https://doi.org/10.3389/fsufs.2020.576179

Galhena, D. H., Freed, R., & Maredia, K. M. (2013). Home gardens: A promising approach to enhance household food security and wellbeing. *Agriculture & Food Security, 2*(1), Article 8. https://doi.org/10.1186/2048-7010-2-8

Gillespie, S., Harris, J., & Kadiyala, S. (2012). *The agriculture-nutrition disconnect in India: What do we know?* (IFPRI Discussion Paper No. 01187). Washington, D.C.: International Food Policy Research Institute (IFPRI).

Gopalakrishnan, T., Hasan, M. K., Haque, A. T. M. S., Jayasinghe, S. L., & Kumar, L. (2019). Sustainability of coastal agriculture under climate change. *Sustainability, 11*(24), Article 7200. https://doi.org/10.3390/su11247200

Goshu, D., Kassa, B. A., & Ketema, M. (2012). Measuring smallholder commercialization decisions and interactions in Ethiopia. *Journal of Economics and Sustainable Development*, *3*, 150–160. https://api.semanticscholar.org/CorpusID:153715141

Greene, W. H. (2012). *Econometric analysis* (7th ed.). Prentice Hall.

Haggblade, S., Hazell, P. B. R., & Reardon, T. (Eds.). (2007). *Transforming the rural nonfarm economy: Opportunities and threats in the developing world*. Johns Hopkins University.

Hamed, Y. (2008). Soil structure and salinity effects of fish farming as compared to traditional farming in Northeastern Egypt. *Land Use Policy, 25*(3), 301–308. https://doi.org/10.1016/j.landusepol.2007.08.006

Hasan, M. K., Desiere, S., D'Haese, M., & Huylenbroeck, G. V. (2018). Impact of climate-smart agriculture adoption on the food security of coastal farmers in Bangladesh. *Food Security*, *10*(5), 1073–1088. https://doi.org/10.1007/s12571-018-0824-1

Hasan, M., Sutradhar, I., Shahabuddin, A., Hasan, M. M., Biswas, T., & Ahmed, S. (2017). Double burden of malnutrition among Bangladeshi women: A literature review. *Cureus*, *9*(12), e1986. https://doi.org/10.7759/cureus.1986

Headey, D. D., & Hoddinott, J. (2017). Agriculture, nutrition and the green revolution in Bangladesh. *Agricultural Systems*, *149*, 122–131. https://doi.org/10.1016/j.agsy.2016.09.001

Headey, D., Hirvonen, K., & Hoddinott, J. (2018). Animal sourced foods and child stunting. *American Journal of Agricultural Economics, 100*(5), 1302–1319. https://doi.org/10.1093/ajae/aay053

Herforth, A., & Ahmed, S. (2015). The food environment, its effects on dietary consumption, and potential for measurement within agriculture-nutrition interventions. *Food Security, 7*, 505–520. https://doi.org/10.1007/s12571-015-0455-8

Herforth, A., Arimond, M., Álvarez-Sánchez, C., Coates, J., Christianson, K., & Muehlhoff, E. (2019). A global review of food-based dietary guidelines. *Advances in Nutrition, 10*(4), 590–605. https://doi.org/10.1093/advances/nmy130

Hirvonen, K., & Hoddinott, J. (2017). Agricultural production and children's diets: Evidence from rural Ethiopia. *Agricultural Economics, 48*(4), 469–480.

HLPE. (2017). Nutrition and food systems. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome.

Hoddinott, J., & Yohannes, Y. (2002). *Dietary diversity as a food security indicator* (FCND Discussion Paper No. 136). International Food Policy Research Institute (IFPRI). https://ideas.repec.org/p/fpr/fcnddp/136.html

Hoque, M. Z., Cui, S., Lilai, X., Islam, I., Ali, G., & Tang, J. (2019). Resilience of coastal communities to climate change in Bangladesh: Research gaps and future directions. *Watershed Ecology and the Environment, 1*, 42–56. https://doi.org/10.1016/j.wsee.2019.10.001

Hossain, B., Sohel, M. S., & Ryakitimbo, C. M. (2020). Climate change induced extreme flood disaster in Bangladesh: Implications on people's livelihoods in the char village and their coping mechanisms. *Progress in Disaster Science, 6*, Article 100079. https://doi.org/10.1016/j.pdisas.2020.100079

Hossen, B., Yabar, H., & Faruque, M. J. (2022). Exploring the potential of soil salinity assessment through remote sensing and GIS: Case study in the coastal rural areas of Bangladesh. *Land, 11*(10), Article 1784. https://doi.org/10.3390/land11101784

Idrisa, Y. I., Gwary, M. M., & Shehu, H. (2008). Analysis of food security status among farming households in Jere local government of Borno State, Nigeria. *Agro-Science*, *7*(3), 124–129. https://doi.org/10.4314/as.v7i3.45552

Ignowski, L., Belton, B., Ali, H., & Thilsted, S. H. (2023). Integrated aquatic and terrestrial food production enhances micronutrient and economic productivity for nutrition-sensitive food systems. *Nature Food, 4*, 866–873. https://doi.org/10.1038/s43016-023-00840-8

Islam, A. H. M. S., von Braun, J., Thorne-Lyman, A. L., & Ahmed, A. U. (2018). Farm diversification and food and nutrition security in Bangladesh: Empirical evidence from nationally representative household panel data. *Food Security, 10*, 701–720. https://doi.org/10.1007/s12571-018-0806-3

Islam, M. S., Sallu, S. M., Hubacek, K., & Paavola, J. (2014). Vulnerability of fishery-based livelihoods to the impacts of climate variability and change: Insights from coastal Bangladesh. *Regional Environmental Change*, *14*(1), 281–294. https://doi.org/10.1007/s10113-013-0487-6

Jahan, K. M., Belton, B., Ali, H., Dhar, G. C., & Ara, I. (2015). *Aquaculture technologies in Bangladesh: An assessment of technical and economic performance and producer behavior* (Program Report No. 2015-52, p. 123). WorldFish.

Jodlowski, M., Winter-Nelson, A., Baylis, K., & Goldsmith, P. D. (2016). Milk in the data: Food security impacts from a livestock field experiment in Zambia. *World Development, 77*, 99–114.

Jones, A. D., Shrinivas, A., & Bezner-Kerr, R. (2014). Farm production diversity is associated with greater household dietary diversity in Malawi: Findings from nationally representative data. *Food Policy, 46*, 1–12.

Kabir, M. J., Alauddin, M., & Crimp, S. (2017). Farm-level adaptation to climate change in western Bangladesh: An analysis of adaptation dynamics, profitability and risks. *Land Use Policy, 64*, 212–224. https://doi.org/10.1016/j.landusepol.2017.02.026

Keding, G. B., Msuya, J. M., Maass, B. L., & Krawinkel, M. B. (2012). Relating dietary diversity and food variety scores to vegetable production and socio-economic status of women in rural Tanzania. *Food Security, 4*(1), 129–140.

Kehinde, A. D., & Ogundeji, A. A. (2023). Distributive impacts of non-farm income on output and farm income of cassava farmers in Southwestern Nigeria. *Scientific African, 19*, Article e01535. https://doi.org/10.1016/j.sciaf.2022.e01535

Khandoker, S., Singh, A., & Srivastava, S. K. (2022). Leveraging farm production diversity for dietary diversity: Evidence from national level panel data. *Agricultural and Food Economics, 10*, Article 15. https://doi.org/10.1186/s40100-022-00221-y

Kolog, J.D., Asem, F.E., & Mensah-Bonsu, A. (2023). The state of food security and its determinants in Ghana: An ordered probit analysis of the household hunger scale and household food insecurity access scale. Scientific African, 19, e01579. https://doi.org/10.1016/j.sciaf.2023.e01579

Koppmair, S., Kassie, M., & Qaim, M. (2017). Farm production, market access and dietary diversity in Malawi. *Public Health Nutrition, 20*(2), 325–335.

Kumar, N., Harris, J., & Rawat, R. (2015). If they grow it, will they eat and grow? Evidence from Zambia on agricultural diversity and child undernutrition. *The Journal of Development Studies, 51*(8), 1060–1077.

Lam, Y., Winch, P. J., Nizame, F. A., Broaddus-Shea, E. T., Harun, M. G. D., & Surkan, P. J. (2022). Salinity and food security in Southwest coastal bangladesh: Impacts on household food production and strategies for adaptation. *Food Security, 14*(1), 229–248. https://doi.org/10.1007/s12571-021-01177-5

Magurran, A. E. (2004). *Measuring biological diversity*. Blackwell Publishing. https://www.wiley.com/en-us/Measuring+Biological+Diversity-p-9780632056330

Mahfuz, M., Murray-Kolb, L. E., Hasan, S. M. T., Das, S., Fahim, S. M., Alam, M. A., Caulfield, L., & Ahmed, T. (2019). Why do children in slums suffer from anemia, iron, zinc, and vitamin A deficiency? Results from a birth cohort study in Dhaka. *Nutrients, 11*(12), Article 3025. https://doi.org/10.3390/nu11123025

Mango, N., Makate, C., Mapemba, L., & Sopo, M. (2018). The role of crop diversification in improving household food security in central Malawi. *Agriculture & Food Security, 7*, Article 7. https://doi.org/10.1186/s40066-018-0160-x

Martey, E., Al-Hassan, R. M., & Kuwornu, J. K. M. (2012). Commercialization of smallholder agriculture in ghana: A Tobit regression analysis. *African Journal of Agricultural Research*, *7*(14), 2131–2141. https://academicjournals.org/journal/AJAR/article-stat/F96A14939032

McKelvey, R. D., & Zavoina, W. (1975). A statistical model for the analysis of ordinal level dependent variables. *The Journal of Mathematical Sociology, 4*(1), 103–120. https://doi.org/10.1080/0022250X.1975.9989847

Mengistu, D. D., Degaga, D. T., & Tsehay, A. S. (2021). Analyzing the contribution of crop diversification in improving household food security among wheat dominated rural households in Sinana District, Bale Zone, Ethiopia. *Agriculture & Food Security*, *10*, 7. https://doi.org/10.1186/s40066-020-00280-8

Mitu, M. M. P., Islam, K., Sarwar, S., Ali, M., & Amin, M. R. (2022). Spatial differences in diet quality and economic vulnerability to food insecurity in Bangladesh: Results from the 2016 household income and expenditure survey. *Sustainability, 14*(9), Article 5643. https://doi.org/10.3390/su14095643

Moroda, G. T., Tolossa, D., & Semie, N. (2018). Food insecurity of rural households in Boset district of ethiopia: A suite of indicators analysis. *Agriculture & Food Security*, *7*, 65. https://doi.org/10.1186/s40066-018-0217-x

Nahar, N., Rahman, M. W., Miah, M. A. M., & Hasan, M. M. (2024). The impact of crop diversification on food security of farmers in northern Bangladesh. *Agriculture & Food Security, 13*, Article 9. https://doi.org/10.1186/s40066-023-00463-z

NIPORT, & ICF. (2024). *Bangladesh demographic and health survey 2022: National Institute of Population Research and Training and ICF. Final report*. Dhaka, Bangladesh, and Rockville.

Okezie, C. A., Sulaiman, J., & Nwosu, A. C. (2012). Farm-level determinants of agricultural commercialization. *International Journal of Agriculture and Forestry, 2*(2), 1–5. https://doi.org/10.5923/j.ijaf.20120202.01

Osmani, A. G., & Hossain, E. (2015). Market participation decision of smallholder farmers and its determinants in Bangladesh. *Economics of Agriculture*, *62*(1), 163–179. https://doi.org/10.5937/ekoPolj1501163G

Parven, A., Pal, I., Witayangkurn, A., Pramanik, M., Nagai, M., Miyazaki, H., & Wuthisakkaroon, C. (2022). Impacts of disaster and land-use change on food security and adaptation: Evidence from the delta community in Bangladesh. *International Journal of Disaster Risk Reduction, 78*, Article 103119. https://doi.org/10.1016/j.ijdrr.2022.103119

Pellegrini, L., & Tasciotti, L. (2014). Crop diversification, dietary diversity and agricultural income: Empirical evidence from eight developing countries. *Canadian Journal of Development Studies / Revue Canadienne D'études Du Développement, 35*(2), 211–227.

Pingali, P., & Sunder, N. (2017). Transitioning toward nutrition-sensitive food systems in developing countries. *Annual Review of Resource Economics, 9*, 439–459. https://doi.org/10.1146/annurev-resource-100516-053552

Powell, B., Thilstead, H., Ickowitz, S., Termote, A., Sunderland, C., T., & Herforth, A. (2015). Improving diets with wild and cultivated bioversity from across the landscape. *Food Security*, *7*, 535–554.

Rahman, K. M. M., & Islam, M. A. (2014). Nutrition-sensitive agriculture in Bangladesh: A review. *Food Security, 6*(5), 671–683. https://doi.org/10.1007/s12571-014-0380-2

Rahman, M. A., Rahman, M. S., Rahman, M. A., Szymlek-Gay, E. A., Uddin, R., & Islam, S. M. S. (2021). Prevalence of and factors associated with anaemia in women of reproductive age in Bangladesh, Maldives and Nepal: Evidence from nationally-representative survey data. *PLoS One, 16*(1), Article e0245335. https://doi.org/10.1371/journal.pone.0245335

Rahman, M. M., Chowdhury, M. M. I., Amran, A., Malik, M. I. U., Abubakar, K., Aina, I. R., Hasan, Y. A., Rahman, M. A., M. S., & Rahman, S. M. (2024). Impacts of climate change on food system security and sustainability in Bangladesh. *Journal of Water and Climate Change*, *15*(5), 2162–2187. https://doi.org/10.2166/wcc.2024.631

Rahman, M. M., Giedraitis, V. R., Lieberman, L. S., Akhtar, T., & Taminskienė, V. (2013). Shrimp cultivation with water salinity in bangladesh: The implications of an ecological model. *Universal Journal of Public Health*, *1*(3), 131–142. https://doi.org/10.13189/ujph.2013.010313

Rahman, S., Rahman, A. S., Alam, N., Ahmed, A. S., Ireen, S., Chowdhury, I. A., Chowdhury, F. P., Rahman, S. M., & Ahmed, T. (2017). Vitamin A deficiency and determinants of vitamin A status in Bangladeshi children and women: Findings of a national survey. *Public Health Nutrition, 20*(6), 1114–1125. https://doi.org/10.1017/S1368980016003049

Romeo, A., Meerman, J., Demeke, M., Scognamillo, A., & Asfaw, S. (2016). Linking farm diversification to household diet diversification: Evidence from a sample of Kenyan ultra-poor farmers. *Food Security, 8*(6), 1069–1085.

Rosegrant, M. W., & Hazell, P. B. R. (1999). *Rural Asia transformed: The quiet revolution*. International Food Policy Research Institute (IFPRI).

Roy, D., Zulfiqar, F., Tsusaka, T. W., & Datta, A. (2022). Household food insecurity and dietary diversity of women of reproductive age among smallholder farming households in Northwest Bangladesh. *Ecology of Food and Nutrition, 61*(4), 460–483. https://doi.org/10.1080/03670244.2021.2024176

Ruel, M. T., Quisumbing, A. R., & Balagamwala, M. (2018). Nutrition-sensitive agriculture: What have we learned so far? *Global Food Security, 17*, 128–153. https://doi.org/10.1016/j.gfs.2018.01.002

Saikia, D. S., & Gogoi, B. (2017). Why is agricultural diversification?—A theoretical framework. *Social Science Journal of Gargaon College, Volume V. https://gargaoncollege.ac.in/pdf/publications/1/pub_more/65.pdf*

Sarker, M. N. I., Wu, M., Alam, G. M. M., & Shouse, R. C. (2020). Life in riverine Islands in bangladesh: Local adaptation strategies of climate-vulnerable riverine Island dwellers for livelihood resilience. *Land Use Policy*, *94*, 104574. https://doi.org/10.1016/j.landusepol.2020.104574

Sekaran, U., Lai, L., Ussiri, D. A. N., Kumar, S., & Clay, S. (2021). Role of integrated crop-livestock systems in improving agriculture production and addressing food security – A review. *Journal of Agriculture and Food Research, 5*, Article 100190. https://doi.org/10.1016/j.jafr.2021.100190

Shannon, C. E. (1948). A mathematical theory of communication. *The Bell System Technical Journal, 27*(3), 379–423. https://doi.org/10.1002/j.1538-7305.1948.tb01338.x

Shively, G., & Sununtnasuk, C. (2015). Agricultural diversity and child stunting in Nepal. *The Journal of Development Studies, 51*(8), 1078–1096.

Sibhatu, K. T., Krishna, V. V., & Qaim, M. (2015). Production diversity and dietary diversity in smallholder farm households. *Proceedings of the National Academy of Sciences of the United States of America, 112*(34), 10657–10662.

SibhatuKT, & QaimM (2017). Rural food security, subsistence agriculture, and seasonality. *Plos One*, *12*(10), e0186406. https://doi.org/10.1371/journal.pone.0186406

Sraboni, E., Malapit, M. J., Quisumbing, A. R., & Ahmed, A. (2014). Women's empowerment in agriculture: What role for food security in bangladesh? *World Development*, *61*, 11–52. https://doi.org/10.1016/j.worlddev.2014.03.025

Sultan, M. T., Mahmud, U., & Khan, M. Z. (2023). Addressing soil salinity for sustainable agriculture and food security: Innovations and challenges in coastal regions of Bangladesh. *Future Foods, 8*, Article 100260. https://doi.org/10.1016/j.fufo.2023.100260

Swindale, A., & Bilinsky, P. (2006). *Household dietary diversity score (HDDS) for measurement of household food access: Indicator guide*. Food and Nutrition Technical Assistance Project, Academy for Educational Development.

Toufique, K. A., & Islam, A. (2014). Assessing risks from climate variability and change for disaster-prone zones in Bangladesh. *International Journal of Disaster Risk Reduction, 10*, 236–249. https://doi.org/10.1016/j.ijdrr.2014.08.008

Usman, M. A., & Haile, M. G. (2022). Market access, household dietary diversity and food security: Evidence from Eastern Africa. *Food Policy, 113*, Article 102374. https://doi.org/10.1016/j.foodpol.2022.102374

von Braun, J., & Kennedy, E. (Eds.). (1994). *Agricultural commercialization, economic development, and nutrition*. Johns Hopkins University.

World Bank. (2007). *From agriculture to nutrition: pathways, synergies and outcomes (English)*. World Bank. http://documents.worldbank.org/curated/en/241231468201835433

Zezza, A., & Tasciotti, L. (2010). Urban agriculture, poverty, and food security: Empirical evidence from a sample of developing countries. *Food Policy, 35*(4), 265–273.

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