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Regular Article

From soil to sustainability: A comparative dive into technical efficiency in organic and conventional vegetable production in Northeastern Bangladesh

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ABSTRACT

Organic vegetable farming is promoted in Bangladesh for its environmental sustainability and health benefits, yet concerns persist about whether it can match the technical efficiency of conventional systems without sacrificing productivity. In Sylhet district, Northeastern Bangladesh, both systems have expanded rapidly with marked variation in performance, but context-specific comparative evidence is lacking—limiting policies that must simultaneously support productivity, farmer livelihoods, and sustainability. This study addresses this critical gap. Primary data were collected from 232 vegetable farmers (116 conventional, 116 organic) using multistage sampling and structured questionnaires. Technical efficiency was estimated via stochastic frontier production function analysis. Results show organic tomato farmers achieved markedly higher technical efficiency (0.94) than conventional farmers (0.72). Conventional systems exhibited lower efficiency in gourd (0.804) and bean (0.85) production. In both systems, efficiency was significantly influenced by plot size, seed use, labor, fertilizers (organic/inorganic), integrated pest management (IPM), pesticide application, and irrigation. Technical inefficiency was further driven by education, farming experience, family size, training access, extension services, and credit availability. Overuse of irrigation, seed, and labor was common across systems. Among organic farmers, limited experience and engagement in secondary occupations increased inefficiency. These findings indicate that dedicated, experienced farmers adopting scientific organic practices can attain superior efficiency and advance sustainable vegetable production in Bangladesh.

1. Introduction

Global vegetable production has continued its strong upward trend, increasing more than threefold since the 1970s, driven by population growth, urbanization, and rising dietary awareness (FAO, 2023). In Bangladesh, vegetable cultivation has expanded significantly in recent years. According to the Bangladesh Bureau of Statistics (BBS, 2023), vegetables were cultivated on approximately 0.263–0.283 million hectares, producing over 20 million metric tons annually (including both winter and summer vegetables, horticultural estimates). Vegetables also constitute an important component of Bangladesh's agricultural exports, particularly to Middle Eastern and European markets.

Despite this growth, per capita consumption remains below recommended levels. Recent estimates suggest that daily intake in Bangladesh is around 180–200 g of vegetables and about 50–60 g of fruits per person, which still falls short of the WHO recommendation of at least 400 g of fruits and vegetables per day (WHO, 2023). To meet these nutritional standards, increasing vegetable and fruit production is essential. Vegetables play a critical role in both economic and nutritional security (Ngo et al., 2025), and farmers engaged in vegetable cultivation often earn higher incomes than those growing cereal crops. Vegetable cultivation in Bangladesh occurs primarily in two seasons: summer and winter. Key

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winter vegetables include tomato, bean, gourd, winter brinjal, cauliflower, cabbage, rabi pumpkin, radish, Bengali spinach, red amaranth, and carrot. Over time, there has been a notable increase in overall vegetable production, particularly in the yields of tomatoes, gourds, and beans.

Concurrently, the cost of growing vegetables is rising due to increasing input prices for items such as fertilizer and insecticides (Fernández et al., 2022). Bangladeshi farmers primarily rely on chemical pesticides and fertilizers, which harm the environment and soil fertility. Deterioration in the quality of natural resources and decreased crop output are the negative effects of increased usage of chemical pesticides and fertilizers. The only long-term solution to the issue and to ensure the agricultural sector's sustainability is organic farming (Irham et al., 2022). In the context of vegetable production in Bangladesh, organic farming can be defined as a system that sustains soil health, ecological balance, and human well-being by avoiding synthetic fertilizers, pesticides, growth regulators, and genetically modified organisms. It relies on locally available organic inputs, natural ecological processes, and traditional knowledge adapted to the country's agro-climatic conditions (DS, 2011). In the study area of this research, approximately 23.42% of farmers employed organic vegetable production methods during the data collection period. These organic farmers predominantly used open-pollinated traditional or locally adapted seed varieties (commonly referred to as landraces or heirloom varieties), while strictly avoiding genetically modified organisms (GMOs) and chemically treated seeds. This choice aligns with organic principles, as open-pollinated varieties enable farmers to save, select, and exchange seeds across seasons without loss of desirable traits, practices that remain widespread among farming communities in the study area and actively contribute to the preservation of local agrobiodiversity. Vegetable production in this region is seasonal and occurs primarily during the winter (Rabi) season, from mid-October to mid-March; data collection for this study was conducted during this winter production window.

Generally, organic farming prioritizes the use of renewable natural resources and recycling (Boateng et al., 2022) and involves growing crops and raising livestock without synthetic pesticides, growth hormones, or antibiotics (Boateng et al., 2022; Singla et al., 2025). On the other hand, the conventional, or inorganic, agricultural system has long been thought to produce better results than the organic approach (Gou et al., 2025). However, concerns about the long-term sustainability of conventional agriculture are pervasive today (Tal, 2018). Thus, the development of organic technologies presents important research challenges in terms of productivity and efficiency (Chouhan et al., 2025; Gadashov, 2025). Despite the growing body of international research comparing the technical efficiency of organic and conventional farming systems—with studies reporting mixed results, such as higher average technical efficiency among organic vegetable farmers in Nigeria (89.57% vs. 75.64% for conventional; Omotoso et al., 2021) in Thailand (Kramol et al., 2013), and in several European contexts (Guesmi et al., 2012; Marchand & Gao, 2014; Oude Lansink et al., 2002; Tzouvelekas et al., 2001), contrasted with lower efficiency for organic systems in parts of India (Charyulu & Biswas, 2010), Nepal (Adhikari, 2009), in Spain (Serra & Goodwin, 2009), in Italy (Madau, 2007), and Germany (Tiedemann & Latacz-Lohmann, 2013)—empirical evidence remains limited in Bangladesh. Recent reviews confirm that organic farming offers clear benefits for soil health, food safety, and environmental sustainability in Bangladesh, yet they also document persistent yield gaps of 5–34% and major adoption barriers without providing rigorous technical efficiency comparisons (Hossain et al., 2025). Existing national studies on vegetable production efficiency (e.g., Hasan, Islam, Kameyama, & Bau, 2020 on bean, brinjal, and tomato) have focused primarily on conventional systems or overall profitability and have not examined organic–conventional differences using stochastic frontier analysis, nor have they delivered crop-specific insights (such as for tomato, gourd, or bean) or identified sources of inefficiency with recent data.

This absence of context-specific, comparative technical efficiency research for organic vegetable farming in Northeastern Bangladesh constrains evidence-based policies aimed at scaling sustainable practices while safeguarding productivity and farmer livelihoods. To address this gap, the present study poses the following research question: Do the technical efficiency levels differ between conventional and organic vegetable farming practices in the study area of Bangladesh?

2. Methodology

2.1. Description of the study area

The study was carried out in the Sylhet district, situated in the northeastern region of Bangladesh. Over the last decade, vegetable cultivation in this area has grown rapidly. Sylhet features a typical tropical monsoon climate, characteristic of Bangladesh, with a humid subtropical climate in its higher elevations. Agriculture serves as the main livelihood in the area, encompassing both crop production and livestock rearing. The major crops cultivated include rice, maize, and a variety of vegetables. Fig. 1 presents the map of the study area.

2.2. Sampling procedure and sample size

Sylhet district was purposively selected from Northeastern Bangladesh because of its substantial contribution to national vegetable output. Within the Sylhet district, *Sylhet Sadar Upazila* (sub-administrative district) was chosen for having the highest concentration of both organic and conventional vegetable farmers. The study focused on three key winter vegetables—tomato, gourd, and bean—selected for their high production intensity, economic importance to smallholder farmers, wide agro-ecological adaptability, and contrasting input requirements, which make them particularly suitable for comparative technical efficiency analysis.

A multistage random sampling procedure was employed to select 232 vegetable farmers (116 organic and 116 conventional). In the first stage, four unions were randomly selected from the 13 unions of *Sylhet Sadar Upazila*. In the second stage, six villages were randomly selected from these four unions. With the assistance of the *Upazila Agriculture Office (UAO)*, complete lists of vegetable farmers cultivating tomato, gourd, or bean during the 2022–2023 winter season were compiled for the selected villages. These lists constituted the sampling frame for both farming systems.

For organic farmers, the sampling frame contained 164 growers (certified or practicing organic methods as verified by UAO records and self-identification). Sample size was determined using Yamane's (1967) formula with a 5% margin of error:

$$n = \frac{N}{1 + N \times e^2} = \frac{164}{1 + 164 \times 0.05^2} \approx 116$$

Thus, 116 organic farmers were selected through simple random sampling.

For conventional farmers, the sampling frame comprised 749 growers in the same six villages. Although the above formula indicated a required sample size of approximately 260, an equal sample of 116 conventional farmers was drawn by following the same sampling strategy mentioned above for organic farmers. This equal-sample-size design was deliberately adopted to ensure direct methodological comparability between the two groups in the stochastic frontier analysis, to maintain balanced statistical power, and to respect practical constraints of time, budget, and enumerator availability. The final sample was further stratified by crop (tomato, gourd, and bean) to guarantee proportional representation across the three vegetables (Table 1).

2.3. Data collection

Primary quantitative data were collected through face-to-face

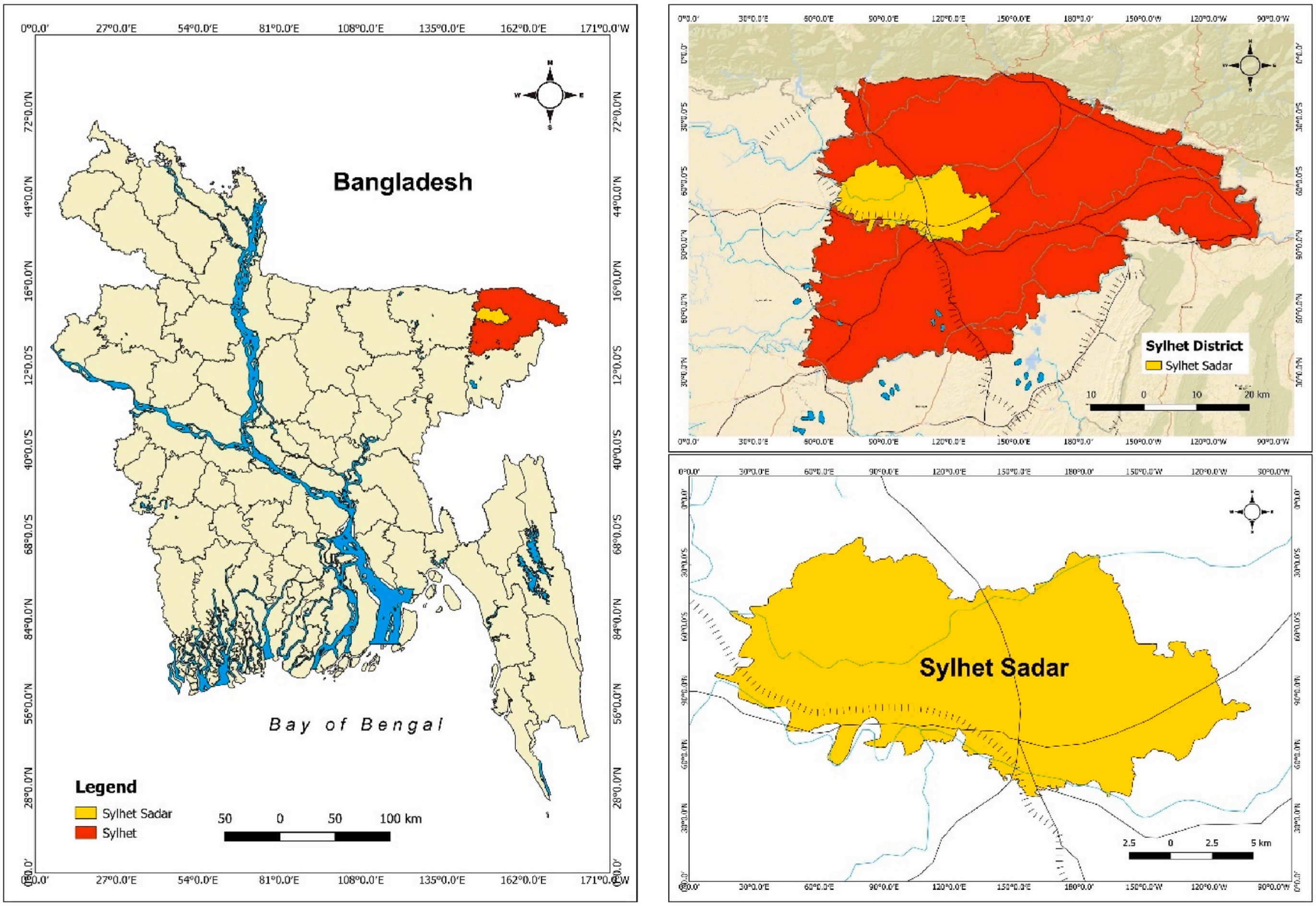

Fig. 1. Map of the study area.

Table 1
Distribution of respondents by farming system and crop.

Crop	Organic (no. of farms)	Conventional (no. of farms)	Total
Tomato	46	46	92
Gourd	32	32	64
Bean	38	38	76
Total	**116**	**116**	**232**

interviews using a structured questionnaire. The questionnaire was designed to capture detailed farm-level input and output quantities, socioeconomic characteristics of the household, and institutional factors relevant to technical efficiency. To ensure data quality, reliability, and replicability, the following procedures were followed:

The questionnaire was developed after a thorough review of the stochastic frontier literature and was reviewed by agricultural economists and local extension officers for content validity. A pilot study was conducted in January 2023 with 20 vegetable farmers (10 organic and 10 conventional) from a non-sample village in *Sylhet Sadar Upazila*. The pilot tested question clarity, cultural appropriateness, recall accuracy, and response burden. Feedback from the pilot led to minor revisions in wording, sequencing, and units of measurement. No major changes to core variables were required. Six trained enumerators (three male, three female) fluent in the local dialect conducted the interviews under close supervision. All interviews were carried out in Bengali. The main survey was conducted from late March to April 2023, corresponding to the late-harvest and immediate post-harvest period of the 2022–2023 winter vegetable season (mid-October 2022 to mid-March 2023). This timing enabled farmers to provide an accurate recall of all inputs used and yields obtained for the completed season. Completed questionnaires were checked daily for completeness and internal consistency. Any discrepancies were resolved by re-contacting the respondent within 48 h. These steps ensured high data reliability and full replicability of the survey process.

2.4. Description of variables and measurement

All variables were measured at the individual farm level for the specific vegetable crop (tomato, gourd, or bean) grown during the 2022–2023 winter season and were standardized to a per-hectare basis prior to analysis. This standardization eliminates scale effects arising from differences in plot size and permits direct comparison of technical efficiency across farmers and between farming systems in the Cobb–Douglas stochastic frontier model.

Dependent variable (output, Y_i): Total yield of the specific vegetable (tomato, gourd, or bean) harvested from the farmer's plot during the winter season, expressed in kilograms per hectare (kg/ha).

Independent variables (inputs):

- **Plot size (X_1)**: Area devoted to the specific vegetable during the winter season, recorded in hectares (ha). Farmers reported plot size in local units (decimals); these were converted using the standard factor 1 ha = 247 decimals.
- **Tillage cost (X_2)**: Total cost of land preparation in Bangladeshi Taka per hectare (BDT/ha). Farmers reported the number of ploughings (times) and the prevailing cost per ploughing; total cost was calculated as number of ploughings × cost per ploughing per hectare.

- **Seed (X_3)**: Quantity of seed used, measured in kilograms per hectare (kg/ha). Farmers reported seed quantities in grams or kilograms for their plot; all values were converted to kg/ha.
- **Labor (X_4)**: Total labor input (family + hired) measured in man-days per hectare (man-days/ha). One man-day was defined as 8 h of work. Both family and hired labor were recorded and included in the production function as physical input quantity.
- **Fertilizer (X_5)**: Total quantity of organic soil amendments (cow-dung manure, vermicompost, quick compost, crop residues, green manure, etc.) applied, measured in kilograms per hectare (kg/ha). Total quantity of chemical fertilizers (urea, triple superphosphate [TSP], muriate of potash [MoP], gypsum) applied, measured in kilograms per hectare (kg/ha). Quantities of individual fertilizer types were recorded separately during the interview and aggregated for the production function.
- **Irrigation (X_6)**: Total irrigation cost in Bangladeshi Taka per hectare (BDT/ha) for tomato and bean. For gourd, which is frequently grown with supplementary canal or rain-fed irrigation, farmers reported the number of irrigations (times); these were converted to approximate cost (BDT/ha) using average local water charges. In the final model specification, irrigation entered uniformly as cost (BDT/ha) to maintain consistency across all three crops.
- **Pest management (X_7)**: Two distinct measures were used to reflect system-specific practices. For organic farmers, Integrated Pest Management (IPM) intensity was recorded as the number of IPM applications or practices adopted during the season (times/ha). Then converted it into cost (BDT/ha). For conventional farmers, the volume of synthetic pesticides applied was recorded in liters per hectare (L/ha). Then converted it into cost (BDT/ha).
- **Bamboo cost (X_7)**: Total bamboo cost per hectare of land (BDT/ha), used for fencing and supporting vegetable plants.

All monetary values were recorded in current (2023) prices. Outliers and missing values were verified and corrected through follow-up telephone calls with respondents. This transparent, standardized measurement protocol minimizes measurement error and ensures full replicability of the stochastic frontier estimation.

2.5. Theoretical framework and empirical methods

Farm efficiency can be assessed using either parametric or non-parametric approaches. Among these, non-parametric methods such as "Data Envelopment Analysis (DEA) are the most widely applied. DEA employs linear programming techniques to construct a non-parametric, piecewise frontier that represents the most efficient level of production, enclosing the observed input–output data. Production inefficiency is then measured as the deviation of each observation from this efficient frontier (Asodina et al., 2021). Because random errors occur alongside non-negative random effects linked to production inefficiency, the Stochastic Frontier Analysis (SFA) is widely regarded as a more suitable method for evaluating efficiency and productivity in agricultural production (Aigner et al., 1977). Therefore, this study adopts the SFA approach to examine the efficiency of both conventional and organic vegetable farmers. To empirically assess the technical efficiency of vegetable production, this study estimates the general stochastic frontier production model and adopts the technical inefficiency model proposed by Battese and Coelli (1995). Given the relatively small sample size, the Cobb–Douglas production function is considered more suitable than the translog function. Moreover, the Cobb–Douglas model remains widely applied in empirical research because of its analytical simplicity and ease of interpretation (Begum et al., 2023; Islam et al., 2023).

Following Battese (1992), the Cobb–Douglas stochastic production frontier used to examine the technical efficiency of vegetable production in the study area is specified as follows:

$$Y_i = f\ (X_i,\ \beta)\ \exp(\varepsilon_i) = f\ (X_i,\ \beta)\ \exp(V_i\text{- } U_i) i = 1,\ 2,\ 3\ \ldots.N$$

Where Y_i represents the observed output of the ith sampled farm, $f(X_i, \beta)$ denotes an appropriate functional form, and β is a vector of unknown parameters to be estimated. The error term ε_i consists of two components: V_i and U_i. The term V_i is a random error with zero mean, capturing random factors beyond the farmer's control—such as topography, weather variations, measurement errors, and supply disruptions—and is assumed to be independently and identically distributed as $N(0, \delta_v^2)$, independent of U_i. In contrast, U_i is a non-negative random variable representing technical inefficiency, which lies under the farmer's control. It is assumed to follow an independently and identically distributed non-negative truncation of the $N(0, \delta^2)$ distribution and is independent of V_i.

The technical efficiency of an individual farm can be defined as the ratio of the actual (observed) output to the potential (frontier) output, given the existing technology. Accordingly, the technical efficiency of a farmer is expressed as:

$$\text{Technical efficiency (TE)} = \frac{Y_i}{Y_i^*} = \frac{f\ (X_i, \beta)\ exp(V_i - U_i)}{f(X_i, \beta) exp\ V_i} = \exp(-\mathrm{U_i})$$

where Y_i is the observed output and Y_i^* is the frontier output.

Since U_i represents a non-negative random variable capturing technical inefficiency—an element influenced by the farmer's management and decision-making—the factors contributing to this inefficiency can be expressed as:

$$\mathrm{U_i} = \gamma_0 + \sum_{j=1}^{j} \gamma_j Z_{ij} + \varepsilon$$

Here, γ represents the parameters, and Z_i denotes the socio-economic and other farm-specific factors under the farmer's control that influence efficiency. The variance parameters are defined as:

$$\delta^2 = \delta_v^2 + \delta_v^2\ \gamma = \frac{\delta_u^2}{\delta}$$

The specified Cobb-Douglas stochastic production frontier (SPF)" model for both organic and conventional vegetable production is given by.

$$\ln \mathrm{Y_i} = \beta_0 + \sum_{j=1}^{n} \beta_j lnX_{ji} + \mathrm{V_i} - \mathrm{U_i}$$

where, Y_i = vegetables production (Kg/ha); X_{1i} = Plot size (Ha), X_{2i} = Tillage cost (BDT/ha) X_{3i} = Seed (kg/ha), X_{4i} = Labor (man-days/ha), X_{5i} = Fertilizer (Kg/ha), X_{6i} = Irrigation cost (BDT/ha), X_{7i} = Pesticides cost (BDT/ha), X_{8i} = Bamboo cost (BDT/ha), β_0 = Constant, β_i = Coefficient of parameter, j = 1, … … … … ….,7, V_i is an independently and identically distributed random error term, while U_i is a non-negative variable representing technical inefficiency in production. The technical inefficiency effects (U_i) are specified, following Coelli (1995), as:

$$\mathrm{U_i} = \delta_0 + \delta_j\ \mathrm{Z_i}$$

Where Z_1 = Years of schooling, Z_2 = Subsidiary profession, Z_3 = Family size (number of members), Z_4 = Experience in organic/conventional vegetable farming (years), Z_5 = Distance to the nearest market (km), Z_6 = Agricultural training dummy (1 if the farmer received training, 0 otherwise), Z_7 = Extension contact dummy (1 if the farmer had contact with an extension worker, 0 otherwise), Z_8 = Credit dummy (1 if the farmer received any credit, 0 otherwise), δ_0 = Constant term, and δ_j = Parameters to be estimated.

3. Results and discussion

3.1. Socioeconomic characteristics of organic and conventional vegetable farmers

Table 2 presents a summary of the demographic characteristics of tomato, gourd, and bean farmers, along with key statistical information on the variables used in the technical efficiency models. Summary statistics of output, input, and socio-economic variables for organic and conventional tomato farmers reveal notable differences in input costs and production across tomato, gourd, and bean growers (Table 2).

The average yield for organic tomato farmers was 20,362 kg/ha, compared to 23,612 kg/ha for conventional farmers. Human labor emerged as a major cost driver in both systems. Labor use, measured in man-days per hectare (1 man-day = 8 h), was slightly lower for organic farming (235 man-days/ha) than for conventional (240 man-days/ha), indicating modest labor savings in planting, pest control, and soil preparation. Fertilizer use differed markedly: organic farms applied 3362 kg/ha of compost and manure, while conventional farms used 1480 kg/ha of synthetic fertilizer. Among the socioeconomic characteristics, organic tomato farmers reported higher average years of schooling (8.48 years) compared to their conventional counterparts (7.9 years). Household size was also slightly larger among organic farmers, with an average of 8 members versus 7.2 members for conventional farmers. On average, organic farmers had 10.57 years of experience in organic cultivation, nearly half of their total vegetable farming experience of 17.5 years—indicating a gradual transition from conventional to organic practices. Additionally, access to training was significantly higher among organic farmers (71.7%) compared to conventional farmers (41.3%).

For gourd farmers, the results indicated that average yields were 20,890 kg per hectare for conventional farmers and 19,067 kg per hectare for organic farmers. These findings are consistent with those of Islam et al. (2015), who reported yields of 22,680 kg/ha for organic and 21,060 kg/ha for conventional gourd production. In Bangladesh, where resource scarcity and inefficient farming practices persist, monitoring productivity is essential to enhance efficiency and ensure sustainable agricultural development (Hoque et al., 2019). Seed usage—an input that directly influences output—was higher in organic farming (10.906 kg/ha) compared to conventional methods (7.875 kg/ha). Organic gourd farmers also applied more fertilizer, using 2488.7 kg/ha of compost and manure, versus 1510 kg/ha of synthetic fertilizer by conventional farmers. Pesticide use was significantly higher among conventional farmers than organic farmers, a difference well-supported by Islam et al. (2015).

Organic gourd farmers reported a higher average level of education (8.72 years) compared to their conventional counterparts (6.43 years), contrasting with Kucinska et al. (2009), who found that organic farmers were generally less educated. On average, organic farmers had 5.03 years of experience in organic cultivation, indicating that many had recently transitioned from conventional practices. Vegetable farming was their main occupation, while livestock rearing and fish cultivation served as secondary sources of income. Notably, 54.5% of organic farmers kept cattle, likely driven by the need for organic inputs, whereas 62.5% of conventional farmers engaged in alternative livelihood activities. In terms of institutional support, organic gourd farmers had greater access to extension services, with 75% reporting engagement, compared to their conventional counterparts.

In terms of bean producers, the mean total yield was 19,281.74 kg/ha for organic farmers and 24,396.93 kg/ha for conventional farmers. This aligns with Begum et al. (2023), who reported a yield of 22,855 kg/ha for conventional bean production in the Narsingdi district of Bangladesh. The average farm sizes for organic and conventional farmers were 0.22 ha and 0.19 ha, respectively. Organic bean producers used more seeds (6.89 kg/ha) than their conventional counterparts (6.29 kg/ha). Tillage cost was higher among conventional farmers compared to organic farmers. Organic farmers used only manure (2284.53 kg/ha) as fertilizer, whereas conventional farmers relied on both chemical fertilizers and manure. Average irrigation costs were slightly higher for conventional farming than for organic farming. Socioeconomic factors such as education, farming experience, distance to markets, secondary occupations, training, and access to credit significantly influence farmers' efficiency. Both organic and conventional bean farmers had education levels around the high school level, though organic farmers were generally more educated, suggesting that higher education may be linked to greater interest in organic farming. Conventional farmers had more farming experience (9.42 years) compared to organic farmers (4.63 years). However, organic farmers had better access to agricultural training (63.2%) and credit facilities (68.4%), which can play a crucial role in enhancing their efficiency and adoption of sustainable practices.

Table 2
Socioeconomic characteristics of tomato, gourd, and bean farmers (per hectare).

Variables	Mean (S.D)					
	Tomato		Gourd		Bean	
	Organic	Conventional	Organic	Conventional	Organic	Conventional
Yield (Kg/ha)	20362 (3774)	23611 (7632)	19066 (3636)	20889 (5912)	19281 (3132)	24396 (1904)
Plot size (ha)	0.3 (0.14)	0.27 (0.08)	0.2 (0.1)	0.2 (0.1)	0.2 (0.1)	0.2 (0.1)
Tillage cost (BDT/ha)	4526.02 (7.11)	4573.19 (5.79)	-	-	4776.87 (9.29)	4978.95 (6.76)
Seeds (Kg/ha)	0.217 (0.941)	0.208.85 (0.125)	10.9 (4.0)	7.9 (3.5)	6.89 (3.4)	6.29 (2.38)
Labor (Man-days/ha)	235 (44)	240 (47)	-	-	-	-
Organic/Inorganic fertilizer (Kg/ha)	3362 (1109)	1480 (596)	2488 (692)	1509 (337)	2284 (578)	2328 (551)
Pest management cost (BDT/ha)	3900 (6.95)	4225 (4.62)	-	-	4377(4.89)	4890 (6.29)
Bamboo cost (BDT/ha)	7010 (2264)	16524 (2447)	7695 (2452)	7968 (1801)	-	-
Irrigation cost (BDT/ha)	18222 (2225)	17774 (2729)	3200 (7.55)	3550 (7.20)	7797 (2227)	7867 (1732)
Year of schooling (Years)	8.5 (1.41)	7.9 (2.19)	8.7 (2.6)	6.4 (1.4)	8.9 (2.0)	7.6 (2.1)
Family size	8.0 (2.19)	7.2 (1.85)	-	-		
Experience in farming (Years)	10.6 (5.1)	17.50 (6.85)	5.0 (2.4)	14.4 (4.3)	4.6 (2.4)	9.42 (4.1)
Distance to nearest market (Km)	4.3 (1.63)	5.17 (1.94)	4.8 (1.8)	4.5 (1.2)	3.9 (1.6)	5.9 (1.8)
	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)
Access to training (1 = yes)	33 (71.7)	19 (41.3)	-	-	24 63.2)	20 (52.6)
Subsidiary profession (1 = livestock)	-	-	18 54.5)	1 (3.1)	19 (50)	17 (44.7)
Subsidiary profession (2 = Fishing)	-	-	10 30.3)	11 (34.4)	8 (21.1)	12 (31.6)
Subsidiary profession (3 = Others)	-	-	4 (12.1)	20 (62.5)	11 (29)	9 (23.7)
Access to extension service (0 = no)	-	-	8 (25.0)	14 (42.4)	-	-
Access to credit (1 = yes)	-	-	-	-	26(68.4)	21(55.3)

Source: Authors' estimation. Note: BDT is the Bangladeshi currency (Taka). 1 BDT is equivalent to 0.0082 USD (as of July 18, 2025). S.D means Standard deviation.

3.2. Production frontier estimates: Key inputs and cross-system patterns

The Cobb–Douglas stochastic frontier estimates (Table 3) reveal both common and system-specific drivers of vegetable yields. Across all three crops and both farming systems, plot size and fertilizer application (organic or inorganic) consistently show positive and significant coefficients. A 1% increase in plot size raises output by 0.47–1.12%, reflecting economies of scale and more uniform management on larger holdings. Fertilizer elasticity is positive and significant in five of the six models, confirming that nutrient management remains critical even in organic systems where compost and manure substitute for synthetic sources. These patterns align with the broader literature on smallholder vegetable production in South Asia (Haq, 2013; Begum et al., 2023).

Labor and irrigation display more heterogeneous effects. Labor is positive and significant for organic tomato and conventional tomato, but negative and significant for organic bean (−0.301). The negative labor coefficient in organic bean production is counterintuitive yet plausible in the Bangladeshi context. Organic bean cultivation is highly labor-intensive (manual weeding, staking, and frequent monitoring), yet many smallholders rely on unpaid family labor whose marginal productivity declines rapidly once basic tasks are completed. Additional labor may therefore reflect disguised unemployment or misallocation rather than productive intensification. Similar diminishing returns to labor have been documented in labor-abundant organic systems elsewhere (Madau, 2007; Oladeji et al., 2017). In contrast, conventional systems can substitute chemical weed control and mechanized operations, rendering extra labor less critical.

Irrigation cost is positive for organic tomato and conventional gourd but negative and significant for both organic and conventional bean. Beans are highly sensitive to waterlogging during the cool, low-rainfall winter season in Bangladesh. Excessive or poorly timed irrigation raises costs while damaging roots and reducing pod set. This finding contrasts with Begum et al. (2023), who reported positive irrigation effects for conventional beans; the difference likely stems from regional variation in drainage infrastructure and farmer water-management skills. In poorly drained fields typical of parts of Sylhet, higher irrigation expenditure often signals inefficient water use rather than beneficial input.

Seed use and tillage produce several counterintuitive negative coefficients. Seed quantity is negative and significant in conventional tomato (−0.099), organic gourd (−0.431), and conventional bean (−0.083). These results are consistent with Begum et al. (2023) for beans in Bangladesh and reflect widespread overuse. Farmers frequently apply 20–40% more seed than recommended because of poor germination rates of locally available or subsidized seed, risk aversion, and lack of extension guidance on optimal plant density. Over-seeding leads to overcrowding, nutrient competition, and lower individual plant productivity. Tillage cost is positive for conventional tomato and bean but insignificant or negative elsewhere, suggesting that the productivity gains from additional tillage are quickly exhausted once basic seedbed preparation is achieved.

Bamboo cost (staking) is strongly positive for organic tomato and gourd, underscoring the importance of physical support structures that improve light interception and reduce disease in organic systems that cannot rely on prophylactic fungicides. Bio-pesticide use shows positive elasticities in organic systems, confirming the effectiveness of integrated pest management when properly implemented (Hoque et al., 2019).

3.3. Technical efficiency levels: Magnitude and economic implications

Mean technical efficiency (TE) differs markedly across crops and systems (Table 4). Organic tomato farms achieve the highest average TE (0.94), substantially outperforming conventional tomato farms (0.72). This 0.22-point gap implies that, on average, conventional tomato farmers could increase output by 28% using the same input bundle, while organic farmers operate only 6% below the frontier. In economic terms, closing the conventional tomato efficiency gap would raise gross margins by an estimated 18–25% (assuming constant input prices and modest output price effects), directly improving household income and food security. The 82.6% of organic tomato farms operating at TE ≥ 0.90 demonstrate that well-managed organic systems can achieve near-frontier performance even with lower external input intensity.

For gourd, mean TE is statistically indistinguishable between systems (organic 0.786, conventional 0.804), yet both groups could raise output 20–22% through better input allocation. Bean production shows the reverse pattern: conventional farms (0.85) outperform organic farms (0.80). The 0.05-point advantage for conventional bean producers translates into approximately 6% higher potential output, sufficient to offset the yield penalty often associated with organic conversion in legumes.

These TE differentials are consistent with the mixed international evidence but require contextual explanation. Organic tomatoes' superior efficiency mirrors Oude Lansink et al. (2002) in Finland and Omotoso et al. (2021) in Nigeria, where organic systems benefit from lower input costs and premium prices that reward careful management. Conversely, the higher conventional efficiency in bean production aligns with Madau (2007) in Italy and Charyulu and Biswas (2010) in India, where conventional farmers exploit scale economies and synthetic inputs more effectively for crops with tight quality specifications. The crop-specific reversal in Sylhet likely reflects differences in input substitutability:

Table 3
Maximum likelihood estimates of parameters of the Cobb-Douglas production frontier model for tomato, gourd, and bean cultivation.

Variable	Coefficient (t-value)					
	Tomato		Gourd		Bean	
	Organic	Conventional	Organic	Conventional	Organic	Conventional
Intercept	5.98*** (7.58)	5.211*** (6.271)	10.363*** (8.761)	8.549*** (8.513)	12.332*** (15.376)	10.148*** (24.443)
Plot size	0.472* (1.938)	−0.738** (−2.165)	0.751*** 6.046(.)	0.548*** (2.823)	1.116*** (9.548)	0.885*** (7.233)
Tillage cost	−0.136 (−1.285)	0.353** (2.095)	−0.311 (−0.959)	0.034 (0.359)	−0.102 (−1.192)	0.092* (1.659)
Seeds	0.083 (1.139)	−0.099*** (−2.804)	−0.431*** (−4.544)	−0.009 (−0.078)	0.159 (1.451)	−0.083** (−2.208)
Fertilizer	0.003 (0.048)	0.159** (1.953)	0.665*** (5.312)	0.168* (1.675)	0.177** (2.201)	0.179* (1.959)
Labor	0.204* (1.73)	0.855*** (5.842)	0.133 (0.041)	−0.227 (−0.929)	−0.301** (−2.266)	0.032 (0.381)
Pesticide	0.137 1.562(.)	0.479** (2.53)	0.245*** (2.663)	0.073 (0.605)	0.294*** (3.415)	0.065** (2.473)
Bamboo cost	0.254*** (3.892)	−0.008 (−0.079)	0.431** (2.391)	0.015 (0.162)	-	-
Irrigation cost	0.133** (2.091)	0.889 (1.167)	0.178 (0.369)	0.207* (1.646)	−0.216** (−1.993)	−0.103*** (−3.326)
σ^2	0.019*** (5.452)	0.009*** (4.919)	0.063*** (9.231)	0.027*** (5.631)	0.016*** (5.685)	0.025*** (4.089)
Υ	0.147*** (4.65)	0.999*** (237.443)	0.999*** (1120.01)	0.999*** (68.67)	0.99*** (966.635)	0.999*** (43.192)
Log likelihood function	117.398	75.87	97.05	91.83	129.793	109.561

Source: Authors' estimation based on field survey, 2023; *, **, and *** indicate significance at $p < 0.10$, $p < 0.05$, and $p < 0.01$, respectively.

Table 4
Distribution of technical efficiency score.

Technical efficiency score	Frequency (Percent)					
	Tomato		Gourd		Bean	
	Organic	Conventional	Organic	Conventional	Organic	Conventional
<0.50	-	-	2 (6.3)	0 (0)	-	-
0.50-0.59	0 (0)	4 (8.7)	4 (12.5)	1 (3.1)	2 (5.3)	0 (0)
0.60-0.69	0 (0)	14 (30.4)	2 (6.3)	6 (18.8)	4 (10.5)	0 (0)
0.70-0.79	2 (4.3)	21 (45.7)	8 (25.0)	9 (.)	11 (28.9)	9 (23.7)
0.80-0.89	6 (13)	4 (8.7)	6 (18.8)	10 (.)	11 (28.9)	18 (47.4)
0.90- 1.00	38 (82.6)	3 (6.5)	10 (31.3)	6 (18.8)	10 (26.3)	11 (28.9)
Mean	0. 94	0.72	0.786	0.804	0.80	0.85
Min	0.70	0.55	0.33	0.55	0.56	0.72
Max	1.00	0.99	0.99	0.99	0.99	0.99
Std. Dev.	0. 0689	0.0988	0.166	0.124	0.10	0.07

Source: Authors' estimation

tomato responds strongly to organic practices (compost, staking, IPM), while bean's sensitivity to water and nutrient timing favors conventional chemical control. Methodological differences (Cobb–Douglas vs. translog, cross-section vs. panel) and agro-ecological conditions (winter vs. summer cropping, irrigation reliability) further explain divergence across studies.

3.4. Determinants of technical inefficiency

In the technical inefficiency model (Table 5), a negative coefficient reduces technical inefficiency and therefore raises efficiency, while a positive coefficient increases inefficiency. This sign convention is maintained consistently throughout the discussion.

Education exhibits contrasting effects. In organic tomato production, years of schooling increase inefficiency (positive coefficient 0.048). Educated farmers in the study area frequently treat vegetable farming as a secondary activity or maintain urban employment linkages, resulting in lower on-farm supervision and greater reliance on hired labor whose effort is imperfectly monitored. This finding echoes Oladeji et al. (2017) in Nigeria and reflects the broader Bangladeshi reality that secondary and tertiary education often signal intent to exit full-time agriculture. In contrast, schooling reduces inefficiency in conventional gourd and bean systems, consistent with Haq (2013) and Murthy et al. (2009): literate conventional farmers more readily adopt recommended fertilizer doses, pesticide schedules, and market information.

Farming experience generally improves efficiency (negative coefficients) in organic tomato, conventional tomato, and organic bean, confirming that accumulated tacit knowledge enhances input allocation and risk management (Ogunmola et al., 2021; Bozoğlu & Ceyhan, 2007). The anomalous positive coefficient for organic gourd experience may indicate path dependence: long-term organic gourd growers in Sylhet have been slow to adopt newer bio-pesticide formulations or improved staking techniques.

Institutional variables show clear policy relevance. Access to training and credit consistently reduces inefficiency where significant (conventional tomato, conventional bean), supporting the findings of Hoque et al. (2019) and Balogun et al. (2018). Each additional training event or loan access lowers the inefficiency index by 0.06–0.10 points, implying meaningful efficiency gains from modest public investment. Extension contact, however, is positively associated with inefficiency in organic gourd, suggesting either adverse selection (less efficient farmers seek more advice) or limited effectiveness of current extension messages for organic practices—patterns also noted by Abate et al. (2019).

Subsidiary occupation raises inefficiency in organic gourd and both bean systems, confirming that off-farm employment dilutes managerial attention (Bashir, 2016). Distance to market increases inefficiency for organic tomato (logistical constraints on timely input purchase) but reduces inefficiency for organic gourd, possibly because more remote farmers face stronger incentives to optimize scarce purchased inputs.

4. Conclusion and policy implications

This study provides the first crop-specific comparison of technical efficiency between organic and conventional vegetable farming in Sylhet, Northeastern Bangladesh, using stochastic frontier analysis for tomato, gourd, and bean—the three most important winter vegetables in the region. The results reveal a nuanced pattern rather than a uniform advantage for either system. Organic tomato farms achieve markedly

Table 5
Maximum likelihood estimates of parameters of the technical inefficiency effect model for tomato, gourd, and bean cultivation.

Variable	Coefficient (t-value)					
	Tomato		Gourd		Bean	
	Organic	Conventional	Organic	Conventional	Organic	Conventional
Intercept	−0.401 (−0.924)	0.632*** (5.729)	−0.594 (−1.525)	0.54* (1.916)	0.684*** (2.894)	0.368*** (4.191)
Year of schooling	0.048* (1.692)	−0.014 (−1.18)	0.024 (0.892)	−0.023* (−1.728)	−0.017 (−1.098)	−0.037*** (−3.471)
Subsidiary profession	−0.051 (−0.707)	0.013 (0.0568)	0.365*** (3.258)	0.006 (0.101)	0.059** (2.164)	0.027** (2.316)
Family size	−0.01 (−0.561)	−0.013* (−1.673)	0.006 (0.215)	0.003 (0.139)	−0.007 (−0.515)	−0.001 (−0.217)
Experience in organic/conventional vegetable farming	−0.033*** (−11.424)	−0.072*** (−2.675)	0.107*** (24.998)	0.007 (0.291)	−0.056*** (−4.659)	0.007 (1.305)
Distance	0.108*** (4.348)	0.005 (0.566)	−0.207*** (−5.573)	−0.041* (−1.668)	−0.013 (−0.506)	0.017** (2.139)
Access to training	−0.018 (−0.262)	−0.063* (−1.649)	0.028 (0.185)	−0.046 (−0.483)	−0.082 (−1.229)	−0.069*** (−2.702)
Access to extension service	−0.052 (−0.508)	0.637 (0.149)	0.585*** (23.901)	0.196* (1.701)	−0.102 (−0.983)	−0.039 (−0.816)
Access to credit	0.054 (0.338)	−0.0005 (−0.001)	−0.297 (−1.545)	−0.116 (−1.162)	−0.039 (−0.615)	−0.101*** (−4.567)

Source: Author's estimation based on field survey, 2023. Note: *, ** and *** indicate significance at $p < 0.10$, $p < 0.05$ and $p < 0.01$ respectively higher technical efficiency (0.94) than conventional farms (0.72), indicating that well-managed organic practices can outperform conventional methods for high-value, input-responsive crops. In contrast, conventional systems show modest efficiency advantages for gourd (0.804 vs. 0.786) and bean (0.85 vs. 0.80). These crop-specific differences arise because tomato responds strongly to organic practices such as staking, compost application, and integrated pest management, which improve plant health and reduce disease pressure. Bean and gourd, however, are more sensitive to precise water and nutrient timing, where conventional chemical inputs currently offer greater control and lower risk of waterlogging or nutrient imbalance under Northeastern Bangladesh's winter conditions.

The academic contribution of this study lies in demonstrating that the relative efficiency of organic versus conventional farming is not universal but contingent on crop physiology, input substitutability, and local agro-ecological conditions, findings that help reconcile contradictory results reported across countries and farming systems. Economically, the 0.22-point efficiency gap in tomato implies that conventional farmers forgo approximately 28% of potential output (equivalent to BDT 18,000–25,000 per hectare annually at 2023 prices), while even small improvements in organic bean and gourd efficiency could raise household incomes by 15–20% without additional inputs.

To translate these findings into practice, we recommend the following targeted, evidence-based interventions:

- **Address input overuse:** Implement mandatory short training modules on optimal seed rates and plant spacing for all three crops, directly targeting the significant negative seed coefficients observed across conventional tomato, organic gourd, and conventional bean models. Similar focused training on labor allocation and task prioritization should be introduced for organic bean farmers to reduce the negative labor elasticity.
- **Crop-specific irrigation management:** Develop and disseminate simple irrigation scheduling guidelines for bean cultivation, emphasizing timing and volume to prevent waterlogging—the primary driver of the negative irrigation coefficients in both organic and conventional bean models.
- **Strengthen organic-specific extension:** Expand extension services with dedicated modules on compost quality testing, bio-pesticide application timing, and staking techniques for organic tomato and gourd producers, addressing the currently positive (inefficiency-increasing) extension coefficient in organic gourd.
- **Enhance access to credit and quality inputs:** Provide seasonal credit linked to verified seed and organic fertilizer purchases, combined with subsidies for high-germination seed varieties, to reduce compensatory over-seeding and improve input quality.
- **Promote experience-based learning platforms:** Establish farmer field schools that pair experienced organic tomato growers (who demonstrate the highest efficiency) with less efficient organic bean and gourd farmers to facilitate peer learning, capitalizing on the strong positive effect of farming experience on efficiency in most models.

5. Limitations of the study and further research

This study has several limitations that should be considered when interpreting the results. First, the analysis is based on cross-sectional data from a single winter season (2022–2023). This design prevents the examination of temporal dynamics, learning effects, or the impact of weather shocks and price fluctuations on technical efficiency over time. Second, the study was conducted only in *Sylhet Sadar Upazila*, Northeastern Bangladesh. While this area was selected for its high concentration of both organic and conventional vegetable farmers, the findings may not be fully generalizable to other regions of Bangladesh with different soil types, irrigation infrastructure, or market conditions.

Third, although equal sample sizes (116 organic and 116 conventional) were deliberately chosen to enable direct comparison, this approach may under-represent the larger population of conventional farmers (749) relative to organic growers (164) in the sampling frame. Fourth, input and output data were self-reported by farmers, which introduces the possibility of recall bias and measurement error, particularly for quantities of seeds, labor, and organic manure. Fifth, the Cobb–Douglas functional form assumes constant elasticity of substitution and may not fully capture complex interactions among inputs or non-linear relationships present in vegetable production.

Additionally, the study focused exclusively on technical efficiency and did not collect detailed cost or price data, limiting the ability to assess economic or profit efficiency. The definition of "organic" relied on farmer self-identification and *Upazila Agriculture Office* records rather than third-party certification, which may introduce heterogeneity in actual farming practices. Finally, the analysis treated each crop separately and did not account for whole-farm efficiency or synergies from crop diversification.

Future research could broaden its geographic focus to include more regions across Bangladesh, offering a fuller understanding of vegetable production practices. Future research should incorporate panel data to separate time-invariant farmer ability from transient shocks and should collect detailed cost-of-production data to translate TE gaps directly into profit-efficiency estimates. Incorporating modern agricultural technologies, such as digital tools and precision farming, could further enrich analyses. Additionally, future studies should explore factors like market accessibility and climate change to present a more comprehensive perspective. Investigating regional differences in crops and farming methods could aid in optimizing agricultural productivity. Moreover, assessing the impact of implemented policies on both conventional and organic farming would provide valuable insights to guide policymakers.

CRediT authorship contribution statement

Muslima Akter: Writing – original draft, Formal analysis, Data curation, Conceptualization. **Romaza Khanum:** Writing – original draft, Formal analysis, Data curation. **Sadika Haque:** Writing – original draft, Project administration, Methodology, Investigation. **Khadija Akter:** Writing – original draft, Resources, Methodology, Investigation. **Tumpa Datta:** Writing – original draft, Software, Data curation. **Md. Emran Hossain:** Writing – review & editing, Validation, Supervision.

Data availability statement

Data can be made available from the corresponding author upon a reasonable request.

Ethical declarations

Ethical approval for this research was obtained from the Sylhet Agricultural University Research System (SAURES/2025/3632104). No human or animal rights were violated during the data collection process.

Declaration of AI use

The manuscript does not contain AI-generated content in terms of its ideas, theoretical development, literature review, methodology, analysis, results, or conclusions. All intellectual contributions and scholarly content presented in the paper were developed by the authors. However, the authors occasionally used AI-based language assistance tools solely for grammatical correction, language refinement, and improving readability. The authors carefully reviewed, edited, and verified all text to ensure its accuracy, originality, and consistency with the study's objectives.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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