

Transforming agriculture with vermicompost: 7-year empirical evidence from drought-prone and salinization-affected regions of Bangladesh

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ARTICLE INFO

Handling Editor: Dr. Govindan Kannan

Keywords:

Soil fertility
Soil nutrient
Soil salinity
Sustainable agriculture
Vermicompost
Coastal region

ABSTRACT

Global agricultural production has been affected by the increased frequency of climate extremes (e.g., droughts) in dry regions and heightened soil and water salinity in coastal regions. Exploration of sustainable agricultural practices is central to addressing the impacts of climate-induced shocks, restore soil fertility, and ensure food security. While there is growing evidence of crop losses due to increased drought and soil salinity, empirical evidence on nature-based solutions for increasing crop production through soil fertility recovery remains limited and poorly understood. Investigating the soil nutrients (nitrogen, phosphorus, potassium) and salinity from the 37 field experiments (22 treatments and 15 control plots in 11 villages) over 2017–2023, this study examined the effects of vermicompost on soil nutrients and salinity (electrical conductivity [EC]) in drought-prone and salinization-affected regions of Bangladesh. Results reveal that the application of vermicompost reduced soil salinity in salinization-affected region and enhanced soil nutrient contents in both regions over 7 years. In vermicompost-utilized experiments in the salinization-affected region, soil salinity (EC1:5) levels decreased from 5.56–7.65 dS m⁻¹ in 2017 to 4.93–5.89 dS m⁻¹ in 2023. Soil salinity and nutrient contents showed significant differences among the vermicompost-applied experiments, while no detectable changes in salinity and nutrient contents were found in the controlled experiments. None of the cropping patterns in salinization-affected region (brinjal-watermelon and potato-watermelon) and drought-prone region (brinjal-pointed gourd and brinjal-sesame) had significant effects on the observed changes in soil salinity and nutrient contents. These findings suggest that regardless of the crop combinations, vermicompost is a sustainable and versatile soil amendment, which can be effectively used in diverse agricultural systems and environments. The study provides empirical evidence to support policy decisions aimed at promoting sustainable agricultural practices and enhancing soil health using vermicompost. The findings inform strategies for reducing soil salinity and enhancing sustainable agriculture in comparable regions worldwide.

1. Introduction

Agriculture is one of the most vulnerable sectors to global climate

change (Aryal et al., 2021). This sector is currently facing numerous challenges, including the occurrence of extreme weather events (e.g., droughts and heatwaves) (Knox et al., 2012), land degradation due to

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<https://doi.org/10.1016/j.jclepro.2025.145595>

Received 6 October 2024; Received in revised form 4 April 2025; Accepted 25 April 2025

Available online 26 April 2025

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unsustainable farming practices (Sharma et al., 2019), outbreak of pest and diseases (Li et al., 2024), and increasing crop production to meet the future food demand (van Dijk et al., 2021). To feed increasing population, the demand for agricultural crop production is projected to increase by 50 % by 2050 (Alexandratos and Bruinsma, 2012; van Dijk et al., 2021). Farmers are required to apply chemical fertilizers and pesticides extensively to meet the rising crop demand, leading to soil degradation and lowering soil fertility (Sharma et al., 2019). A growing body of evidence reported the loss of crop yield resulted from different natural hazards (droughts, tropical cyclones, storm surges and floods) (Knox et al., 2012; Cottrell et al., 2019; Aryal et al., 2021).

Although agricultural productivity has generally increased over the past 50 years, climate change has slowed this growth globally, with related negative crop yield impacts primarily recorded in mid- and low-latitude regions and some positive impacts in some high-latitude regions (IPCC et al., 2023). With a rapidly growing global population, an increase in climate-induced shocks, and the adoption of unsustainable agricultural practices (e.g., water mismanagement, and reliance on chemical pesticides and fertilizers), ensuring food security has become a critical concern (Ahmed et al., 2021; Zhang et al., 2023a). In this context, the adoption of sustainable agricultural practices becomes vital to address climate-induced shocks, restore soil fertility, and ensure food security. The pressing issue of sustainable agriculture was prioritized on the first day of the 28th Conference of the Parties (COP28), highlighting the need to address the multifaceted challenges posed by climate change in the agricultural sector (Bauck, 2023).

Agriculture is the backbone of Bangladesh's economy and food security, with substantial progress made in transitioning from import dependence to self-reliance in crop productivity. For example, a positive trend has been observed for rice (30 million metric tons [MMT] per year in 2000s to 35.8 MMT in 2020), and wheat (1.5 MMT/year in 2000s to 2.3 MMT in 2020) production (FAO, 2021). While efforts have been made to improve yield and meet the improving demand for food, the nation's arable land productivity has declined extensively due to over-use, misuse, and negligence, leading to a deterioration in soil fertility (Hasan et al., 2020). The rapid increase in fertilizers and pesticides to meet food demands has resulted in land degradation and declining soil nutrients [e.g., nitrogen (N), phosphorus (P), and potassium (K)] and soil organic carbon (SOC) contents in arable land in Bangladesh (Hasan et al., 2020; Uddin et al., 2022; Shapna et al., 2024). Over the past decade, Bangladesh has witnessed a decline in arable cropland, with the percentage dropping from 65 % in 2010 to 59 % in 2020 (Hasan et al., 2020) and a notable increase in fertilizer usage in the soil, rising from 95 kg ha⁻¹ in 1990 to 275 kg ha⁻¹ in 2020 (Fig. S1; FAO, 2023; Ritchie et al., 2023). Notably, the level of fertilizer application in Bangladesh is the highest among South Asian countries (Fig. S1; FAO, 2023). Given the decline in soil nutrients and organic carbon content, adopting sustainable practices like vermicomposting is crucial for enriching soil health and fostering resilient agricultural systems in Bangladesh.

Due to their low elevation of 1–4 m above sea level, the coastal regions of Bangladesh are exceptionally vulnerable to sea level rise, leading to increased soil salinity (Clarke et al., 2015; Hossain and Li, 2024; Shapna et al., 2024), which threatens food production and livelihoods through negative impacts on crop cultivation, homestead gardening, livestock, and aquaculture (Lam et al., 2022; Shapna et al., 2024). Soil electrical conductivity (EC) in agricultural land in the southwest coastal region of the county has been reported to range between 7.9 dS m⁻¹ and 8.4 dS m⁻¹ (Hossain and Li, 2024). Despite projections of increasing precipitation across the northeast (Mymensingh and Sylhet divisions) and northwest (Rajshahi division) regions of Bangladesh (Aziz et al., 2023), the southwestern (Khulna division) region of the country is predicted to experience droughts (Kamruzzaman et al., 2023), exacerbated by increasing frequency and severity (Rahman et al., 2021; Das et al., 2023) that significantly reduce crop production (Habiba et al., 2013; Mamun et al., 2024) and threaten the livelihoods of farmers (Rahman et al., 2022). For example, 1.2 million ha of cultivated

paddy area in the northwest and southwestern regions of Bangladesh has been affected by drought during the dry season (Islam et al., 2017), and a severe drought event in 2012 reduced nearly 30 % crop production in Bangladesh (Habiba et al., 2013). Therefore, there is an urgent need to implement sustainable agricultural practices to address these climate change-induced challenges and ensure food security for the country's growing population.

Vermicompost (nutrient-rich compost) is widely recognized as a measure of sustainable agriculture (Rashid et al., 2023; Sengupta et al., 2023). Studies on vermicompost have been growing in popularity in recent decades (Ghorbani and Sabour, 2021; Enebe and Erasmus, 2023; Van Hoof et al., 2024). For example, 4345 vermicompost research articles have been published in Science Citation Index journals for the period 1987–2024, of which only 87 articles are from Bangladesh (Fig. S2). The regular application of vermicompost in degraded soils has proven to improve soil structure, water holding capacity and fertility (Datta et al., 2016). This compost also helps enhance soil aeration, and nutrient retention, creating a favorable environment for plant root growth. Currently, vermicompost is widely recognized for its efficacy in promoting high crop yields and has been extensively utilized in the cultivation of various crops such as paddy, maize, wheat, peppermint, tomatoes, capsicum, and garlic (Barmon and Tarafder, 2019; Ayyobi et al., 2014; Zucco et al., 2015; Rekha et al., 2018; Gichaba et al., 2020). A recent meta-analysis (Blouin et al., 2019) examining the effects of vermicompost application on crop productivity has revealed significant improvements in various yield and biomass parameters, which reported that, on average, vermicompost led to a 26 % increase in commercial yield, a 78 % (57 %) increase in shoot (root) biomass, and a 13 % increase in total biomass (Blouin et al., 2019).

Vermicompost not only enhances crop productivity and agricultural sustainability but also plays a vital role in addressing the impacts of climate change (Vambe et al., 2023) and salinization (Hossain and Li, 2024). A growing body of evidence shows that the application of vermicompost helps crops in managing the harmful effects of salinity (Abbott et al., 2018; Shilev, 2020). Research indicates that vermicompost mitigates the adverse effects of salt stress on various crops by enhancing plant tolerance through increased enzymatic activity, protein synthesis and overall physiological functions (Abbott et al., 2018; Shilev, 2020). In water deficit stress, Hosseinzadeh et al. (2018) reported that the application of vermicompost reduces drought stress and boosts crop growth. Like the growing evidence of positive effects of vermicompost in improving soil nutrients and crop productivity in drought-affected (Ahmad et al., 2022) and salinization-affected (Ding et al., 2021; Sahab et al., 2021) regions in many countries, farmers in Bangladesh are encouraged to use vermicompost in nutrient-poor soils, particularly in salinization-affected (Shapna et al., 2024) and drought-prone regions (Barmon and Tarafder, 2019; Rahman and Barmon, 2019). Despite the empirical evidence of the positive impacts of vermicompost on improving soil structure, microbial communities, and soil moisture retention capacity and crop productivity (Barmon and Tarafder, 2019; Rahman and Barmon, 2019; Sahab et al., 2021; Ahmad et al., 2022; Villafuerte et al., 2024), our understanding of its impacts in recovering the soil nutrients and reducing soil salinity in highly degraded soils (e.g., saline and low nutrients soils) remains poorly understood.

While in qualitative studies, farmers have expressed their positive impressions of vermicompost application in improving soil fertility and reducing soil salinity (Barmon and Tarafder, 2019; Rahman and Barmon, 2019; Hasan et al., 2021; Hossain and Li, 2024; Shapna et al., 2024), it is essential to rely on experiment-based scientific evidence of the impacts of vermicompost in improving soil fertility and ameliorating soil salinity. In addition to farmers' experiences and experts' opinions on vermicompost, the empirical evidence for an extended period will help to establish evidence-based recommendations for farmers to optimize the application of vermicompost and achieve desired outcomes. To establish robust scientific evidence, our study was carried out across 37

field experiments (22 vermicompost-treated and 17 control plots) for the period 2017–2023 in drought-prone and salinization-affected regions of Bangladesh to evaluate the role of vermicompost in improving soil fertility and reducing soil salinity. The study aims to achieve the following three objectives.

- to examine the temporal changes of the nutrient contents in vermicompost-utilized soils in two different environmental settings (drought-prone and salinization-affected regions) for the period 2017–2023;
- to explore the impact of vermicompost in ameliorating soil salinity in salinization-affected region over 7 years; and
- to explore whether different cropping patterns have any effect on changing soil nutrient and salinity levels in drought-prone and salinization-affected soils over the study period.

This study provides novel insights into how vermicompost utilization into soil in two different environmental settings (i.e., drought-prone and salinization-affected regions) influences soil nutrient (total N, available P, and available K) dynamics and contributes to decreasing soil salinity over 7 years, enabling a better understanding of the effectiveness and adaptability of vermicompost as a soil amendment and as a nature-based solution. The research revealed that vermicompost not only reduced salinity in salinization-affected region but also improved soil nutrient content across both salinization-affected and drought-prone regions. This dual benefit underscores the value of vermicompost in enhancing soil fertility. The insignificant effects of different cropping patterns on changing soil nutrients and salinity further supports the positive effects of vermicompost in enhancing soil nutrients and reducing soil salinity, indicating its versatility and effectiveness regardless of the specific crops grown. This suggests that farmers can adopt vermicompost without worrying about the specific crop combinations used. The insights gained from this study are not limited to the specific regions examined; they offer valuable evidence for similar agricultural contexts worldwide.

2. Methodology

2.1. Description of study area

We selected two districts (Khulna and Jessore) in the southwestern region of Bangladesh (Fig. 1). Khulna district is considered as a salinization-affected region because soil and water salinity in most areas

of this district exceeded the threshold for agriculture, irrigation and drinking purposes (Chen and Mueller, 2018). Moderate to severe soil and water salinity in Dacope sub-district of Khulna district has been reported in recent studies (Hossain and Li, 2024; Shapna et al., 2024). This salinity threatens household food production, impacting livelihoods such as crop farming, gardening, livestock, and aquaculture (Barbour et al., 2022; Lam et al., 2022). Jessore district is recognized as a drought-prone region, with studies indicating an increase in drought frequency and intensity for the period 1984–2013 (Islam et al., 2017), which is also evident in recent 33 years (1991–2023) of drought analysis in our study (Fig. S3). Additionally, it has been identified as the second most susceptible region to rising drought conditions in Bangladesh, following the northwestern region (Rahman and Lateh, 2016).

In this study, we selected 7 villages from the drought-prone Jessore and 4 villages from the salinization-affected Khulna districts (Fig. 1). The climate in both regions is marked by elevated temperatures, high humidity, and heavy precipitation during the monsoon season. The demography of these study regions is largely rural, with agriculture being the primary source of income for most of the population. The population density in Khulna and Jessore districts is 1031 and 1261 people km^{-2} , respectively. The geology of these regions is characterized by alluvial plains, formed by the deposition of sediment by rivers and the Bay of Bengal. The soil type in these regions is mainly alluvial soil, which is fertile and appropriate for agriculture. The soil nutrients in both districts are mainly deficient in N, P, and K, which can limit crop growth and productivity (Hasan et al., 2020; Shapna et al., 2024).

Salinity intrusion is a significant problem in the coastal belt (e.g., Dacope, Kamarkhola, and Sutarkhali union) of Khulna district (Shaibur et al., 2021), which adversely affects crop productivity (Lam et al., 2022; Shapna et al., 2024). For instance, in our salinization-affected region, high salinity levels have been reported in cropland ($7.9\text{--}8.4\text{ dSm}^{-1}$), pond water ($13.19\text{--}13.99\text{ dSm}^{-1}$) and canal water ($65\text{--}78\text{ dSm}^{-1}$) (Hossain and Li, 2024). In contrast, the Jessore district is not located within the coastal region and as a result, soil and water salinity do not pose a problem in this region (Salehin et al., 2018). Thus, while salinity is a critical challenge in Khulna district, it is not a concern in Jessore district.

2.2. Agriculture in the study area

The drought-prone Jessore district is known for its diverse agriculture, with the cultivation of various crops throughout the year, including

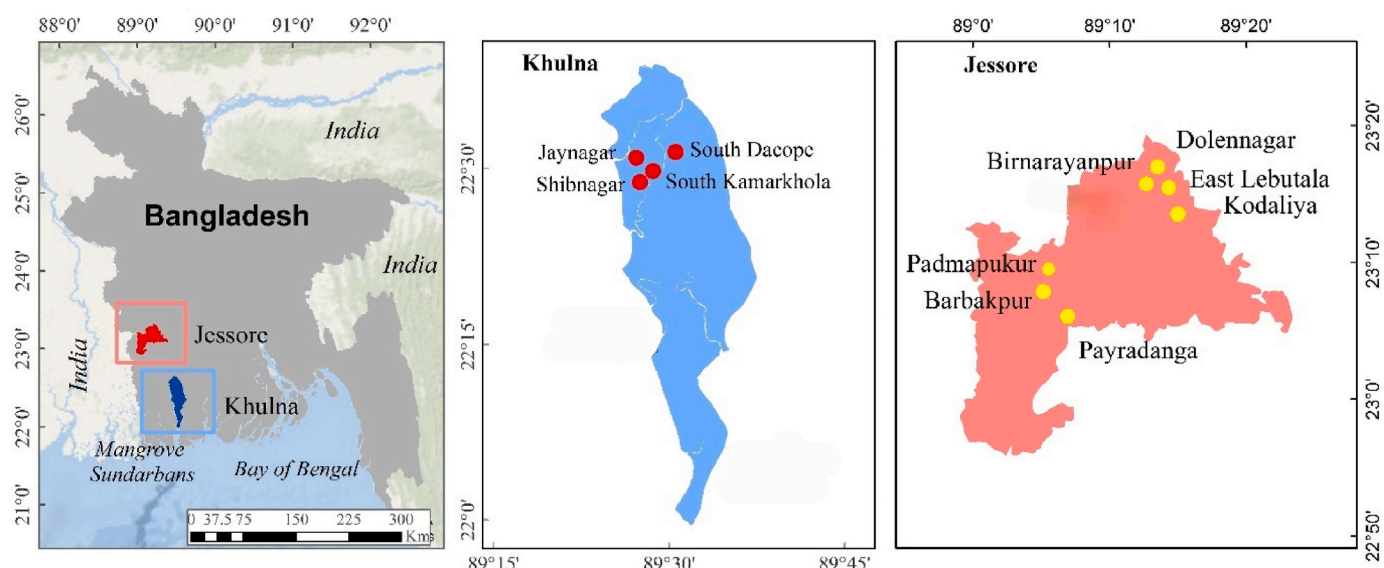


Fig. 1. Location of the field experimental sites across 4 villages in salinization-affected Khulna district and 7 villages in drought-prone Jessore district in the study.

paddy, wheat, maize, potato, brinjal, sesame, pointed gourd, onion, chili, and jute (Dewan et al., 2018). The cropping intensity in this district is relatively high compared to salinization-affected Khulna district, with double and triple cropping systems (e.g., brinjal-sesame, brinjal-pointed gourd, and paddy-potato-chili) prevalent in many areas. Farmers in Khulna district cultivate both traditional and high-yielding varieties of rice (e.g. salt-tolerant rice; Shapna et al., 2024) and a wide range of other crops, including watermelon, tomato, potato, onion, brinjal, pumpkin, cucumber, and various leafy greens (Ashrafuzzaman et al., 2022).

The application of fertilizer in agricultural land in Jessore district is widespread. The excessive use of chemical fertilizers has led to soil degradation and nutrient imbalances, which can adversely affect crop growth and yield (Hasan et al., 2020). In Khulna district, moderate to extreme salinity in soil and water is the most critical issue that affects agricultural practices and crop production (Lam et al., 2022; Shapna et al., 2024). To address the challenge posed by soil and water salinity, farmers in Khulna district often apply high dose of fertilizers (Hossain and Li, 2024). Because of soil salinity and scarcity of freshwater irrigation water, farmers in this region often cultivate one crop in a year (Shapna et al., 2024). The over-reliance on chemical fertilizers (Hossain

et al., 2022) and the challenges posed by drought and salinity highlights the need for exploration of sustainable agriculture practices in these drought-prone and salinization-affected regions of the country.

2.3. Vermicompost production by the study participants

Before conducting our field experiments in 2017, twenty-two women from the farming community (14 from drought-prone and 8 from salinization-affected regions) received capacity-building training on the preparation, processing, and field utilization of vermicompost (Fig. 2a & S4). The selection criteria for the research participants were focused on marginalized farmers who either own crop land or work as sharecroppers, and who also own cows. The training covers topics such as the setup of vermicomposting units, proper layering of organic waste and bedding materials, maintenance of moisture levels, harvesting process and field application (Fig. S4). After the training, these participants received 2 medium-sized earthen pots (locally available) and 900 g earthworms (transported from another district). Specific species of earthworms, such as *Eisenia fetida* (red worms) or *Lumbricus rubellus* (red wigglers), were used in vermicomposting. These worms are well-suited for consuming organic matter and breaking them down into nutrient-

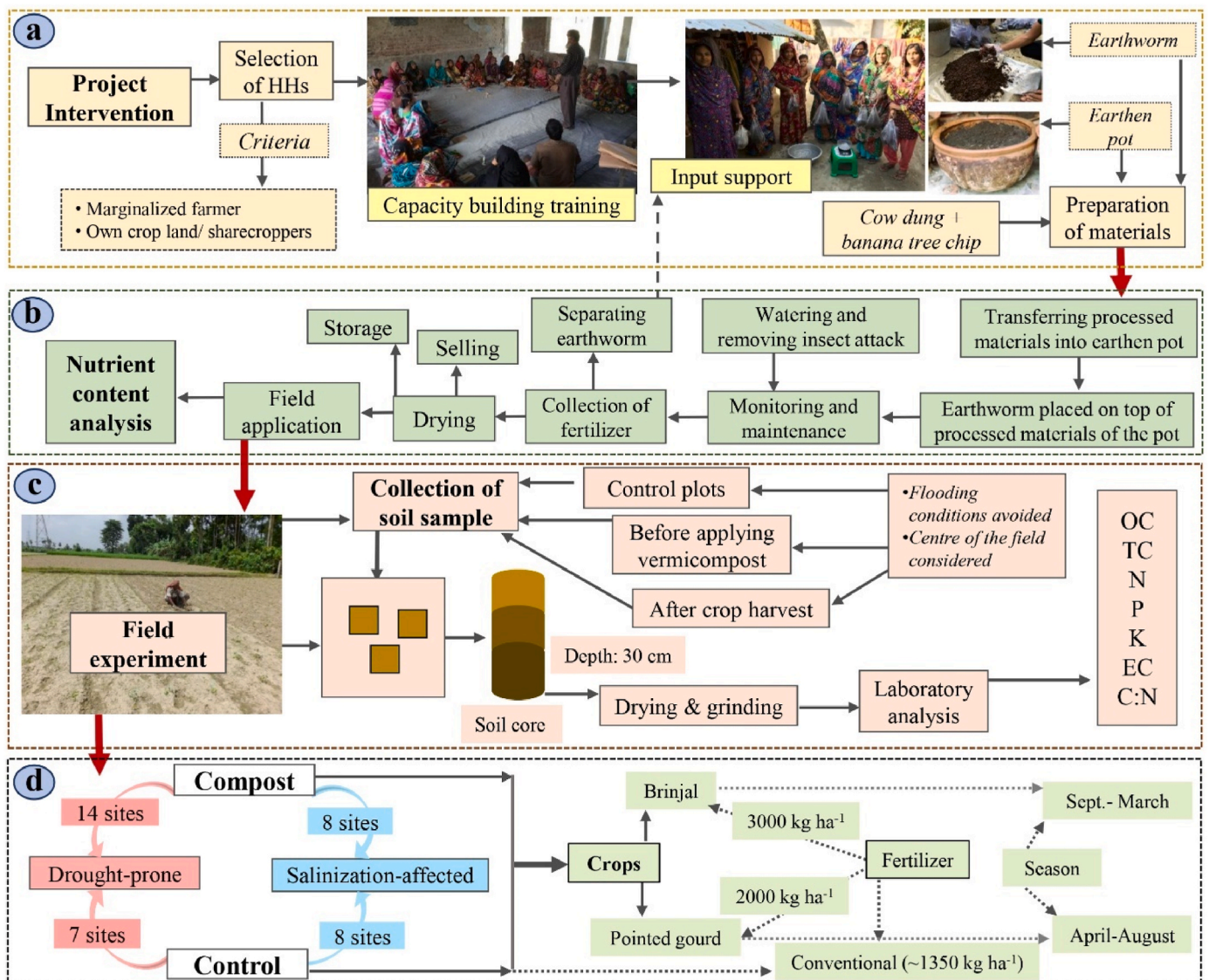


Fig. 2. The steps of vermicompost preparation training and input support (earthworm and earthen pot) (a), production (b), field application and soil sampling (c), and doses and cropping pattern (example given for cropping pattern 1) (d) in the drought-prone and salinization-affected regions of Bangladesh.

rich castings. In the preparation stage, the earthworms were introduced into the earthen pot along with the organic waste (Fig. 2b). Over time, the earthworms consume the materials in the pot, breaking them down through their digestive process. The excreted nutrient-rich castings of earthworms are known as vermicompost. As the earthworms processed the cow dung, the vermicompost gradually accumulated in the pot. After several weeks, usually 3–6 weeks depending on earthworm quantity and seasonality, the vermicompost can be harvested by separating the earthworms from the vermicompost (Fig. 2b). The harvested vermicompost is then ready for use as a fertilizer or soil amendment (Fig. 2c).

2.4. Description of the experiments

A total of 37 field experiments were conducted at the 22 households' farmlands (Fig. 2d), including 22 vermicompost-amended plots and 15 control (traditional farming) plots in both regions. Specifically, over 7 years, we carried out 14 vermicompost-amended and 7 control plots belonging to 14 households in drought-prone Jessore district, and 8 vermicompost-amended and 8 control plots belonging to 8 households in salinization-affected Khulna district (Fig. 2d). Because of differences in land ownership and lease among the selected households, the size of the experimental plots ranges between 1650 m² and 2120 m². Before starting the experiments, we collected soil samples from all the fields to measure concentration of selected soil parameters (i.e., soil texture, SOC concentration, total N, available P, available K, and EC) (Table S1). Additionally, we also measured the nutrient contents of produced vermicompost in respective households in March 2017 (before applying to the field) (Table 1). The mean values in most of the chemical parameters (i.e., organic carbon [OC], total carbon [C], total N, available P, calcium [Ca], manganese [Mn], copper [Cu], and C:N ratio) in the measured vermicompost were higher in the drought-prone region compared to the salinization-affected region, except available K, sodium [Na], iron [Fe], zinc [Zn], magnesium [Mg], and pH (Table 1).

Based on the farmers' preference and their previous experience in cultivating crops, we have selected 5 crops: *Solanum melongena* L. (brinjal), *Trichosanthes dioica* Roxb. (pointed gourd), *Sesamum indicum* L. (Sesame), *Citrullus lanatus* (watermelon) and *Solanum tuberosum* L. (potato) (Table 2). We then designed two cropping patterns for each region (Rashid et al., 2017; Hajong et al., 2024). Specifically, for the drought-prone region, two cropping patterns were brinjal-pointed gourd (cropping pattern 1), and brinjal-sesame (cropping pattern 2). Brinjal-watermelon (cropping pattern 1) and potato-watermelon (cropping pattern 2) were the two selected cropping patterns for the salinization-affected regions. The growing seasons were April–August for pointed gourd, May–August for sesame, September–March for brinjal, March–May for watermelon and November–March for potato (Table 2) (Rashid et al., 2017; Hajong et al., 2024).

The twenty-two trained women received input support (i.e., seed, seedling, organic pesticides and vermicompost) to implement vermicompost application in their 22 vermicompost experimental fields throughout the study period. Among these 22 vermicompost-amended plots, the following cropping patterns were cultivated: in the drought-prone region, 7 plots were dedicated to brinjal-pointed gourd and another 7 to brinjal-sesame, and in the salinization-affected region, 4 plots were cultivated with brinjal-watermelon, and 4 plots with potato-watermelon. The remaining 15 experimental fields served as control plots (vermicompost was not applied), where households employed traditional farming methods (e.g., application of chemical fertilizer and pesticides). Likewise, in drought-prone region, 4 control plots were allocated for brinjal-pointed gourd, and 3 control plots for brinjal-sesame. Similarly, in the salinization-affected region, 4 control plots were used for brinjal-watermelon, and 4 control plots for potato-watermelon.

While households were permitted to cultivate the selected crops on 15 control plots using their traditional ways (e.g., chemical fertilizers and pesticides, and integrated pest management), vermicompost,

Table 1
Nutrient composition of vermicompost produced in 22 households in the drought-prone and salinization-affected regions.

Nutrient element in vermicompost	OC (%)	Total C (%)	Total N (%)	Available P	Available K	Total Ca	Total Mg	Total Na	Total Mn	Total Fe	Total Cu	Total Zn	Total C:N ratio	pH
Drought-prone region ^a	12.6 ± 0.13	21.72 ± 0.85	1.43 ± 0.06	0.97 ± 0.05	0.68 ± 0.04	0.44 ± 0.02	0.28 ± 0.01	0.13 ± 0.01	98.2 ± 1.44	1957 ± 27.29	24.3 ± 0.99	269 ± 4.51	15.19 ± 0.33	6.7 ± 0.03
Salinization-affected region ^a	11.2 ± 0.29	19.31 ± 1.12	1.37 ± 0.08	0.84 ± 0.09	0.71 ± 0.03	0.39 ± 0.03	0.28 ± 0.02	0.14 ± 0.02	94.3 ± 2.60	2014 ± 10.91	23.7 ± 0.46	273 ± 6.58	14.09 ± 0.28	6.8 ± 0.04
Measurement method	Wet oxidation	Dry combustion	Kjeldahl method	Olsen method	ammonium acetate followed by AAS	Acid digestion followed by AAS	Acid digestion followed by AAS	Flame Photometry	Acid digestion followed by AAS	Acid digestion followed by AAS	Acid digestion followed by AAS	Acid digestion followed by AAS	Calculated from TC & Total N	pH meter

^a mean of 14 experimental households; ^a mean of 8 experimental households; AAS: Atomic Absorption Spectroscopy; ppm: parts per million; ± indicates the standard deviation.

Table 2

Crop selection and cropping patterns for the 37 experiments in the drought-prone and salinization-affected regions.

Region	Selected crops	Botanical name	Growing season	Cropping pattern 1	Cropping pattern 2
Drought-prone region	Brinjal	<i>Solanum melongena</i> L.	September–March	Brinjal-Pointed gourd	Brinjal-Sesame
	Pointed gourd	<i>Trichosanthes dioica</i> Roxb.	April–August		
	Sesame	<i>Sesamum indicum</i> L.	May–September		
Salinization-affected region	Brinjal	<i>Solanum melongena</i> L.	September–March	Brinjal-Watermelon	Potato-Watermelon
	Watermelon	<i>Citrullus lanatus</i>	March–May		
	Potato	<i>Solanum tuberosum</i> L.	November–March		

organic pesticides (e.g., extract of *Swietenia mahagoni* seeds, and extract of *Azadirachta indica* leaves) and integrated pest management were utilized on the 22 vermicompost-amended experimental plots for the period 2017–2023. The doses of vermicompost (chemical fertilizer) application varied depending on the selected crops, ranging from 3000 kg ha⁻¹ (900 kg ha⁻¹) in brinjal and potato, and 2000 kg ha⁻¹ (450 kg ha⁻¹) in pointed gourd, sesame, and watermelon. Regardless of cropping patterns, farmers implemented a specific application of vermicompost at a rate of 5000 kg ha⁻¹ year⁻¹ in the experimental plots (Mustafayeva et al., 2022; Ruan et al., 2023) and chemical fertilizer at a rate of 1350 kg ha⁻¹ year⁻¹ in the control plots (Azad et al., 2019) over 7 years. The doses for vermicompost and chemical fertilizer in the selected crops are recommended by Bangladesh Agriculture Research Institute (Azad et al., 2019). This standard operating procedure for experimental and control plots was consistently maintained throughout the study period.

Our methodology is unique in multiple facets, including experimental design, the variety in environmental settings, the incorporation of local agricultural practices, the use of diverse patterns in cropping, and the consideration of natural climatic variability without imposing of control in terms of temperature and precipitation. We emphasized natural experimental settings, allowing us to capture real-world climatic variability and the effects of vermicompost on soil nutrients and salinity. By conducting 22 experiments across diverse environmental contexts, we minimized experimental bias and enhanced the generalizability of our findings. Additionally, we respected and integrated indigenous agricultural practices, ensuring cultural relevance and community engagement. Our examination of multiple crop combinations provided deeper insights into the multifaceted effects of vermicompost, prioritizing practical implications over theoretical constructs. This experimental protocol consequently yielded more reliable and applicable findings than traditional manipulated experiments (e.g. greenhouse or control setting), making our study particularly relevant for sustainable agricultural practices.

2.5. Data collection and laboratory analysis

Soil samples from vermicompost-applied fields were collected before applying vermicompost (field preparation stage) and after crop harvest once a year for 7 consecutive years. Soil samples from control plots were obtained after crop harvest once a year. Regardless of whether the experiments were amended with vermicompost or served as control experiments, 27 samples (3 quadrats × 3 plots × 3 replications) were collected from each experimental field. The soil samples were collected from the center of the field, at a depth of 30 cm. Recent studies increasingly focus on shallower soil depths in agricultural contexts. For example, Huang et al. (2024) assessed the 0–20 cm depth in paddy fields in the Pearl River Delta region, highlighting available nutrient elements, while Wang et al. (2025) reviewed 994 observations in 131 articles, underscoring the importance of top 0–15 cm layer for nutrient availability and soil health. Many studies highlight the significance of the 0–30 cm soil depth for assessing nutrient availability and the effects of amendments (e.g., biochar, vermicompost, and biofertilizer) on crop production (Padbhushan et al., 2016; Adhikari et al., 2024; Hossain and Li, 2024). This depth captures the upper soil layers where most biological activity occurs and encompasses the root zone of our selected

crops (Table 2). While dissolved vermicompost can penetrate deeper soil layer (>30 cm) due to high precipitation, the top 30 cm is crucial for initial nutrient absorption, allowing us to evaluate how effectively these nutrients are integrated into the soil and made available to plants (Padbhushan et al., 2016). For example, in a 9-year-long empirical study conducted in eastern India, which shares the similar climatic conditions (annual precipitation ~1600 mm, mean annual temperature 25.6 °C) with our study region, Padbhushan et al. (2016) reported that the top 30 cm of soil depth effectively explains the trajectories of most nutrients in vermicompost-utilized soils within a rice-potato-onion cropping system.

We utilized a manually operated soil core sampler (Jackson, 1987) to collect soil samples. The sampler was positioned vertically at the designated sampling quadrats and pushed into the ground to a depth of 30 cm. Once the sampler was fully inserted, we twisted it slightly to break the soil's adhesion to the edges, then pulled the sampler out of the ground, ensuring that the cylindrical core of soil remained intact inside. The samples were then placed in ziplock bags and labeled with relevant information (e.g., sample number, location and date). Following collection, these samples were transported to the laboratory for analysis. In the laboratory, the samples were air-dried to remove moisture, debris was removed, and the soil was ground into a homogeneous powder using a mortar and pestle. The concentrations of total N, available P, available K, and EC in the soil were measured using standard laboratory methods (Kjeldahl, 1883; Olsen et al., 1954; Helmke and Sparks, 1996; Jackson, 1962).

The total N content in the soil samples was determined using the Kjeldahl method (digestion-distillation-titration; Kjeldahl, 1883). This process involved digesting the soil with concentrated sulfuric acid (H₂SO₄) and a catalyst (selenium) to convert all forms of N into ammonium sulfate [(NH₄)₂SO₄]. Following digestion, the solution was neutralized with sodium hydroxide (NaOH), liberating ammonia gas (NH₃), which was then distilled and captured in standard hydrochloric acid (HCl). The amount of ammonia was quantified through titration with NaOH, allowing for the calculation of total N content.

Olsen method was used for measuring the available P (Olsen et al., 1954). In this method, 5 g of air-dried soil was placed in a conical flask with 100 mL of sodium bicarbonate (NaHCO₃) solution (0.5 M) at pH 8.5. The mixture was shaken for 30 min to facilitate the extraction of P into the solution. After shaking, the mixture was filtered to separate the liquid from the soil residue. A 3 mL aliquot of the filtrate was then treated with 3 mL of mixed reagent (ammonium molybdate and ascorbic acid) to develop a blue-colored complex. The absorbance of this solution was measured using a spectrophotometer at 882 nm. By comparing the absorbance against a standard curve of known P concentrations, the amount of available P in the soil sample was determined.

For measuring available K in soil, 5 g of air-dried soil was placed in a conical flask and added 50 mL of 1 M ammonium acetate (NH₄OAc) solution at pH 7. Then the mixture was shaken for 1 h to allow K to extract into the solution. The solution was then filtered to separate the liquid from the solid residue. The filtered solution was analyzed using an atomic absorption spectrophotometer to measure the K concentration (Helmke and Sparks, 1996).

To measure the EC in soil samples, we placed 10g of soil in a beaker and added 50 mL of distilled water, achieving a soil-to-water ratio of 1:5. We stirred the mixture thoroughly to ensure complete saturation and

then allowed it to sit for about 30 min to enable larger particles to settle. After this settling period, we obtained a clear supernatant for measurement. The electrodes of the conductivity meter were carefully immersed in the soil extract, and the meter recorded the EC1:5 of the solution (Jackson, 1962).

2.6. Climate data

Climate data including monthly and annual temperature (mean, maximum, and minimum) and precipitation of two weather stations (Jessore: drought-prone region and Khulna: salinization-affected region) for the period 1991–2023 were obtained from the Bangladesh Meteorological Department (BMD, 2025; <https://live8.bmd.gov.bd/>) to assess the temporal trend of temperature and precipitation. Mean annual precipitation for the recent 33 years (1991–2023) in Khulna (Jessore) district is 1812 mm (1689 mm), and the minimum and maximum annual temperature in Khulna (Jessore) ranges from 21.48 °C (20.66 °C) to 31.68 °C (32.11 °C), with a mean annual temperature of 26.22 °C (25.93 °C) (Table S2, BMD, 2025). The 33-year (1991–2023) climate data in both the districts showed an increasing trend of mean annual temperature, maximum and minimum annual temperature (Fig. S5–S7). Annual precipitation in drought-prone region exhibited a slightly decreasing trend, while in salinization-affected region exhibited slightly increasing trend over recent 33 years (Fig. S8).

Using climate data, we calculated Standardized Precipitation Evapotranspiration Index (SPEI) values for both regions (Vicente-Serrano et al., 2010). We considered SPEI-3, SPEI-6, SPEI-9, and SPEI-12, which represents 3-month, 6-month, 9-month and 12-month climatic conditions. Based on SPEI values, climatic conditions were categorized into five classes: extreme wet, moderate wet, normal, moderate dry, and extreme dry (Isbell et al., 2015) (Table S3; Fig. S9). The details of climate data processing have been given in Supplementary Information (SI Materials and Methods). The temporal trend of all SPEI values (i.e., SPEI-3 to SPEI-12) showed an increasing dry condition in the drought-prone region, with a significant increase observed specifically for SPEI-3 values ($p < 0.05$; Fig. S3). In the salinization-affected region, both SPEI-3 and SPEI-6 showed an increasing dry condition, whereas SPEI-9 and SPEI-12 showed a trend towards increased wet conditions. However, these trends were not statistically significant for all SPEI values (all $p > 0.05$; Fig. S10).

2.7. Data analysis

We employed the Mann-Kendall (MK) trend test (Mann, 1945) to examine the temporal patterns of soil nutrient contents (total N, available P, and available K) in 22 vermicompost-utilized experiments and 15 control plots located in 11 villages in both regions. Likewise, we used the MK trend test to assess the temporal changes in soil salinity levels in 8 vermicompost-utilized experiments and 8 control experiments in salinization-affected region. To visualize the data, we plotted the values of soil nutrient contents and salinity levels over the respective years. This was done using the 'geom_point' function in the 'ggplot' package within the statistical software R (R Core Team, 2020). The significance of the obtained temporal trends was detected using the MK test (Mann, 1945).

We employed the non-parametric Kruskal-Wallis test to analyze the variation in soil nutrient contents in the experiments (Thomas et al., 2016) and the Wilcoxon test to analyze the differences in soil nutrient contents in Year-1 and Year-7 (Wilcoxon, 1945). Moreover, using the Wilcoxon test, we conducted pairwise comparisons N, P, K and EC level between different cropping patterns in the corresponding year.

Scatter plots were created to visualize the distribution of N, P, and K contents against annual precipitation. A generalized linear model (GLM) was fitted using polynomial regression to capture potential non-linear relationships (Salinas et al., 2023). The model specified a fourth-degree polynomial of the independent variable annual

precipitation, represented by the formula $y \sim \text{poly}(x, 4)$. This choice allows for a more flexible fit to the data compared to simple linear regression. The corresponding p -values of the GLMs were displayed on the plot using the `stat_cor` function.

3. Results

3.1. Soil nutrient contents

3.1.1. Temporal trend of soil nutrient contents

The results show that in the vermicompost-utilized experiments total N, available P and available K contents in soil showed a significant monotonic trend in most of the experiments across villages (Fig. 3). For example, the total N content in the soil of vermicompost-utilized experiments has shown a significant increase in all villages (all $p < 0.05$, Fig. 3a and b), except one village (Barbapukur) in the drought-prone region ($p > 0.05$, Fig. 3a). When we assessed the total N content of vermicompost-utilized experiments in the first and final year of the study, we found that total N content in the soils of all villages was significantly higher in Year-7 compared to Year-1 (all $p < 0.01$, Fig. 4a and b).

Like the temporal trend of total N, the soil P and K contents in the vermicompost-utilized experiments across villages in the drought-prone region increased significantly over the study period (all $p < 0.05$, Fig. 3c, & e), except soil K content in one village (East Lebutala). In the salinization-affected region, temporal trend analysis reveals that soil P content increased in one village and soil K content increased in three villages (Fig. 3d and f). However, the soil P and K contents in the remaining villages in this region did not exhibit significant changes over the study period (Fig. 3d and f). Pairwise comparisons of nutrient contents between the beginning and end of the study demonstrate that, across all the experimental plots in drought-prone and salinization-affected regions, the soil P and K contents in vermicompost-utilized experiments were significantly higher in Year-7 compared to those in Year-1 (all $p < 0.05$, Fig. 4c–f).

We assessed the robustness of our findings by assessing (i) the temporal trend (2017–2023; Fig. S11) and differences (between Year-1 and Year-7) in soil nutrient levels in control plots (Fig. 5) and (ii) the effects of cropping patterns on soil nutrients in vermicompost-utilized experiments (Fig. S12). In the control plots located in salinization-affected regions, soil nutrient contents in most villages did not exhibit significant differences between Year-1 and Year-7 (Fig. 5), except the observed significant decline in total N in Jaynagar (Fig. 5b) and K in Shibnagar (Fig. 5f) from Year-1 to Year-7. In the control plots located in drought-prone region, soil N, P, and K contents in Payradanga, P and K contents in Kodaliya and East Lebutala and K content in Padmapukur decreased significantly from Year-1 to Year-7 (Fig. 5). Temporal trend analysis reveals that soil nutrient contents in control experiments remained largely unchanged across most villages, except the significant decreases in total N and P content in Payradanga (both $p < 0.05$; Fig. S11a and c), available P content in East Lebutala (Fig. S11c) and available K content in Shibnagar (Fig. S11f). Moreover, in the vermicompost-utilized experiments, changes in cropping patterns did not show significant effects on soil N, P, and K contents over the seven-year period ($p > 0.05$, Fig. S12), except for soil K content in 2017 within salinization-affected region (Fig. S12f).

3.1.2. Variation of soil nutrient contents among the experimental villages

There were significant differences in soil nutrient contents among the vermicompost-utilized experiments across villages in the drought-prone region ($p < 0.05$, Fig. 6a–c, & e) and in the salinization-affected region ($p < 0.001$, Fig. 6b–d, & f). The total N, available P and available K contents in soil were consistently higher in the drought-prone region compared to the salinization-affected region (Fig. 6).

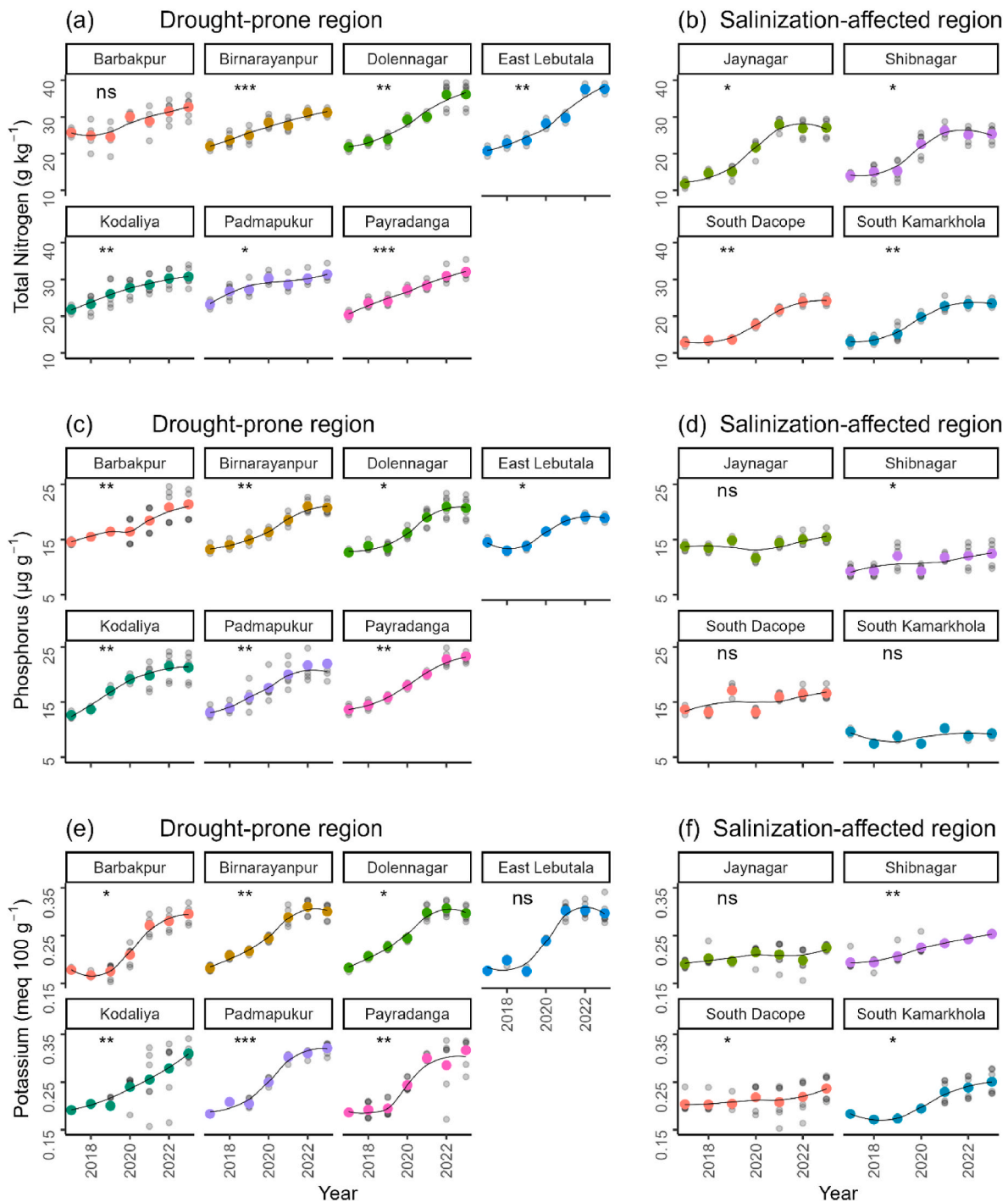


Fig. 3. Temporal patterns of total N, available P, and available K contents in soil samples collected from the 22 experimental fields in 7 villages (Barbakpur, Birnarayanpur, Delennagar, East Lebutala, Kodaliya, Padmapukur, and Payradanga) in drought-prone Jessore district (a, c, e) and 4 villages (Jaynagar, Shibnagar, South Dacope, and South Kamarkhola) in salinization-affected Khulna district (b, d, f) for the period 2017–2023. The asterisks (*, **, and ***) obtained by the Mann-Kendall test indicate the significance ($p < 0.05$, $p < 0.01$ and $p < 0.001$) of the trend of soil N, P, and K contents over 7 years. The solid-colored points represent the mean values of soil nutrients for each respective year. The symbol 'ns' represents the trend is not significant.

3.2. Soil salinity

3.2.1. Temporal trend of soil salinity in salinization-affected region

The results revealed a consistent decrease in soil salinity levels over the 7 years in all the vermicompost-utilized experiments in four villages in salinization-affected region, of which soil salinity significantly decreased in Jaynagar, South Dacope and South Kamarkhola (all $p < 0.05$; Fig. 7a). In South Kamarkhola, the mean soil salinity levels in

vermicompost-utilized experiments decreased from 7.39 dS m^{-1} in 2017 to 5.06 dS m^{-1} in 2023. Similarly, the vermicompost-utilized experiments in Shibnagar, Jaynagar and South Dacope exhibited a decline in soil salinity levels from 6.56 dS m^{-1} , 7.65 dS m^{-1} , and 7.27 dS m^{-1} in 2017 to 5.89 dS m^{-1} , 5.70 dS m^{-1} , and 4.93 dS m^{-1} in 2023, respectively (Fig. 7a). Despite the observed decreasing trend of soil salinity levels in vermicompost-utilized experiments in all four villages, it is important to note that the soil salinity levels still fall within the

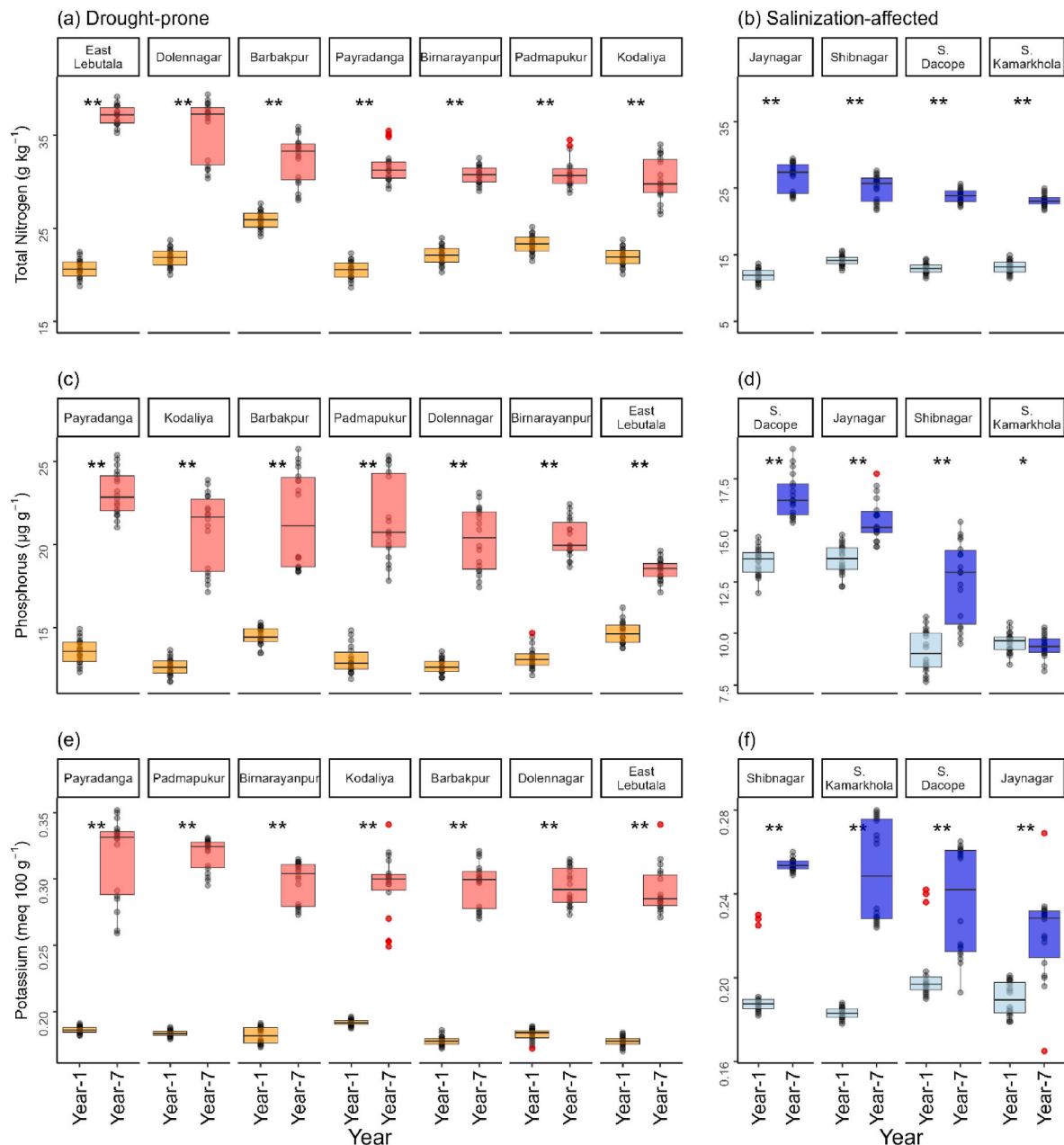


Fig. 4. Comparison of total N (a & b), available P (c & d) and available K (e & f) contents of the start and end of the study in the vermicompost-utilized experiments in drought-prone (a, c, & e) and salinization-affected (b, d, & f) regions. The box plots depict the distribution of total N, P, and K contents in soils, with each box representing the interquartile range of nutrient contents in soils in the respective village. The line within each box indicates the mean nutrient contents in the respective year (Year-1 or Year-7). The whiskers extend to the minimum and maximum values, excluding any outliers (red points), which are represented by individual data points outside the whiskers. The asterisks (*, and **) indicate the statistical significance of the differences ($p < 0.05$, and $p < 0.01$) in nutrient contents in soils between Year-1 and Year-7 obtained by the Wilcoxon test.

moderate salinity class (Fig. 7a). This indicates that while improvements have been observed, there is still room for further enhancement in soil quality and a reduction of soluble salt concentrations. When control experiments were considered, it is observed that none of the villages showed a distinct pattern of the temporal trend in their soil salinity levels (Fig. 7b, all $p > 0.05$). The mean salinity levels in soils of controlled plots ranged within the moderate salinity class (Fig. 7b). Given that Jessore is a drought-prone region and not affected by salinity, we did not account for salinity changes in the soil of the experimental plots in this region.

3.2.2. Effects of cropping patterns on soil salinity

We further assessed the robustness of our findings by comparing soil

salinity differences between two cropping patterns (Fig. 8a and b) and the temporal trends of salinity level (Fig. 8c and d) in both vermicompost-utilized and control experiments. The results showed no significant differences in soil salinity levels between the cropping patterns (brinjal-watermelon, and potato-watermelon). These insignificant differences in soil salinity levels between cropping patterns were evident for both vermicompost-utilized and control experiments (all $p > 0.05$, Fig. 8a and b). In the vermicompost-utilized experiments, the temporal trend of soil salinity levels exhibited significant decreasing trends for both cropping patterns (both $p < 0.05$, Fig. 8c). However, the control experiments did not show any detectable patterns in soil salinity levels for either cropping pattern (both $p > 0.05$, Fig. 8d).

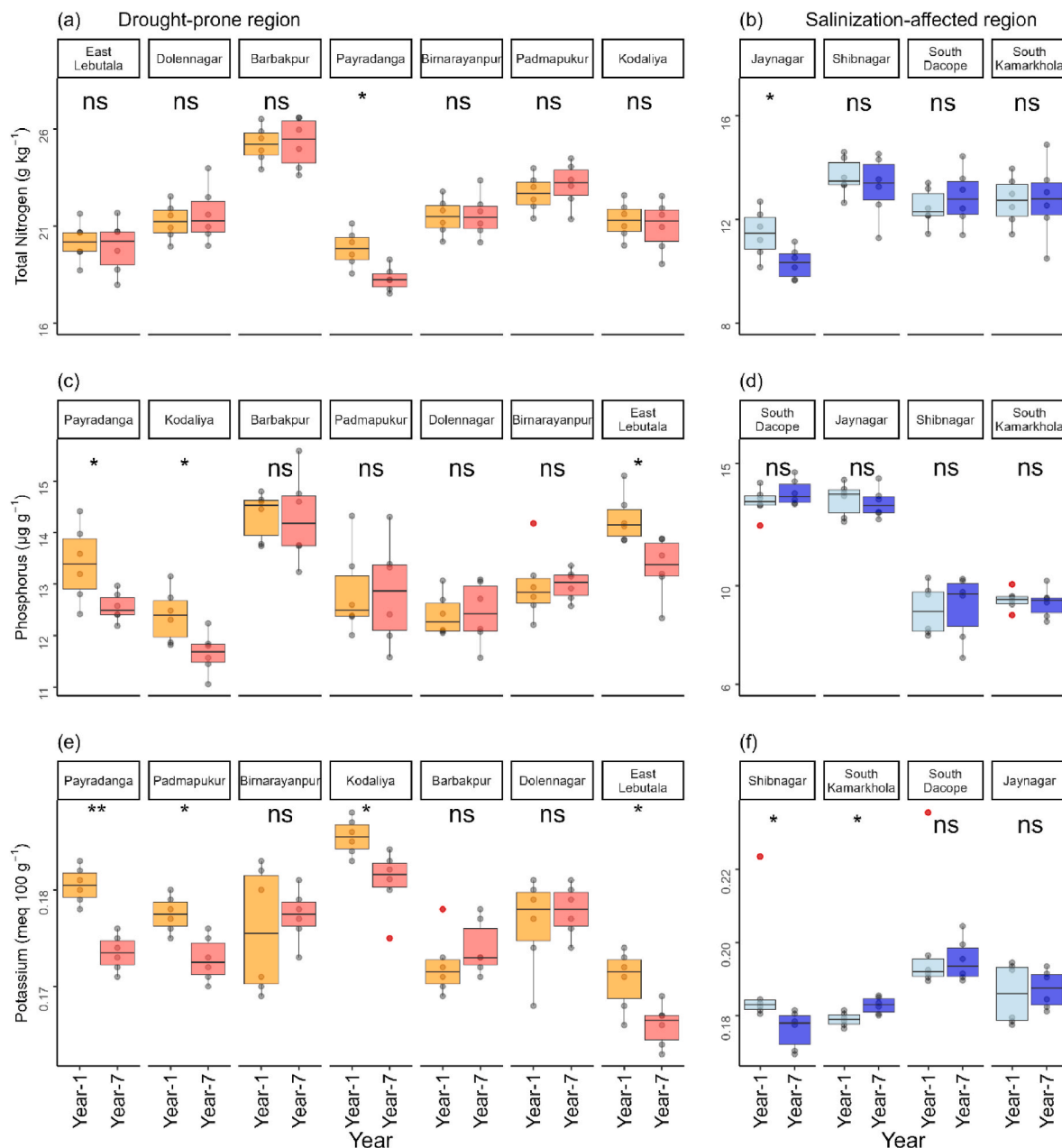


Fig. 5. Comparison of total N (a & b), available P (c & d) and available K (e & f) contents of the start and end of the study in the control experiments. The box plots depict the distribution of total N, P, and K contents in soils, with each box representing the interquartile range of nutrient contents in the respective village. The line within each box indicates the mean nutrient contents in the respective year (Year-1 or Year-7). The whiskers extend to the minimum and maximum values, excluding any outliers (red points), which are represented by individual data points outside the whiskers. The asterisks (*, and **) indicate the statistical significance of the differences ($p < 0.05$, and $p < 0.01$) in nutrient contents in soils between Year-1 and Year-7 obtained by the Wilcoxon test.

4. Discussion

4.1. Soil nutrient contents

Understanding how vermicompost application influences soil nutrients and salinity in croplands in climate-vulnerable regions is crucial for agricultural sustainability. The results of our study on the dynamics of soil total N, available P, and available K contents in vermicompost-utilized experiments in the salinization-affected and drought-prone regions (Figs. 3–5 & S12) reveal appealing patterns. The significant increase in soil total N content in most of our studied villages (Fig. 3) aligns with similar findings in other studies (Arancon et al., 2006; Usmani et al., 2019). This indicates that the interventions implemented, such as vermicompost amendments, have had a positive impact on soil N

levels over time. The increased soil N content indicates potential improvements in soil fertility and nutrient availability. Initially, we observed that the increase in total N content during the first three years was not noteworthy compared to the subsequent four years. This evidence proposes that the long-term effects of vermicompost amendments may take time to become apparent in terms of increasing total N content. This aligns with previous studies that have shown the gradual release of nutrients from vermicompost, as they undergo decomposition and mineralization processes in the soil (Arancon et al., 2006; Usmani et al., 2019; Chatterjee et al., 2020). For example, the increasing concentration of soil N contents in vermicompost-treated soils was reported in strawberry fields (Arancon et al., 2006). Similarly, improved soil N content was reported in vermicompost-amended soils in vegetable (tomato and brinjal) fields (Usmani et al., 2019).

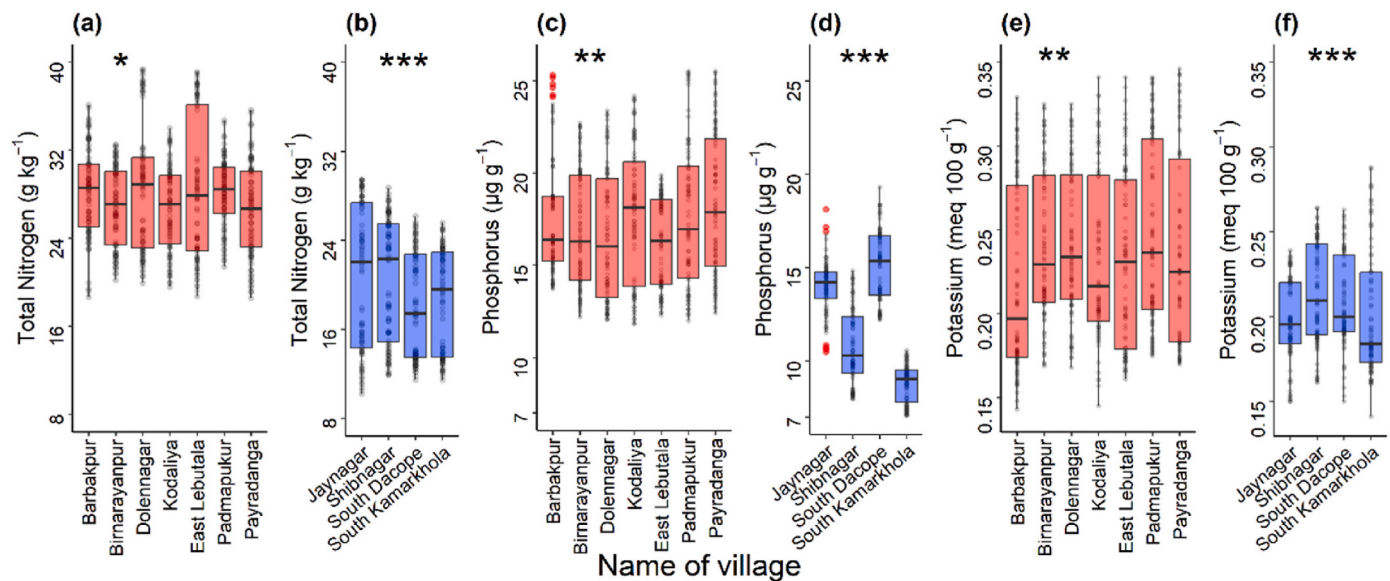


Fig. 6. Comparison of soil nutrient contents: (a & b) total Nitrogen, (c & d), available Phosphorous, and (e & f) available Potassium in the vermicompost-utilized experiments in the drought-prone (a, c, & e) and salinization-affected (b, d, & f) regions. The asterisks (*, **, and ***) indicate the statistical significance ($p < 0.05$, $p < 0.01$, $p < 0.001$) of the differences in soil nutrient contents among the villages. The horizontal lines within the boxes represent the medians, which indicate the central values of data distribution. The boxes themselves represent the interquartile range, with the lower and upper quartiles delineated by the bottom and top edges of the box, respectively. Any data points beyond the whiskers are considered outliers.

Like previous studies (Chalhoub et al., 2013; Lim et al., 2015; Toselli et al., 2019; Przemieniecki et al., 2021), the increasing trend of soil N content in vermicompost-amended soil in our study supports several mechanisms. Firstly, vermicompost releases nutrients through decomposition and mineralization, providing readily available N for plants (Al-Maamori et al., 2023). Secondly, beneficial microorganisms in vermicompost contribute to nitrogen transformation processes, such as nitrification and denitrification (Hao et al., 2021). Thirdly, vermicompost improves soil structure, reducing nutrient leaching and increasing N retention (Bhat et al., 2018). Fourthly, it enhances plant nutrient uptake by improving soil fertility and root development. Lastly, vermicompost acts as a slow-release fertilizer, providing a sustained supply of N over time. These combined mechanisms make vermicompost a valuable tool for promoting soil fertility and sustainable nutrient management in the long run. This aligns with our study finding that the total N content in all villages was significantly higher in year-7 compared to year-1 of the study (Fig. 4).

Precipitation plays a critical role in soil nutrient dynamics, particularly influencing the behavior and availability of N in the soil (Zhou et al., 2025). Given the high precipitation levels in our study regions (Table S2), total N content in the soil may be leached from the top-soil layer. The GLM analysis in our study indicates a humped-back (i.e., reverse U shape), albeit insignificant, relationship between annual precipitation and total N content in the top 30 cm soil in vermicompost-utilized experiments (Fig. S13), suggesting that despite an increase in total N content over the past seven years (Fig. 3), higher precipitation may have contributed to a reduction in total N levels in the top 30 cm soil. Similar findings have been reported in a recent 37-year empirical study in the Loess Plateau of China (Zhou et al., 2025), which demonstrated that soil total N decreased with increasing local precipitation. Moreover, the leaching of N due to excessive irrigation cannot be ruled out as a significant factor in diminishing its availability, as documented by Lv et al. (2020), who reported that soil N leaches into subsoils because of conventional flooding irrigation.

The available P content in the soil exhibited an increasing trend in our seven villages (Fig. 3), indicating the accumulation of available P over time (Fang et al., 2023). This suggests that vermicompost application has contributed to the rise in P levels (Zhang et al., 2020). In our

salinization-affected soils, the application of vermicompost initially led to an increase in P content. However, a subsequent decline was recorded in 2020, indicating that other factors, such as extreme weather events, changes in soil pH or nutrient interactions, might have affected the long-term effectiveness of vermicompost in maintaining P levels. These dissimilar findings highlight the complex nature of P dynamics in different soil and climatic conditions (Fig. S14). The recorded drought in 2020 (Fig. S3) in our salinization-affected region could have reduced the soil P content in this year. Despite the growing evidence of positive effects of vermicompost on building P content in soil (Zhang et al., 2020; Al-Maamori et al., 2023; Fang et al., 2023), our study showed that soil P content was not significantly increased in four villages, of which three are from salinization-affected region. One possible mechanism is that salt-tolerant crops (e.g., watermelon) in our salinization-affected region fully utilize the released P from the vermicompost-amended soil. The other mechanisms could be attributed to the presence of moderate to high levels of salinity, extreme weather events (e.g., periods of high precipitation; Fig. S14), and salt concentration in irrigation water in salinization-affected region affected the P content in soil. This evidence has been reported in several studies in salinization-affected coastal regions of the world (Khoshgoftarmanesh and Nourbakhsh, 2009; Vanissa et al., 2020; Xie et al., 2022). For example, soil P availability in coastal soils in Jiangsu Province in China has been found affected by soil salinity (Xie et al., 2022).

Like total N and available P content in soils, the temporal trend of available K content in soil also showed distinct patterns (Fig. 3). For instance, there was a significant build-up of available K content in soils of 9 villages over 7 years, indicating the influence of vermicompost on soil K availability (Elissen et al., 2023). Despite the use of similar cropping patterns and comparable climatic conditions, the insignificant temporal patterns in K content observed in the control experiments across these villages further confirm that the addition of vermicompost significantly enhanced K content over the seven-year period. Although vermicompost-utilized experiments in two villages (East Lebutala and Jaynagar) did not exhibit a significant positive trend in K content over 7 years, a pairwise comparison of K levels between the beginning and end of the study revealed a significantly higher K content in Year-7 compared to Year-1 (Fig. 4). One notable reason for the lack of

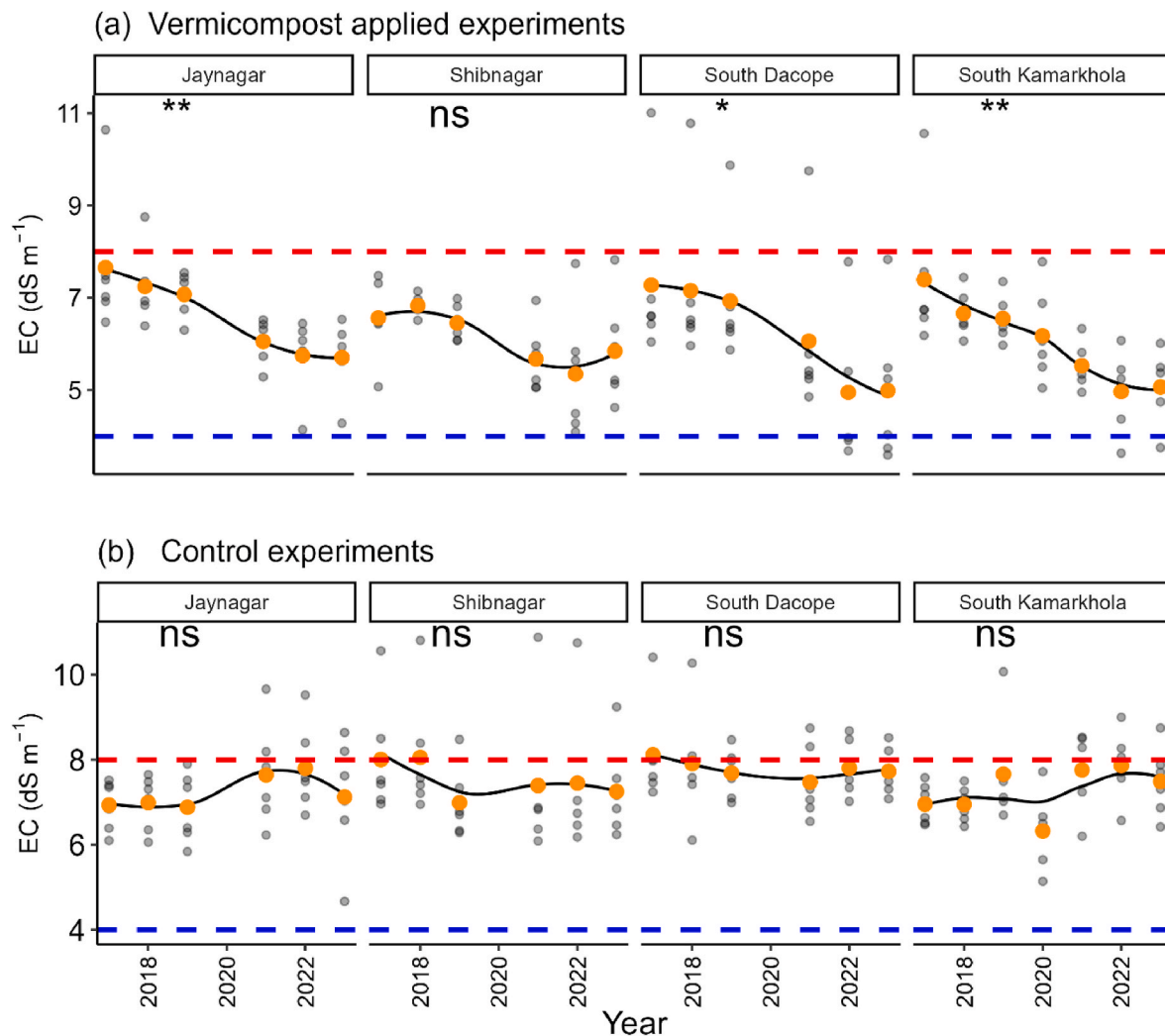


Fig. 7. Temporal trend of soil salinity levels in eight vermicompost-utilized experiments (a) and eight control experiments (b) in 4 villages in salinization-affected region for the period 2017–2023. Soil salinity data for 2020 in 3 villages (Jaynagar, Shibnagar, and South Dacope) are not available in the analysis. Grey points represent soil salinity values in each experiment, dark orange points represent mean values of soil salinity in each year in the respective village. The Loess line represents the temporal trend of soil salinity over 7 years. The blue dashed line indicates the margin (4 dS m^{-1}) of slightly saline soil and the red dashed line represents the margin (8 dS m^{-1}) of moderately saline soil. Points above the red dashed line represent the strong salinity level and points below the blue dashed line indicate the non-salinity levels in soils. Asterisks (*) and (**) indicate the level of significance ($p < 0.05$ and $p < 0.01$) of the temporal trend of soil salinity levels in respective villages. The symbol 'ns' represents the trend is not significant.

significant positive temporal trend of soil K content in these two villages could be resulted from increased precipitation in certain years (Fig. S15), which reduced the K content by leaching from the topsoil. For example, when higher precipitation years were considered, a significant negative relationship was observed between soil K content and annual precipitation in these two villages (Fig. S16). Another possible reason is attributed to the leaching of K due to excess irrigation. This leaching process can wash away K from the root zone, reducing its availability for plant uptake (Ruan et al., 2014). Despite these complex interactions, the positive effect of vermicompost application on increasing soil K content in salinization-affected regions highlight that continuous application of vermicompost over the long run can contribute to soil organic matter buildup, leading to improved soil K content and overall soil health.

In the control plots, the observed insignificant differences of soil N, P, and K between Year 1 and Year 7 (Fig. 5) suggest that under conventional farming practices without vermicompost application, soil nutrient levels may be relatively unchanged over time (Montgomery and Bickel, 2021). However, in certain control plots where significant differences were noted, we found a marked decline in soil nutrient levels by Year 7. This decline highlights the vulnerability of soil health in these areas,

indicating that without proper nutrient management, essential soil nutrients can diminish, potentially leading to reduced agricultural productivity (Ma et al., 2023). In the control plots, the significant reductions in N, P, and K in Payradanga, along with declines in P and K in Kodaliya and East Lebutala, suggest that localized factors (e.g., soil type, and water management) may be influencing nutrient retention and availability. Moreover, the vermicompost-utilized experiments demonstrated that changes in cropping patterns did not significantly affect soil N, P, and K contents over the seven-year period (Fig. S12). This stability indicates that the application of vermicompost may enhance soil resilience, allowing it to maintain nutrient levels despite variations in cropping practices (Pourhosseini et al., 2024).

4.2. Variations of soil nutrient content

The findings of variation of soil nutrient contents among the 11 villages (Fig. 6) indicate that total N, P, and K levels were consistently higher in the drought-prone regions compared to the areas affected by salinity. This suggests that these regions might benefit from vermicompost inputs to mitigate any potential nutrient deficiencies.

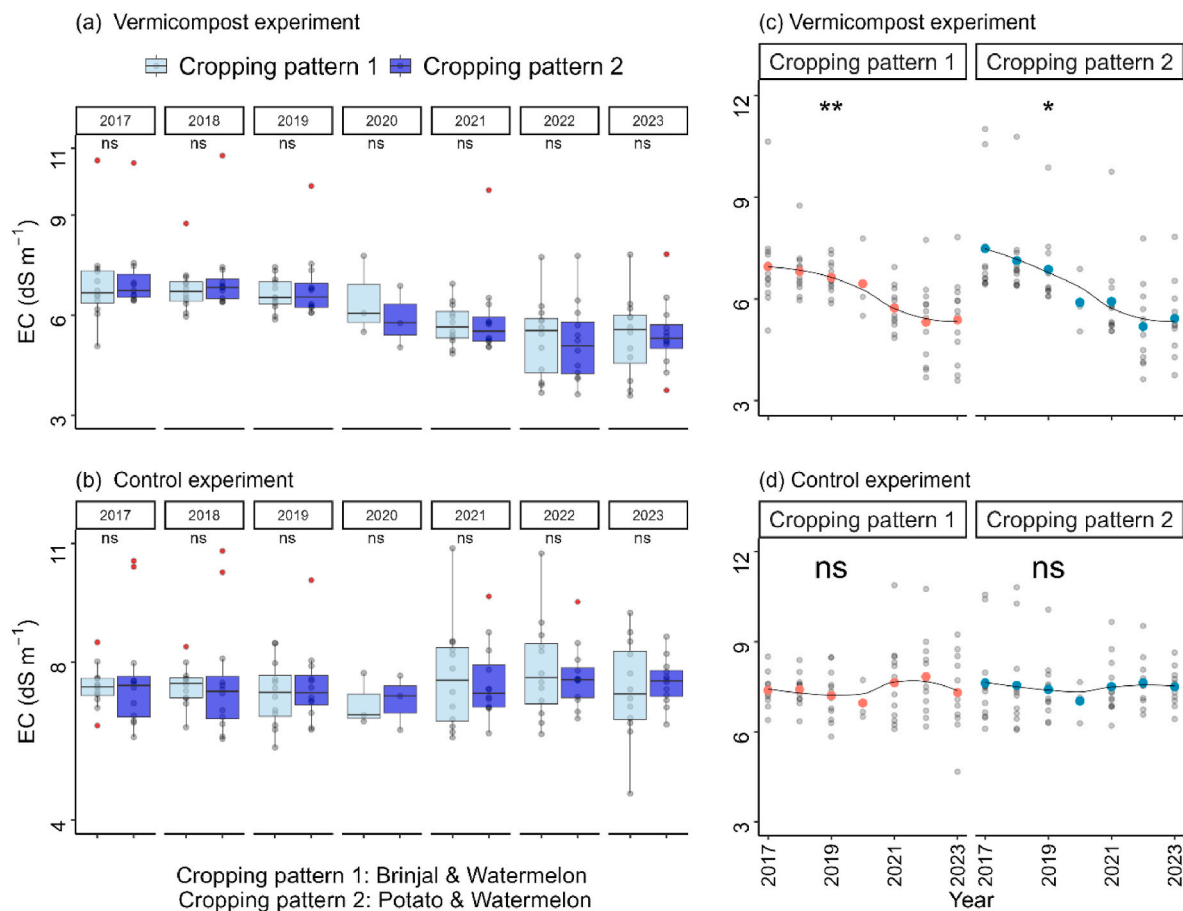


Fig. 8. Comparison of soil salinity between cropping patterns in vermicompost-utilized (a) and control (b) experiments and the temporal trend of soil salinity under two cropping patterns in vermicompost-utilized (c) and control (d) experiments in salinization-affected region. The box plots (a & b) depict the distribution of soil salinity levels, with each box representing the interquartile range of salinity contents in soils. The line within each box indicates the mean salinity levels in the respective cropping pattern (brinjal-watermelon or potato-watermelon). The whiskers extend to the minimum and maximum values, excluding any outliers (red points), which are represented by individual data points outside the whiskers. The Loess lines (c & d) represent the temporal trend of soil salinity in different cropping patterns over 7 years. The asterisks (*, and **) indicate the statistical significance of the trends ($p < 0.05$, and $p < 0.01$) in soil salinity levels. The symbol 'ns' represents the differences or trends is not significant.

Vermicompost is known to be rich in N, P, K, and other essential nutrients. Therefore, the application of vermicompost in drought-prone regions could provide a valuable source of nutrients to supplement the existing soil nutrient levels. However, despite the application of vermicompost, the lower nutrients in soils in salinization-affected regions could have resulted from the leaching of nutrients, ion competition, reduced microbial activity, and limited nutrient mobility (Vanissa et al., 2020; Xie et al., 2022).

In a recent study in the southwestern coastal region (Shapna et al., 2024), the reported soil N ($20.30\text{--}21.91 \text{ g kg}^{-1}$), P ($13.41\text{--}15.23 \text{ } \mu\text{g g}^{-1}$), K ($0.196\text{--}0.216 \text{ meq } 100 \text{ g}^{-1}$) in crop lands is comparable to our observed soil nutrient contents in the control plots in salinization-affected region. The excess salts can create unfavorable conditions for nutrient uptake by plants, causing them to be washed away with excess water, resulting in nutrient depletion in the soil (Fu et al., 2023). The presence of high salt levels, particularly sodium ions, can disrupt the balance of other essential nutrients in the soil. Sodium ions compete with and replace nutrient ions, such as nitrate and phosphate, reducing their availability for plant uptake. This competition negatively impacts the N and P contents in the soil. Salinity can adversely affect soil microbial communities responsible for nutrient cycling. Microbes play a vital role in breaking down organic matter and releasing nutrients in plant-available forms. Salinity stress can inhibit microbial activity, leading to a decreased capacity for nutrient mineralization and nutrient release in the soil (Zhang et al., 2023b).

4.3. Soil salinity in salinization-affected region

Bangladesh exhibits a heightened susceptibility to the ingress of saltwater due to its extensive low-lying coastal region and frequent exposure to tropical storms (Rezaie et al., 2019), and sea level rise (Talukder et al., 2023). The intrusion of saltwater has adverse effects on terrestrial environments, as it leads to an elevation in saline levels of both soil and surface water (Dasgupta et al., 2015). The observed decrease in soil salinity levels in vermicompost-applied soils across all four villages (South Kamarkhola, Shibnagar, South Dacope, and Jaynagar) in our salinization-affected region highlights a positive trend in soil quality and a significant reduction in soluble salt concentrations. These findings suggest potential improvements in soil nutrient levels in these coastal areas. The improvements of soil health because of vermicompost application in salinization-affected region have been reported in several recent qualitative studies (e.g., Hossain and Li, 2024; Shapna et al., 2024). In these previous studies, farmers and agricultural stakeholders expressed the positive effects of vermicompost on soil fertility and pest reduction. Farmers perceptions in previous studies (Hossain and Li, 2024; Shapna et al., 2024) and the empirical evidence in our study of positive effects of vermicompost on soil fertility confirm the role of vermicompost in improving soil health and reducing soil salinity.

The introduction of vermicompost into the soil has facilitated a natural leaching process, allowing salt to be washed away more effectively, thus reducing soil salinity (Sahab et al., 2021). Additionally,

vermicompost application may have enhanced soil organic matter content and microbial activity, leading to improved soil structure and nutrient contents, which has been reported in a maize experiment in saline-alkali soil (Li et al., 2024b). In a recent empirical study, it is evident that the application of vermicompost reduced sodium ion (Na^+) concentration in saline soil and mitigated salinity stress in maize seedlings (Alamer et al., 2022). The vermicompost application in saline-alkali soil in a maize growth experiment also produced similar results, where vermicompost-utilized soil showed reduced Na^+ in topsoil (0–10 cm) and increased in deeper (20–30 cm) layer (Li et al., 2024b). The positive impact of vermicompost on reducing soil salinity in our salinization-affected region is further reinforced by the findings from our control plots. Over 7 years, the control plots in the salinization-affected region, where two different cropping patterns (brinjal-watermelon and potato-watermelon) were practiced using inorganic fertilizers and chemical pesticides, did not exhibit any significant changes in soil salinity. This again supports that irrespective of different cropping patterns, vermicompost application helps in reducing soil salinity level (Hossain and Li, 2024).

It is expected that if vermicompost aids in washing away salts from the topsoil due to high irrigation and increased precipitation, these same factors may also lead to the leaching of soil nutrients (Lv et al., 2020; Zhou et al., 2025). However, in this study, while washing away salts, the use of vermicompost over a seven-year period has been shown to enhance soil nutrient contents. Several mechanisms (e.g. slow release of nutrients, improved soil structure and microbial activity) could contribute to these discrepancies. First, the organic matter in vermicompost breaks down slowly, releasing N, P, and K over time (Raza et al., 2022). This gradual release can effectively counterbalance the leaching of these nutrients that occur with excess irrigation and higher precipitation (Pourhosseini et al., 2024), thereby maintaining or even enhancing soil nutrient levels across the duration of the experiment. Additionally, long-term applications of vermicompost can enhance soil structure and water retention (Li et al., 2024b), which may help reduce the rate at which N is leached away. Improved soil structure facilitates better root penetration and nutrient uptake, thereby enhancing total N availability (Datta et al., 2016). Moreover, the application of vermicompost promotes beneficial microbial activity in the soil (Toor et al., 2024). Over seven years, these microbes can significantly aid in the mineralization of nutrients, converting them into forms that are more readily available for plant uptake (Toor et al., 2024).

In a recent study in southwestern coastal regions (Khulna, Satkhira, and Bagerhat) of Bangladesh, Lam et al. (2022) reported that soil salinity in Bagerhat and Satkhira ranges between moderate to very strong saline ($4\text{--}32\text{ dS m}^{-1}$) and in Khulna ranges between slightly to moderately saline ($2\text{--}8\text{ dS m}^{-1}$) in the year 2015. In our study, we recorded strong salinity in soils in some experimental and control plots in 2017, which is higher than in the previous study (Lam et al., 2022). One explanation for this discrepancy is that our soil samples were collected in March–April (dry period), whereas Lam et al. (2022) assessed the soil salinity level for the samples collected in May–June. Precipitation, particularly during the May–June period (the monsoon starts in June), could contribute to the reduction of salt concentrations in the soil. As rainwater infiltrates the soil, it helps to disperse and leach salt downward, reducing their overall concentration in the soil profile. This dilution effect can lead to a decrease in soil salinity levels. Water percolates through the soil, carrying the soluble salts downward and out of the plant root zone. As raindrops hit the soil surface, they displace salt particles, causing them to move and redistribute (Dasgupta et al., 2015).

It is crucial to acknowledge that the soil salinity levels in vermicompost-utilized experiments, despite showing a declining trend in all four villages in our study, remain classified as moderately saline. This suggests that although improvements have been observed, the soil quality has not yet reached an optimal level, and further enhancement is needed. The moderately saline classification implies that there is still a risk of salinity-related challenges for crops and vegetation in these areas

(Lam et al., 2022). It may hinder optimal plant growth, nutrient uptake, and overall agricultural productivity. The findings of the decreasing trend of soil salinity levels in our study suggest that vermicompost use, along with potential changes in irrigation practices and coastal management strategies, have played a role in reducing soil salinity levels. These results highlight the potential benefits of vermicompost as a soil amendment in coastal areas (Hossain and Li, 2024), offering promising opportunities for sustainable agriculture and improved soil health in the face of sea level rise (Talukder et al., 2023).

4.4. Research implications

Soil fertility is declining while soil salinity level is increasingly becoming a problem in Bangladesh, posing serious challenges toward agricultural productivity and sustainability. The temporal changes in nutrient contents in vermicompost-applied experiments across the drought-prone and salinization-affected areas are valuable in developing an integrated understanding of the long-term efficacy and sustainability of vermicompost as a soil amendment. These insights inform management options for soil fertility, nutrient optimization strategies, and adaptation to climate change that enhance the fertility of soils, reduce environmental hazards, and maintain crop productivity across agroecological regions. The potential of vermicompost to mitigate soil salinity offers promising prospects for improving agricultural productivity in salinization-affected regions. The application of vermicompost to salinization-affected soils can be seen as a nature-based solution in mitigating salinity in soils under increasing soil and water salinity caused by sea level rise in coastal regions worldwide.

4.5. Forward-looking strategies

Vermicompost utilization in nutrient-deficit and salinity-affected fields is a transformative strategy for controlling soil salinity and enhancing soil fertility in arable land. Our study reveals that vermicompost application not only declines soil salinity in salinization-affected region but also enhances soil total N, available P, and available K content in both regions, which is crucial for improving agricultural crop productivity. This innovative approach aligns with sustainable agricultural practices, boosting healthier soil ecosystems while minimizing reliance on inorganic fertilizers. We advocate for the development of comprehensive guidelines and training programs for farmers on the effective use of vermicompost, empowering them to adopt these practices and enhance soil management. Ultimately, our findings position vermicompost as a key solution for addressing soil salinity challenges, suggesting its potential as an important tool for agricultural resilience in regions facing similar issues worldwide.

4.6. Study limitations

The study did not extensively explore other potential confounding factors, such as differences in irrigation methods and quality of irrigation water, which may affect the soil nutrients and salinity. The work focused more on soil nutrient levels, and salinity mitigation, without considering the crop yield and economic perspectives, like cost-effectiveness, profitability, and market dynamics. Crop yield, economic viability and plausible constraints to adoption need to be assessed for wide-scale vermicompost implementation in agricultural systems.

5. Conclusion

Understanding the role of vermicompost in ameliorating soil salinity and improving soil nutrient is central to sustainable agriculture and building resilience in climate-vulnerable regions. Using the empirical evidence covering 37 field experiments in two differential geographical settings (drought-prone and salinization-affected regions) of Bangladesh, we assessed the impacts of vermicompost on soil nutrient

(total N, available P and available K) and salinity levels for the year 2017–2023. The significant increase in soil N and K contents across the experiments highlights that the application of vermicompost can help in building up soil fertility and nutrient availability toward sustainable crop cultivation. However, the temporal patterns for soil P content showed an increase for the first 3 years but subsequently experienced a decline in certain salinization-affected experiments. This highlights the complexity of nutrient dynamics in soils affected by salinity, suggesting the need for tailored approaches to address soil nutrient imbalances in such regions. The insignificant differences in soil salinity or nutrient levels between different cropping patterns in vermicompost-utilized experiments further provides compelling evidence of positive impacts of vermicompost on enhancing soil N, P and K while reducing soil salinity, rather than changes in cropping patterns. This study underscores the promising potential of vermicompost as a valuable resource for smallholder farmers in drought-prone and salinization-affected regions. The findings of this study advocate for the widespread adoption of vermicompost as a critical strategy for enhancing soil health and agricultural sustainability in vulnerable regions, ultimately supporting the livelihoods of smallholder farmers facing the challenges of drought and salinity.

CRediT authorship contribution statement

Md Lokman Hossain: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Khusnur Jahan Shapna:** Writing – original draft, Validation, Software, Resources, Methodology, Investigation, Data curation, Conceptualization. **Jianfeng Li:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Md Humayain Kabir:** Writing – review & editing, Resources, Methodology. **Farzana Siddika:** Resources, Investigation, Data curation. **Saifullah Khandker:** Writing – review & editing, Resources, Methodology, Funding acquisition. **Carl Beierkuhnlein:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Data availability

The quantitative data related to soil nutrient and salinity can be obtained from the corresponding author (lokmanbbd@gmail.com). The climate data is available from the Bangladesh Meteorological Department.

Funding

This work was supported by a research grant from the Research Grants Council (RGC) of the Hong Kong Special Administrative Region (SAR), China [project number RFS2223-2H02]. Parts of this study were supported by the EU Horizon 2020 Project e-shape under grant No. 820852. M.L. Hossain was supported by the RGC of the Hong Kong SAR, China through RGC Postdoctoral Fellowship Scheme 2024/25 [Award Ref. No.: PDFS2425-4S05]. The German University Bangladesh provided grant support for data collection and soil tests conducted in this study.

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.

Acknowledgements

The authors express sincere gratitude to the household members and other respondents who participated in this research over seven years. Their valuable contributions and willingness to engage in the experiments have been instrumental in the success of this study. Our heartfelt appreciation to all the volunteers who provided their valuable support throughout this research. Climate data was obtained from the Bangladesh Meteorological Department.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2025.145595>.

Data availability

Data will be made available on request.

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