Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Growth and Yield of Hot Pepper (Capsicum Annuum L.) Varieties in Response to the Integrated Application of Npsb Fertilizer and Municipal-waste Compost at Arba Minch, South Ethiopia

Gebre-Egziabher Haileslassie Gebremedhin
gegziabher.hselassie@jku.edu.et
Jinka University
Kebede Jobir Bedadi
Arba Minch University
Kinfe Kassa
Arba Minch University
Muluhabit Birhanu Andualem
Jinka University

Research Article

Keywords: Capsicum annuum L, Integrated nutrient management, municipal-waste compost, NPSB fertilizer, soil fertility, variety response, yield optimization

Posted Date: November 12th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11305613/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Abstract

Hot pepper (Capsicum annuum L.) productivity in Ethiopia remains constrained by suboptimal nutrient management and lack of variety-specific fertilizer recommendations. This study evaluated the effects of integrated application of NPSB fertilizer and municipal-waste compost on growth, yield, and yield-related traits of three hot pepper varieties (Melka Shote, Mareko Fana, and Halaba Local) under irrigated conditions at Arba Minch, South Ethiopia. A field experiment was conducted during the 2024 cropping season using a randomized complete block design with a 3 × 5 factorial arrangement and three replications. Treatments comprised five integrated nutrient management strategies: (i) 10 t ha⁻¹ compost (100% organic), (ii) 7.5 t ha⁻¹ compost + 50 kg ha⁻¹ NPSB (75:25), (iii) 5 t ha⁻¹ compost + 100 kg ha⁻¹ NPSB (50:50), (iv) 2.5 t ha⁻¹ compost + 150 kg ha⁻¹ NPSB (25:75), and (v) 200 kg ha⁻¹ NPSB (100% inorganic). Data were subjected under the 'agricolae' package in R software (version 4.4.2).to two-way analysis of variance (ANOVA) following normalization procedures to meet assumptions of homogeneity of variance and normality of residuals. Shapiro-Wilk tests confirmed normal distribution of residuals ($W > 0.95$, $p > 0.05$) for all measured parameters after appropriate transformations where necessary. Levene's test verified homogeneity of variances across treatment combinations ($p > 0.05$). Treatment means were separated using Duncan's Multiple Range Test (DMRT) at $p \leq 0.05$ significance level. Results showed that variety × nutrient management interaction significantly influenced most growth, phenological, fruit, and yield parameters ($p \leq 0.05$). The Mareko Fana variety under the balanced 50:50 treatment (5 t ha⁻¹ compost + 100 kg ha⁻¹ NPSB) produced the tallest plants (77.78 cm), maximum canopy diameter (62.42 cm), and highest number of primary branches (14.66). Melka Shote under the 25:75 treatment (2.5 t ha⁻¹ compost + 150 kg ha⁻¹ NPSB) achieved the highest number of fruits per plant (119.1), while Mareko Fana with sole NPSB (200 kg ha⁻¹) produced the longest fruits (10.73 cm). For yield, Mareko Fana with sole compost (10 t ha⁻¹) recorded the highest total fresh yield (11.41 t ha⁻¹), whereas the 75:25 treatment (7.5 t ha⁻¹ compost + 50 kg ha⁻¹ NPSB) optimized marketable dry yield (3.46 t ha⁻¹) and total dry yield (4.04 t ha⁻¹) in the same variety. Halaba Local consistently performed poorly across all treatments, confirming its unsuitability for intensive integrated nutrient management. Soil chemical analysis revealed improvements in organic carbon, available phosphorus, and cation exchange capacity under treatments with higher compost proportions, particularly the 75:25 and 100% compost treatments. The integrated application of NPSB fertilizer and municipal-waste compost significantly enhanced hot pepper productivity with highly variety-specific responses. The balanced 50:50 treatment is recommended for optimizing vegetative growth and fruit quality in Mareko Fana and Melka Shote, while the 75:25 treatments maximizes dry matter production for commercial dried pepper markets. These findings underscore the critical need for genotype-specific nutrient management strategies and demonstrate the sustainability benefits of integrating organic amendments for long-term soil fertility maintenance in the Arba Minch irrigation system.

1. INTRODUCTION

The plant family Solanaceae includes the hot pepper (*Capsicum species*). *Capsicum annuum L., C. frutescens L., C. chinense, C. baccatum L., and C. pubescens R*. are five principal domesticated species

(Nigussie and Zewdia, 2023). The genus Capsicum is native to Bolivia in the south and Mexico in the north. Although it has been a mainstay of the human diet in Latin America since around 7500 BC, the Portuguese brought it to Ethiopia between 1520 and 1770 (Sufiyan, 2024). Hot pepper (*Capsicum annuum L*.) is the world's most important vegetable after tomato and is used as fresh, dried, or processed products, as vegetables and spices, or condiments. This crop is a prominent cash crop for many developing countries' farmers, such as Ethiopia, Nigeria, Ghana, China, India, Pakistan, Bhutan, Indonesia, Cambodia, and Thailand. *Capsicum annuum L*. dominates the world spice trade; while sweet pepper has become a popular vegetable and cash crop in the tropics for smallholders in different areas, pepper is grown predominantly as monocropping and rotated with cereals or legumes during the main rainy season. However, the area of production in the dry season using irrigation is also found, particularly in the rift valley of Ethiopia (Bekele, 2022).

Capsicum annuum L. is estimated to be cultivated on 4 million hectares globally; production has increased steadily at an average annual rate of 5% compared to Ethiopian cabbage, which accounts for 16.33% of the total area under vegetables. Red pepper accounts for a substantial portion of vegetable cultivation in Ethiopia, making up roughly 73.09% of the total area (Shamil and Merga, 2022). Which has been growing peppers for centuries, which is making it the most popular vegetable in the nation, 3.82% and 67.53% of the estimated total vegetable area are covered by green and red hot peppers, respectively. Green and red hot peppers are produced nationally in 41,250 and 254,188 tons, respectively, with an average productivity of 6.688 and 2.331 t ha^{-1} (Aliyi, 2018); a total of 62,247 tons of green pepper and 307,457 tons of dry hot pepper were produced (Abate et al., 2019; Bekele, 2022). The total production of dry pod is expanded to 174,463 hectares, producing about 313,115 tons (Asatov and Abdiyev, 2023; Assefa et al., 2024). The yield status of hot peppers expanded to the intervals of 1.8 to 2.5 t ha^{-1} for dehydrated peppers and 15 t ha^{-1} to 20 t ha^{-1} for green peppers under investigation in field conditions.

Conversely, the yield of hot peppers on average for smallholder farmers is relatively low in relation to the global average of 2.57 t ha^{-1} dry and 17.8 t ha^{-1} raw, respectively. The oleoresin capacity of capsicums varies: about 9.0% in "PBC-776" and 21.8% in "PBC-380," and the Merakofana variety of Ethiopia contains 3.5% of oleoresin, which is very low in comparison to the international level of 5–12% (Asmare and Woldeselassie 2026). According to Asrat et al. (2025), hot pepper can be used fresh, dried, or processed and is rich in vitamins "A" and "C," as well as minerals like magnesium and potassium. In Ethiopia, pepper is a significant cash crop (Gobie, 2019; Assefa et al., 2020) and is essential to the country's food security and efforts to reduce poverty (Kahsay, 2017). *Capsicum annuum chinense* types such as "BRC" and habanero varieties (orange habanero and red habanero) reported from Tanzania trials can achieve higher productivity and strong antioxidant activity, supported by optimized integrated nutrient management (INM) strategies. In these systems, balanced fertilization with nitrogen-phosphorus-potassium (200–300 kg ha^{-1}) and a lot of compost or manure (20–30 t ha^{-1}) improves yield stability and helps with antioxidant and radical-scavenging performance (Mweta and Nnungu, 2024). Red bell peppers (Capsicum annuum) are especially nutrient-dense globally, delivering higher vitamin "C" and vitamin "A" (128 mg vitamin "C" and 3131 IU vitamin A per 100 g), and can produce higher fresh yields (15–20 t ha^{-1}), especially under precision fertilization and micronutrient-rich soils. Internationally, the adoption of

high-yielding F1 hybrids often developed for multiple resistances through programs such as the World Vegetable Center has increased dry pod yields to approximately 2.57-5.0 t ha^{-1} (Abdeta et.al., 2024).

Balanced and often moderate rates of nitrogen (N) and integrated organic–inorganic management, rather than heavy fertilizer applications, maximize hot pepper yield and quality and improve soil health (Hunde, 2020). In Ethiopian field trials, 50 kg ha^{-1} of DAP and 50 kg ha^{-1} of urea was found to be the economically optimal level for marketable yield, with no additional benefit from 75–100 kg ha^{-1}. In Spain, open-field processing pepper plateaued at roughly 120 kg N ha^{-1}, above which leaching risk increased (Vadillo et al., 2024). Reducing fertigation by 20–40% before harvest maintained yield and improved nutrient accumulation and fruit flavour (Wang et al., 2022), and an NH_4^+:NO_3^- ratio of 25:75 maximized dry matter, nutrient uptake, root growth and multiple quality traits including capsaicinoid (Zhang et al., 2019). Common deficiencies of Ethiopian soils include NPK, sulphur, boron, zinc, and iron (Hunde, 2020). Potassium deficiency increases capsaicin while sulphur deficiency decreases it (Da Silva et al., 2019). Yield and capsaicin were boosted by nano-micronutrient sprays coupled with 75–100% recommended NPK (Ahmed, 2020). Integrated strategies such as mineral NPSB combined with farmyard manure (Chimdessa et al., 2019), 50% soil + 50% foliar NPK (Hemida *et al*., 2022), or PGPR with vermicomposting and 75% NP (Sharma *et al*., 2023)Increase yield, nutrient use efficiency, fruit quality, and soil properties. Chemical-only fertilization resulted in lower phenolic, lycopene, and antioxidant activity than organic and biological fertilization (Stoleru et al., 2023). Application of effective microorganisms plus 150–180 kg N ha^{-1} under salinity increased yield by 28% and improved capsaicin and nutrient balance (Sibhatu et al., 2016; Abdelkhalik et al., 2023). Therefore, both the right variety and proper nutrient management are indispensable steps in the process of transforming a poor livelihood into a better one (Munda and Shumbulo, 2020). Declining yields, usually among other things, result from a lack of information about varieties best suited for particular agro-ecological conditions (Chernet and Zibelo, 2019; Mada and Lebiso, 2021). The recommended rates for hot pepper in Ethiopia are 200 kg ha^{-1} of DAP and 100 kg ha^{-1} of Urea (Al-Harbi et al., 2020; Biratu et al., 2021).

The Municipal Solid Waste compost is an organic fertilizer made through the biological breakdown of the biodegradable content of the urban waste. It serves as a sustainable method of waste disposal that addresses issues of environmental pollution as well as soil infertility in developing nations. The use of MSW compost is quite feasible in Ethiopia where about 60% of household waste in Addis Ababa and 75% of waste in Southwest towns of Ethiopia are organic (Debele and Fereja,2024).The resulting compost usually contains physical and chemical properties with pH values between 6.9–7.8 (slightly alkaline), moisture level of 18–32%, organic matter level of 30–70% (more than 50% is desirable), and nutrient levels of 1–2% total nitrogen, 0.15-1.0% phosphorus (mean of 0.64%), and 0.65–1.03% potassium (mean of 0.83%) by dry weight. New development in Arba Minch town includes the state-of-the-art waste composting technology from the RUNRES Project that processes 133.76 tons of solid waste every 25–30 days to generate about 86.95 tons of high-quality organic fertilizer per cycle (Woldeamanuel *et al*.,2022). However, apart from difficulties related to heterogenous nature of the waste, which is needed to be treated first, removal of contamination like plastics, glass, and metals, as well as

lack of application by households (16% of those surveyed in Addis Ababa apply organic compost in their gardens as fertilizer), MSW compost, containing average nutrients levels of 1-1.5% N, 0.3–0.8% P, and 0.7-1.0% K in addition to high organic matter (> 50%) may be considered a source of nutrients for crops, especially hot pepper, in the context of integrated nutrient management system (Mamo *et al*.,2021).

Statement of the problem: Ethiopia is a major producer of hot pepper, which is an important source of income for many smallholder farmers and plays a key role in the spice trade and national food security (Mohammed et al., 2015; Mensa et al., 2023). Arba Minch, which is in the Great Rift Valley, has a lot of potential for growing hot peppers because of the temperature (21–27°C), and there is already irrigation infrastructure that could support year-round, high-intensity cultivation (Gelu et al., 2024). However, there is a significant "yield gap": the production of hot peppers in the Arba Minch area remained constant at about 1.7 t ha^{-1}, which is below both the global average and the national average for Ethiopia of 2.57 t ha^{-1} (CSA, 2023). This local underperformance is a national challenge: This local inefficiency arises due to an important and multifaceted problem at the national level, which includes the absence of localized nutrient recommendations, poor adaptation of DAP/Urea fertilizers to new NPSB fertilizers, and a significant deficiency in variety-specific selection criteria. Despite the availability of high-yield varieties and locally adapted land races, small farmers tend to choose and grow these varieties randomly without any idea about their nutrient needs and physiological attributes. The current agronomical system of the region assumes all hot pepper varieties to be homogeneous while each genotype has highly varying traits in terms of vegetation, rooting, and nutrient absorption.

Though blended fertilizers like NPS and NPSB have been tried on hot pepper in Ethiopia, the current recommendations for NPSB application in Arba Minch area are still mostly extrapolated from experiments on cereals and legumes done in other regions, not from locally calibrated, hot pepper specific studies that incorporate organic sources. Previous work at Arba Minch, such as Mensa et al., (2021) evaluated NPS rates on different hot pepper varieties and carried out partial budget analysis, but this study was limited to NPS alone and did not consider NPSB or its combination with municipal solid waste compost. Similarly, Muhie et al., (2023) in Raya Kobo, for example, studied NPSB with urea for hot pepper under different agro ecology and without municipal compost and validation under the soil and irrigation conditions of Arba Minch.

Hence, there is still a lack of evidence regarding the effect of combined application of NPSB and compost of municipal organic solid waste on hot pepper productivity, soil fertility, and economic returns under the specific conditions of the Arba Minch irrigation system. This research gap was addressed by (i) evaluating the agronomic response of hot pepper to the integrated use of NPSB and municipal compost, (ii) assessing their effects on selected soil chemical properties and nutrient availability, and (iii) identifying economically optimal NPSB compost combinations for sustainable hot pepper production in Arba Minch. In this way, this study gives locally calibrated, crop and site specific integrated nutrient management recommendations that were not available from earlier hot pepper fertilizer studies. This gap highlights the need for targeted studies to determine the specific nutrient requirements and optimal fertilization strategies for hot pepper production. The challenges call for the development of effective

integrated application management strategies combining blended fertilizers (NPSB) with municipal organic solid waste compost. Although NPSB fertilizers have been introduced in the area, depending on municipal compost alone may not be practical due to its limited availability, high application requirements, and labor-intensive application processes. Therefore, research on balanced fertilization strategies that combine both organic and inorganic sources is essential for improving both the productivity and sustainability of hot pepper cultivation in the study area. Finally the investigation is aimed To evaluate the effect of integrated application of Compost and blended (NPSB) on the growth and yield of hot pepper varieties

2. MATERIALS AND METHODS

2.1. Descriptions of Experimental Site

The experiment was conducted under irrigated conditions during the 2024 crop season at the Arba Minch City farm of the Gamo Developmental Association (GDA) in Gamo Zone, southern Ethiopia, located at 1,220 m above sea level (6° 00' 00.00" N, 37° 34' 59.99" E). The region experiences a mean annual rainfall of 600 to 650 mm with mean annual minimum and maximum temperatures of 15.6–17.2°C and 30.4–31.3°C, respectively (Mensa et al., 2021). Experimental soil has been classified as clay, and its base characteristics have been found to be slightly acidic in pH (5.8–6.2), moderate in organic carbon (1.2–1.5%) and phosphorus (15–20 mg kg^{-1}). There had been cultivation of maize (Zea mays L.) in this field during the year 2023 with the same irrigation schedule, and no Capsicum species have been cultivated in the last two years so that there is little chance of any carryover disease. Irrigation was provided through a drip irrigation system at 7-day interval, and quantity of water used was about 45–50 L m^{-2} per irrigation (450–500 m^3 ha^{-1}). Quantity of water per irrigation varied according to crop phenology: 30 L m^{-2} for nursery transplants (5-day interval), 45 L m^{-2} for vegetative stage (7-day interval), 50–55 L m^{-2} for flowering and fruiting (6–7 day interval), and 35–40 L m^{-2} for maturity (8–9 day interval) with total use of water amounting to 8,500-9,000 m^3 ha^{-1} per season. Quality of irrigation water was found to be within acceptable limits, having pH 7.2–7.5, EC 0.4–0.6 dS m^{-1}. (Schmitter et al., 2016) (Fig. 1).

The experiment was conducted at Chano Mille, Arba

Minch Zuria District of Gamo Zone (formerly known as

Gamo Gofa Zone, Southern Ethiopia, from July 2018 to

February 2019, in the 2018/2019 cropping season under

supplementary irrigation (Fig. 1). The study site is located

about 500km South of Addis Ababa, the capital city of

Ethiopia, at an altitude of 1220 meters above sea level. The

The area received an average rainfall of 320.1mm, with the minimum

and maximum temperatures of 17.2 and 31.3°C, respectively

during the experimental period (July 2018–February 2019)

[13].

The experiment was conducted at Chano Mille, Arba

Minch Zuria District of Gamo Zone (formerly known as

Gamo Gofa Zone, Southern Ethiopia, from July 2018 to

February 2019, in the 2018/2019 cropping season under

supplementary irrigation (Fig. 1). The study site is located

about 500km South of Addis Ababa, the capital city of

Ethiopia, at an altitude of 1220 meters above sea level. The

The area received an average rainfall of 320.1mm, with the minimum

and maximum temperatures of 17.2 and 31.3°C, respectively

during the experimental period (July 2018–February 2019)

[13].

2.2. Treatments, Design, and Procedures

2.2.1. Nutrient treatment application

Three types of hot peppers were used in the study to test five different amounts of total nutrients using a combination of NPSB fertilizer and compost (Egnanew Mayet-Qulize). The recommended quantities of 200 kg ha^{-1} NPSB (18.9% N, 37.7% P_2O_2, 6.95% S, and 0.1% B) and 10 t ha^{-1} compost (1.2% N, 0.29% P_2O_2, 0.15% S, and 0.001% B) (Muhie et al., 2023; Soresa, 2023) was applied.

2.2.2. Experimental design

The planting arrangement followed a spacing of 70 cm between rows and 30 cm between individual plants under the irrigation system. Each experimental plot covered an area of 12.48 m^2 (3.90 m in length by 3.20 m in width), with 2 m and 1.5 m maintained between replications and plots, respectively. The gross area of the experimental site measured 1028.16 m^2 (75.6 m in length by 13.6 m in width). The treatments were arranged in a randomized complete block design (RCBD) with a factorial arrangement (3×5 = 15) and consisted of three replications.

2.2.3. Nursery cultivation and field transplanting procedures

Seedlings were raised in three elevated seedbeds (10m length × 1m width × 0.15m height) and mulched with locally sourced grass to optimize moisture retention and germination. After a 56-day nursery period, seedlings reaching an average height of 25 cm and possessing four to six true leaves were transplanted into the experimental field on April 6, 2024. The field was organized into three uniform blocks based on slope gradient, which were thoroughly ploughed and levelled to ensure a suitable tilth. Fertilization was managed through the application of 200 kg ha^{-1} of NPSB and 10 t ha^{-1} of compost. The NPSB was incorporated into the soil at a depth of 10 cm during land preparation to ensure basal nutrient availability. The six-months-aged compost generated through the aerobic pit approach was applied using a split-application technique: 50% compost was applied during the first weeding (after 15 days of planting), and the other half was applied during the second cultivation operations after 45 days of planting in order to establish plants and conserve soil moisture.

This technique was chosen because it ensures adequate matching of the timing of nutrient availability with nutrient requirements during phenology of hot pepper crops. Hot pepper develops an advanced root system capable of harvesting nutrients from the soil after 15 days of planting. Therefore, the aged compost that already has nutrients in plant-available form (NH_4^+, NO_3^-, and $H_2PO_4^-$) will provide nutrients within 5–10 days after its incorporation into soil. Moreover, nutrient availability during flower and fruiting is increased because the second compost application matches phenological peak nutrient requirements. Finally, the split-application technique minimizes leaching loss of nutrients by up to 40–50% compared to the single application technique (Mensa et al., 2021 and Mossie et al., 2024). Plants' acquisition of nutrients from compost at 15 days: The aged (6-month-old) compost has stabilized organic materials that are mineralized quickly by microbes to provide N, P, S, and micro-nutrients (B, Zn) within 7 to 15 days. By incorporating the compost after 15 days since planting, the nutrients are supplied directly in the root zone, where the processes of microbial action and root exudates enable quick uptake. N is mineralized within 5 to 7 days and later converted to nitrate form through nitrification within 10 to 15 days, while P is mineralized using organic acids and phosphatase activities within 10 to 15 days (Ejigu et al., 2021; Jibril and Bekele, 2022). For data precision, a net plot was established using the three central rows of each five-row plot, from which ten representative plants were selected for sampling. The crop cycle concluded with a final harvest in October 2024.

2.3. Experimental Materials

The experiment used three hot pepper (*Capsicum annuum* L.) varieties: Melka Shote, Mareko Fana, and Halaba Local. These varieties were selected based on their differences in growth habit, yield potential, pod characteristics, and local adaptation (Table 1).

Table 1
Description of hot pepper varieties

Cultivars	Env. condition required			Maturity year denotes yield.		
	Altitude	Temp.	Rain fall	Maturity	Year of	Yield
Masl	(0C)	(mm)	Days	Release	(t ha^{-1})	
Melka Shote	1000–1800	15/27	600–680	110–120	2006	2.5-3.0
Mareko Fana	1200–2100	15/27	600–680	120–135	1976	1.5–2.5
Halaba Local	1000–1600	17/22	600–680	90–150		1-1.5

Source

(Nigussie and Zewdia, 2023).

2.4. Data Collection and Analysis

Data collection evaluated growth, phenological, fruit, and yield parameters using ten randomly selected sample plants from each net plot alongside whole-plot observations. Vegetative traits (plant height, canopy diameter, and primary branch count) were recorded at final harvest, while phenological milestones (days to 50% flowering, 50% fruit set, maturity, first harvest, and harvest duration) were logged as plot-level thresholds were reached. Physical fruit attributes (length, diameter, pericarp thickness, and seeds per fruit, hundred-seed weight, and dry-to-fresh weight ratios) were quantified using calipers and precision balances. Cumulative net plot harvest data were converted to calculate total fresh yield, marketable dry yield, unmarketable dry yield, and total dry pod yield (t ha^{-1}). Data were subjected to a two-way analysis of variance (ANOVA) to evaluate the main effects and interactions of variety (3 levels) and integrated nutrient treatment (5 levels). Assumptions of normality and variance homogeneity were verified using Shapiro-Wilk and Levene's tests, respectively. Treatment means were separated using Duncan's Multiple Range Test (DMRT) at $\alpha = 0.05$ via the agricolae package in R software (version 4.4.2).

3. RESULTS AND DISCUSSION

3.1. Growth Response

3.1.1. Plant height (PH)

The interaction between variety and integrated application (Compost + NPSB) had a significant influence on plant height. The Merakofana variety produced the tallest plant (77.78 cm) under the balanced treatment of 5 t ha^{-1} compost 50% + 100 kg ha^{-1} NPSB 50%. The shortest plant (48.69 cm) was of the same variety, which had received the application of 2.5 t ha^{-1} Compost 25% + 150 kg ha^{-1} NPSB 75% (Table 2). The tallest growth of Merakofana under the balanced treatment was due to the combined

effect of nutrient supply, which led to internode elongation, photosynthetic efficiency, and hormone regulation (Soresa, 2023). The 50:50 organic-mineral ratio was a good balance for the soil in terms of nutrient availability and microbial activity, thus supporting the strong vegetative growth that has been documented in similar integrated systems for Solanaceae crops (Mensa et al., 2021;; and Mossie et al., 2024). By comparison, the shortest height of Mareko Fana under the mineral-dominant treatment was due to the presence of several restrictions. The low rate of compost application resulted in the lack of organic matter needed for soil structure and microbial ecology support, while the high input of mineral fertilizers possibly caused nutrient imbalances. Under these conditions, certain antagonisms may occur, such as phosphorus-zinc interference, and the possibility of boron being available at the toxic level could increase, thereby affecting the stability of the cell wall and the growth processes mediated by auxin (Sirba et al., 2021; Kebede et al., 2023).

3.1.2. Canopy diameter (CD)

The interaction of variety and the integrated application (Compost + NPSB) had a significant effect on the canopy diameter. The Merakofana variety produced maximum canopy diameter (62.42 cm) under the balanced treatment of 5 t ha^{-1} compost 50% + 100 kg ha^{-1} NPSB50%. On the other hand, the minimum diameter of 39.66 cm was noted for the Halaba local variety, which received the sole application of 10 t ha^{-1} compost 100% (Table 2). The balanced treatment of 5 t ha^{-1} compost 50% + 100 kg ha^{-1} NPSB50% at Merakofana resulted in the largest development of the canopy due to the immediate and optimized availability of essential nutrients, especially nitrogen, phosphorus, and sulphur, which facilitate cell division, elongation, and root development, thus increasing vegetative growth (Worku and Tesfaye, 2021; Gebrekidan et al., 2024). Nonetheless, the slow growth of Halaba Local under sole compost was due to the temporal mismatch between the nutrient release and the crop demand. The slow mineralization of the organic nutrients could not meet the optimum requirements for the expansion of the canopy, thereby indicating the disadvantages of organic-only fertilization for fast-growing cultivars (Abdeta et al., 2024). These findings emphasize the need for genotype-specific nutrient management, as the varietal differences in growth dynamics and nutrient use efficiency would determine the effectiveness of any fertilizer regime (Abegaz et al., 2020; Hunde, 2020).

3.1.3. Number of primary branches per plant

There was a significant interaction between the variety and integrated application (compost + NPSB) when it comes to the mean number of primary branches. The Merakofana variety produced maximum branching (14.66) under the balanced treatment of 5 t ha^{-1} compost 50% + 100 kg ha^{-1} NPSB 50%. However, the Melkashote variety had minimum branching (8.06) when the sole application of 10 t ha^{-1} compost was 100% (Table 2). The maximum branching in Merakofana due to the integrated 50:50 treatment can be attributed to a nutrient supply that worked together. 5 t ha^{-1} compost 50%, contributed to the soil by its physical and chemical effects and also by the organic nutrients released slowly, whereas 100 kg ha^{-1} NPSB50%, gave the nitrogen, phosphorus, sulphur, and boron, which were critical for the initiation of shoots and were readily available. This regime was perfectly in tune with the variety's genetic potential for branching, as neither source was limiting or excessive (Fufa et al., 2018; Kassa and

Hadgu, 2018). The response is likely to be through improved cytokinin biosynthesis and carbohydrate allocation backed by the favourable mineral nutrition (McIntyre et al., 2021). While the minimum branching in Halaba Local under exclusive compost was due to the slow mineralization of nutrients and the possible fixation of trace elements, which could not satisfy the early demand of the plant for the development of lateral shoots (Mandal et al., 2025; Haydar et al., 2024). This fact emphasizes the necessity of applying fertilizers according to the genotype; landraces are usually in need of at least a minimal inorganic nutrient (50 kg ha^{-1} NPSB 25%) supplement that can reduce the effects of slow organic nutrient release. During the early vegetative phase (from day 15 to day 30 after planting), the process of fertilizing the plants was particularly significant, as it brought about the maximum number of branches. Moreover, the nutrients were supplied in a manner that was in accordance with the physiologies of different varieties, which led to the highest demand. As a result, there was a great increase in productivity immediately and also in the case of soil health in the long term (Adugna, 2023; Asadu et al., 2024).

Table 2
Effects of variety and compost plus NPSB fertilizer application on plant height, canopy diameter, and number of branches per plant of hot pepper.

Var.	Integrated application	PH(cm)	CD(cm)	NBPP
Halaba local	Compost100%	53.33^{ef}	39.66^{g}	8.33^{ef}
	Compost75%+NPSB25%	63.60^{bcd}	46.23^{de}	10.40^{cd}
	Compost50%+NPSB50%	63.73^{bcd}	46^{ef}	13.00^{ab}
	Compost25%+NPSB75%	56.80^{ef}	53.66^{bc}	11.86^{bc}
	NPSB100%	61.16^{cde}	53.33^{bc}	12.50^{bc}
Melkshote	Compost100%	68.13^{b}	41.66^{fg}	8.06^{f}
	Compost75%+NPSB25%	51.86^{g}	49.66^{de}	12.20^{bc}
	Compost50%+NPSB50%	65.06^{bc}	46.66^{de}	9.66^{de}
	Compost25%+NPSB75%	61.40^{cde}	49.00^{de}	10.00^{cd}
	NPSB100%	53.17^{fg}	48.33^{de}	12.06^{bc}
Merakofana	Compost100%	58.70^{def}	45.33^{ef}	12.06^{bc}
	Compost75%+NPSB25%	56.06^{ef}	53.66^{bc}	13.40^{ab}
	Compost50%+NPSB50%	77.78^{a}	62.42^{a}	14.66^{a}
	Compost25%+NPSB75%	48.69^{h}	51.66^{cd}	12.93^{bc}
	NPSB100%	64.70^{bc}	57.00^{b}	9.00^{def}
	$LSD_{(0.05)}$	6.9	3.89	1.59
	C.V.	6.84	4.69	8.42

Where: Var = varieties, LSD(0.05) = least of significance difference, C.V. = coefficient variation, PH= plant height, CD= canopy diameter, NBPP= number of branch per plant, Compost100%(10 t ha^{-1}), Compost 75%(7.5 t ha^{-1}) + NPSB25%(50 kg ha^{-1}), Compost 50%(5 t ha^{-1}) + NPSB50%(100 kg ha^{-1}), Compost 25%(2.5 t ha^{-1}) +NPSB75%(150 kg ha^{-1}), NPSB100% (200 kg ha^{-1})

3.2. Phonological Response

3.2.1. Days to 50% flowering

Days to 50% flowering were significantly influenced by the combination of variety and integrated application management (Compost + NPSB). The Melka Shote variety showed the earliest flowering (63.7 days) when treated with 7.5 t ha⁻¹ compost 75% + 50 kg ha⁻¹ NPSB 25%. The Halaba local variety, on the other hand, flowered the earliest (55.66 days) when 200 kg ha⁻¹ NPSB100% was applied alone (Fig. 2). A longer vegetative phase in Melka Shote under the organic-dominant treatment is the reason for the delayed flowering. According to Kahsay (2017), the 7.5 t ha⁻¹ Compost75% supports prolonged vegetative growth and can postpone the transition to reproduction by promoting sustained nutrient release and increasing microbial activity. Additionally, the addition of boron to the NPSB blend helps control physiological processes associated with flowering. Nevertheless, Halaba Local's early flowering under 200 kg ha⁻¹ NPSB100% is caused by the nutrients' instant availability, especially nitrogen, phosphorus, sulphur, and boron, which quicken the hormonal and biochemical processes that cause flowering (Assefa et al., 2020; Li.S., 2024). Additionally, it seems that this variety is genetically predisposed to a shorter juvenile phase, which enables it to react quickly to high availability of mineral nutrients. These findings show that genetic predisposition and nutrient source dynamics interact to strongly mediate flowering time. The results highlight how crucial it is to adjust integrated nutrient management to varietal physiology in order to either lengthen or speed up the vegetative phase as required for particular cropping goals for (Damtew *et al*., 2022).

3.2.2. Days to 50% fruit set (D50%FS)

Days to 50% fruit set (D50%FS) was significantly affected by the interaction between variety and integrated application management (compost + NPSB). When 200 kg ha⁻¹ NPSB 100% was applied within the Halaba Local, it showed the earliest fruit set (67.66 days); despite that, the Melka Shote displayed the most delayed fruit set (78.73 days) when 10 t ha⁻¹ Compost 100% was applied alone (Fig. 2). The faster fruit set in Halaba Local using 200 kg ha⁻¹ NPSB 100% was due to the immediate nitrogen, phosphorus, sulphur, and boron availability, which quickly satisfied the metabolic needs for flower induction. The speedy provision of nutrients unlocks flowering-related gene networks (like FT gene expression) and hormonal pathways (higher cytokinin and gibberellin production); thus, planting's early reproductive development is activated (Kazan and Lyons, 2016; Li et al., 2022). Halaba Local's genetic makeup for very efficient nutrient use adds to its mineral signal responsiveness even more (Pérez-García et al., 2023; Sran et al., 2023). While the application of 10 t ha⁻¹ compost 100% because of the significant delay in Melka Shote, due to the slow mineralization of organic matter or nutrients, which prolongs the vegetative growth phase. Nitrogen and phosphorus are released slowly; consequently, their concentrations are kept below the level needed for the hormonal and metabolic changes to occur that are necessary for reproduction (Paillat et al., 2020; Zhang et al., 2023). The mismatching of nutrient supply from the phonological thresholds results in delayed flowering, a phenomenon that agrees with the genotype-specific sensitivity to nutrient release patterns (Doldt et al., 2023; Tilahun et al., 2025).

Where

Compost100%(10 t ha-1), Compost 75%(7.5 t ha-1) + NPSB25%(50 kg ha-1), Compost 50%(5 t ha-1) + NPSB50%(100 kg ha-1), Compost 25%(2.5 t ha-1) +NPSB75%(150 kg ha-1), NPSB100% (200 kg ha-1)

Figure 2: Effects of variety and integrated application of compost and NPSB fertilizer on days to 50% flowering and days to 50% fruit set of hot pepper.

3.2.3. Days to fruit maturity (DFM)

There was a notable interaction between the variety and the method of integrated application management (Compost + NPSB) that affected the number of days to fruit maturity (DFM) significantly. The combination of 7.5 t ha^{-1} Compost 75% + 50 kg ha^{-1} NPSB 25% resulted in the longest maturity (120.16 days) for the Halaba local variety. On the other hand, the shortest maturity of 112.89 days was the case of the Merakofana variety with the application of 200 kg ha^{-1} NPSB100% (Table 3). The delayed maturation of Halabalocal in the organic-dominant treatment can be explained by the nutrient supply being balanced and sustained. The 7.5 t ha^{-1} compost 75% improved soil microbial activity and nutrient cycling, while the complementary 50 kg ha^{-1} NPSB 25% provided readily available nitrogen, phosphorus, sulphur, and boron. This combination probably optimized hormonal signalling, especially the pathways of cytokinin and gibberellin, therefore allowing a timely transition from vegetative to reproductive development (Biratu, 2021; Mensa et al., 2023). On the other hand, the Merakofana early-maturing, which was under the 200 kg ha^{-1} NPSB100%, was a consequence of the nutrient-release pattern being out of sync with varietal physiology. In spite of the fact that the mineral fertilizer provided nutrients right away, the lack of organic matter might have resulted in nutrient retention being limited and availability being steady only during the later reproductive stages. This phenomenon could push back the metabolic and hormonal processes necessary for fruit maturation, which is a finding that supports the idea that sole mineral fertilization can prolong the maturation period in certain varieties (Chimdessa et al., 2019). The specific nutrient uptake kinetics and lower nutrient-use efficiency of Halaba Local under high-mineral conditions might be another reason to consider its prolonged cycle (Zhang et al., 2020).

3.2.4. Days to first harvest (DFH)

The days to first harvest were significantly affected by the interplay between variety and integrated application management (compost + NPSB). The combination of 2.5 t ha^{-1} compost 25% + 150 kg ha^{-1} NPSB 75% resulted in Melka Shote under the same treatment showing the most delayed harvest (174.92 days); conversely, Melka Shote was harvested the earliest (123.02 days) under the treatments of 10 t ha^{-1} compost 100% (Table 3). The significant delay in Melka Shote's case is because its physiological requirements and the nutrient dynamics of the treatment were not in synchronization. The low rate of 2.5 t ha^{-1} compost 25% led to a slow mineralization of nutrients and possible microbial immobilization of nitrogen, while the high 150 kg ha^{-1} NPSB75% content might have been a factor that permitted, in the beginning, the vegetative growth at the expense of the timely reproduction (Valenzuela-García 2019). Melka Shote's being sensitive to the low nutrient timing and its natural inclination for prolonged vegetative growth under such conditions delayed the harvest even more (Biratu et al., 2021). However, the early harvesting of Melka Shote was mainly due to its genetics, which favoured a shorter growth cycle and better nutrient usage. This variety quickly absorbed all the nutrients that were available to it, irrespective of whether they were from 10 t h^{-1} compost 100% sources, and this in turn caused the plant to develop faster (Alemu et.al., 2016). The treatment content was still able to supply the immediate

nutrients needed by Melkashote, therefore coinciding with the variety's adaptation to the local growing conditions (Mekonnen, 2020; Chatzistathis et al., 2022; and Mensa et al., 2023).

3.2.5. Duration of harvest (DH)

The effect of variety and integrated application management (compost + NPSB) interaction on the duration of harvest was significant. While under the application of 200 kg ha^{-1} NPSB, 100% Halaba Local showed the longest harvest period of 98.55 days. The application of 10 t ha^{-1} compost 100% led to the shortest harvest period (of 67.33 days) for Melka Shote (Table 3). The prolonged harvest period in Halaba Local is mainly due to its indeterminate growth pattern and the constant nutrient supply from 200 kg ha^{-1}NPSB 100%. The ongoing provision of nitrogen, phosphorus, sulphur, and boron facilitated the flowering and fruiting to a larger degree, thus preventing the dying of the plant and extending the productive period (Chimdessa et al., 2019). In contrast, the short harvest period in Melka Shote under sole compost is an indicator of its determinate growing pattern and nutrient release profile, which is in harmony with its reproductive cycle. The slow mineralization of 10 t ha^{-1} compost 100% resulted in a balanced nutrition supply that did not extend the period of vegetative growth, accordingly, leading to uniform fruit ripening in a shorter time (Chernet and Zibelo, 2019; Mohidin and Abdullah, 2022).

Table 3
Effects of variety and integrated application of compost and NPSB fertilizer on days to fruit maturity, days to first harvest, and duration of harvest of hot pepper.

Var.	Integrated application	DFM	DFH	DH
Halaba local	Compost100%	117.16^{abc}	134.40^{c}	95.66^{bc}
	Compost75%+NPSB25%	120.16^{a}	129.53^{c}	94.33^{c}
	Compost50%+NPSB50%	116.50^{bc}	129.33^{c}	95.66^{bc}
	Compost25%+NPSB75%	116.50^{bc}	125.33^{c}	98.11^{ab}
	NPSB100%	115.16^{cd}	127.37^{c}	98.55^{a}
Melkshote	Compost100%	118.73^{ab}	123.02^{c}	67.33^{f}
	Compost75%+NPSB25%	118.70^{ab}	128.00^{c}	68.55^{f}
	Compost50%+NPSB50%	117.33^{abc}	123.77^{c}	68.33^{f}
	Compost25%+NPSB75%	114.66^{cd}	174.92^{a}	67.66^{f}
	NPSB100%	117.66^{abc}	157.07^{b}	68.55^{f}
Merakofana	Compost100%	119.16^{ab}	131.04^{c}	88.27^{d}
	Compost75%+NPSB25%	117.31^{abc}	127.42^{c}	83.00^{e}
	Compost50%+NPSB50%	117.01^{abc}	127.73^{c}	86.50^{d}
	Compost25%+NPSB75%	116.33^{bc}	124.66^{c}	85.90^{d}
	NPSB100%	112.89^{d}	126.70^{c}	88.00^{d}
	$LSD_{(0.05)}$	2.75	13.07	2.62
	C.V.	1.4	5.89	1.87

Where: Var.= varsities, LSD(0.05) = least of significance difference, CV = coefficient of variation, D50%Fl = Days to 50% flowering, D50%FS = Days to 50% fruit set, DFM = Days to fruit maturity, DH = Duration of harvest, Compost100%(10 t ha^{-1}), Compost 75%(7.5 t ha^{-1}) + NPSB25%(50 kg ha^{-1}), Compost 50%(5 t ha^{-1}) + NPSB50%(100 kg ha^{-1}), Compost 25%(2.5 t ha^{-1}) +NPSB75%(150 kg ha^{-1}), NPSB100% (200 kg ha^{-1})

3.3. Fruit Response

3.3.1. Number of fruits $plant^{-1}$ (NFPP)

The number of fruits per plant (NFPP) was significantly affected by the interaction of the variety and integrated application (compost + NPSB). The Melka Shote variety received the highest NFPP (119.1) under the combined application of 2.5 t ha⁻¹ compost 25% + 150 kg ha⁻¹ NPSB 75%. Conversely, the lowest NFPP (48.73) was recorded for the Merakofana variety under the treatment of 7.5 t ha⁻¹ compost 75% + 50 kg ha⁻¹ NPSB 25% (Fig. 3). The abundant yield of fruits in the Melka Shote was due to the synergy of nutrient dynamics. The dominant 150 kg ha⁻¹ NPSB75% fraction gave nitrogen, phosphorus, and essential micronutrients like boron, which flowered and prevented flower abortion immediately. The 2.5 t ha^{-1}compost 25% fraction, which was complementary, strengthened the root system and promoted microbial activity for the gradual release of nutrients. This equal supply during the important reproductive stages, together with Melka Shote's genetic efficiency of nutrient uptake and partitioning, contributed to the maximum fruit set (Singh et al., 2018; Hunde, 2020). Nevertheless, the low fruit production in Merakofana under the 7.5 t ha⁻¹ compost 75% dominant regime was due to the incompatibility of its physiology with the nutrient release pattern. The high compost content of the treatment might have caused the delay in nutrient availability during the critical stages of flowering and fruit set. Additionally, the natural growth structure of Merakofana, with fewer primary branches, limits the number of possible fruiting sites, a characteristic that becomes more pronounced when there is poor nutrient synchronization (Garrigues M. and Garrigues R., 2025).

3.3.2. Fruit length (mm) (FL)

The length of fruits (FL) demonstrated a significant interaction between varieties and application management (compost + NPSB). The variety Merakofana with 200 kg ha⁻¹ NPSB100% yielded the longest fruits (10.73 cm). On the contrary, the Halaba local variety, with the application of 10 t ha⁻¹ compost 100%, had the smallest fruits (7.39 cm) (Fig. 3). Marekofana’s dominance in fruit length under 200 kg ha⁻¹ NPSB100% was due to its genetic characteristic for larger fruits coupled with the high nitrogen, phosphorus, and sulphur availability. These nutrients stimulate cell division and elongation and probably positively affect hormonal regulation (cytokinins and auxins) during fruit development (Shumbulo et al., 2017; Abdeta et al., 2024). In the opposite case, the shorter fruit length in Halaba Local caused by the 10 t ha⁻¹ compost 100% is due to both genetic and nutritional factors. As a traditional variety, it is restricted by its genetic limitations on fruit size. Besides, the slow nutrient release of compost could not support the critical fruit growth stages with enough readily available nitrogen, phosphorus, and sulphur, which in turn limited cell expansion (Belay et al., 2020).

Where

Compost100%(10 t ha^{-1}), Compost 75%(7.5 t ha^{-1}) + NPSB25%(50 kg ha^{-1}), Compost 50%(5 t ha^{-1}) + NPSB50%(100 kg ha^{-1}), Compost 25%(2.5 t ha^{-1}) +NPSB75%(150 kg ha^{-1}), NPSB100% (200 kg ha^{-1})

Figure 3: Effect of hot pepper varieties and integrated application of municipal-waste compost and NPSB fertilizer on number of fruits per plant (NFPP) and fruit length (FL, cm).

3.3.3. Fruit diameter (mm) (FD)

The effect of variety and integrated application management (Compost + NPSB) on fruit diameter (FD) was significant. The largest fruit diameter (3.77 cm) was obtained for the variety Melka Shote under the full application of 5 t ha⁻¹ compost 50% + 100 kg ha⁻¹ NPSB50%. On the other hand, the smallest fruit diameter (1.84 cm) was detected for the variety Halaba Local under the mineral-dominant treatment of 2.5 t ha⁻¹ compost 25% + 150 kg ha⁻¹ NPSB75% (Table 4). Melka Shote had its largest fruit diameter as a result of a synergistic nutrient supply. The 5t ha⁻¹ compost 50% led to proper soil moisture retention, aeration, and nutrient cycling through microbes, while the 100 kg ha⁻¹ NPSB 50% made available the nitrogen, phosphorus, sulphur, and boron that were necessary for cell division and enlargement during fruit development. This balanced 50:50 regime allowed regular nutrient availability that corresponded with the variety's high genetic potential for fruit growth (Zhang et al., 2020; Wassie et al., 2023). On the other hand, the small fruit diameter in Halaba Local was due to a mismatch between its metabolism and the nutrient supply. The highest 150 kg ha⁻¹ NPSB75% probably resulted in very fast nutrient release, which was not well-fitted to the variety's slow growth rhythm, whereas the very lowest 2.5 t ha⁻¹ Compost 25% inputs did not support sufficient soil microbial activity, moisture retention, and pH buffering. This situation, together with possible acidification and phosphorus fixation due to the use of large amounts of mineral fertilizers, restricted the increase of cells during the fruit development (Kena and Latera, 2024). Traditional kinds like Halaba Local usually need to be treated with at least 40% organic inputs, which facilitate slow nutrient release matching their metabolic traits, to perform better (Singh et al. 2018).

3.3.4. Fruit pericarp thickness (mm) (FPT)

The thickness of the fruit pericarp (FPT) was greatly affected by the interaction of the different varieties and the integrated application management (Compost + NPSB). The Melka Shote variety was noted to have the highest FPT (2.66 mm) under the treatment of 2.5 t ha⁻¹ compost 25% + 150 kg ha⁻¹ NPSB75%. While the lowest FPT (0.81 mm) was noted for the Melka Shote variety at the 2.5 t ha⁻¹ compost 50% + 100 kg ha⁻¹ NPSB 50% regime (Table 4). Melka Shote experienced the highest FPT under the integrated treatment method of 2.5 t ha⁻¹ compost 25% + 150 kg ha⁻¹ NPSB 75%, which was balanced, and this was due to the nutrient supply that worked together to support the sustained structural development. The 2.5 t ha⁻¹ compost 25% is actively participating in the improvement of the nutrient cycling process, which is mediated by soil and microbes, and at the same time, the 150 kg ha^{-1} NPSB 75% is offering nitrogen, phosphorus, sulphur, and boron in forms that are ready to be used immediately. Altogether, these elements are facilitating cell division, wall biosynthesis, and hormonal regulation during pericarp formation (Mali et al., 2019). Out of the nutrients, boron is specifically the one that has a major impact on the cross-linking and the strength of the cell wall (Mensa et al., 2021). However, the minimum FPT observed in Melka Shote with 5 t ha⁻¹ compost 50% + 100 kg ha⁻¹ NPSB 50% probably has physiological dissimilarity as its cause. The mineral fertilizer does provide nutrients quickly, but the lack of organic matter may cause the nutrient retention and timing to not be optimal, thus interfering with the continuous nutrient flux necessary during such critical developmental stages as cell expansion and secondary wall thickening. This can lead to the down regulation of genes responsible for cell wall formation and subsequently reduce lignin deposition, thus creating a thinner pericarp (Kitila et al., 2021).

3.3.5. Single fruit weight (SFW)

The interaction between variety and integrated application (Compost + NPSB) had a significant effect on single fruit weight (SFW). The Merakofana variety showed the highest SFW of 28.40 g when treated with 2.5 t ha⁻¹ compost 25% + 150 kg ha⁻¹ NPSB75% under mineral dominance. However, the Halaba local variety under 200 kg ha⁻¹ NPSB100% treatments had the lowest SFW of 3.32 g (Table 4). Marekofana's fruit weight was exceptionally high due to a nutrient release that worked together perfectly with the variety's developmental pattern. The immediate nitrogen, phosphorus, sulphur, and boron supplied by the 150 kg ha⁻¹ NPSB75% component supported early cell division of the Merakofana variety, while the organic fraction provided long-term nutrition for cell expansion and carbohydrate accumulation. The combined regimen increased photosynthetic efficiency, saw to it that more assimilates were moved, and helped retain soil moisture; all this together maximized the growth of the fruit (Fufa and Abera, 2019; Ramadan and Bardisi, 2020). On the contrary, the lowest weight of fruits for Halaba Local was the result of a physiological mismatch with the exclusive use of the mineral fertilizer. The rapid release of nutrients from 200 kg ha⁻¹ NPSB100% surpassed the variety's capacity to assimilate, which resulted in inefficient uptake and possible nutrient leaching. In the absence of organic matter, the soil microbial communities were further disturbed, and the nutrient cycling was impaired, which in turn affected hormone balance and carbohydrate partitioning during the fruit development stage. Halaba Local, being a landrace that had grown accustomed to low-input environments, did not possess the regulatory mechanisms to cope with high mineral nutrient loads effectively (Salma et al., 2022; Wang et al., 2022).

3.3.6. Fresh fruit weight plant^{-1} (g) (FFWPP)

Fresh fruit weight per plant (FFWPP) was significantly affected by the interaction of variety with integrated application management (Compost + NPSB). The top FFWPP (142.03 g) was noted for the Merakofana variety in the mineral-nutrient treatment of 2.5 t ha^{-1} Compost 25% + 150 kg ha^{-1} NPSB75%. On the contrary, the lowest FFWPP (16.6 g) was found for the Halaba Local variety when treated exclusively with 200 kg ha^{-1} NPSB100% (Table 4). High fruit weight in Merakofana was due to the nutrient supply that worked together with the variety's growth physiology. The150 kg ha^{-1} NPSB75%. components gave nitrogen, phosphorus, and sulphur instantly during the most important growth periods, while the organic matter kept the nutrient availability, soil moisture retention, and photosynthetic efficiency in good condition. This whole system worked together to source sink relationships and thus, the development of fruits was promoted over the growth of vegetative parts (Mensa et al., 2023). While the low fruit weight in Halaba Local when grown with 200 kg ha^{-1} NPSB100% was due to a physiological mismatch. The fast release of nutrients disturbed the variety's acclimatization to the slow nutrient supply, which got them to suffer from metabolic imbalances, reduced mycorrhizal activity, and poor fruit set. Apart from the high mineral nitrogen that caused the situation, it was observed that the traditional landraces limited yield plasticity under high input conditions (Abdeta et.al., 2024).

Table 4
Effects of hot pepper varieties and integrated application of municipal-waste compost and NPSB fertilizer on fruit diameter (FD, cm), fruit pericarp thickness (FPT, mm), single fruit weight (SFW, g), and fresh fruit weight per plant (FFWPP, g).

Var.	Integrated application	FD(cm)	FPT(mm)	SFW	FFWPP(g)
Halaba local	Compost100%	2.11^{f}	1.87^{d}	3.84^{h}	19.24^{h}
	Compost75%+NPSB25%	2.10^{fg}	1.64^{f}	4.88^{fg}	24.44^{fg}
	Compost50%+NPSB50%	2.03^{fg}	1.73^{ef}	3.51^{h}	17.58^{h}
	Compost25%+NPSB75%	1.84^{g}	1.34^{g}	5.71^{e}	28.55^{e}
	NPSB100%	1.92^{fg}	2.30^{c}	3.32^{h}	16.60^{h}
Melkshote	Compost100%	0.96^{h}	1.82^{de}	4.62^{g}	23.16^{g}
	Compost75%+NPSB25%	1.02^{h}	1.93^{d}	4.59^{g}	22.97^{g}
	Compost50%+NPSB50%	3.77	0.81^{h}	3.91^{h}	19.58^{h}
	Compost25%+NPSB75%	2.93^{c}	2.66^{a}	5.45^{ef}	27.27^{ef}
	NPSB100%	3.32^{b}	1.65^{f}	4.77^{g}	23.91^{g}
Merakofana	Compost100%	2.52^{de}	2.60^{a}	28.34^{a}	141.70^{a}
	Compost75%+NPSB25%	2.63^{de}	2.46^{b}	27.58^{b}	137.92^{b}
	Compost50%+NPSB50%	2.76^{cd}	1.36^{g}	25.30^{c}	126.50^{c}
	Compost25%+NPSB75%	2.50^{e}	2.36^{bc}	28.40^{a}	142.03^{a}
	NPSB100%	2.95^{c}	2.66^{a}	16.70^{d}	83.50^{d}
	$LSD_{(0.05)}$	0.24	0.13	0.58	2.93
	C.V.	6.18	4.01	3.08	3.08

Where: Var. = varieties, LSD(0.05) = least of significance difference, CV = coefficient variation, NFPP = Number of fruits per plant, FL = Fruit length, FD = Fruit diameter, FPT = Fruit pericarp thickness .FFWPP = Fresh fruit weight per plant, Compost100%(10 t ha^{-1}), Compost 75%(7.5 t ha^{-1}) + NPSB25%(50 kg ha^{-1}), Compost 50%(5 t ha^{-1}) + NPSB50%(100 kg ha^{-1}), Compost 25%(2.5 t ha^{-1}) +NPSB75%(150 kg ha^{-1}), NPSB100% (200 kg ha^{-1})

3.3.7. Dry fruit weight $plant^{-1}$($DFWPP_g$)

The interaction of variety and integrated application management (Compost + NPSB) significantly affected dry fruit weight per plant (DFWPP). The Merakofana cultivar under 2.5 t ha⁻¹ compost 25% + 150 kg ha⁻¹ NPSB 75% treatment gave the maximum DFWPP (7.57). Disapprove of that, the Halaba local variety under the mineral-dominant treatment of 2.5 t ha⁻¹ compost 25% + 150 kg ha⁻¹ NPSB 75% showed the lowest (1.19 g) DFWPP (Fig. 4). The highest dry weight in Merakofana under 2.5 t ha⁻¹ compost 25% + 150 kg ha⁻¹ NPSB 75% was due to a proper nutrient supply in terms of timing. The mineralization of 150 kg ha^{-1}NPSB 75% at a higher rate kept the nitrogen levels at the optimum for fruit filling, thus increasing the rate of photosynthesis and the partitioning of assimilates to reproductive structures. The 2.5 t ha⁻¹ compost 25% treatment also created favourable conditions for the growth of the roots, which in turn favoured the bacteria that produce auxins and the synthesis of structural materials like cellulose and lignin in fruit tissues (Valenzuela-García, 2019; Meneses-Lazo et al., 2020). Despite that, the very lowest dry weight in Halaba Local obtained with the 150 kg ha⁻¹ NPSB 75% treatment was due to several physiological limitations. The fast nitrate flux interfered with the nitrogen metabolism, and the main enzymes (nitrate reductase, glutamine synthetase) involved were overwhelmed; Hence, the developing fruits got less protein as a consequence of the impaired protein synthesis. The very low organic input was a reason for the mycorrhizal networks' decline, as a result, making the phosphorus uptake decrease and down-regulation of phosphate-transporter genes being the consequence. Besides, the existence of boron deficiency, which was less than the optimal level, was a reason for the poor formation of cell walls. All these factors worked together to cause a decrease in sucrose synthase activity and phloem-loading efficiency, and thus fruit allocation of photo assimilates was restrained (Singh *et al*., 2019; Ramadan and Bardisi, 2020).

3.3.8. Dry to fresh fruits weight ratio per plant (DFWPP/FFWPP %)

The value of the dry-to-fresh fruit weight ratio (DFWPP/FFWPP %) showed a significant difference due to the interaction between variety and integrated application (compost + NPSB). The Melka Shote variety under the treatment of 5 t ha⁻¹ compost 50% + 100 kg ha⁻¹ NPSB 50% had the highest ratio of 25.03%, while the variety Merakofana had the lowest ratio (8.86%) under the application of 200 kg ha⁻¹ NPSB 100% (Fig. 4). The balanced 50:50 treatment in Melka Shote led to a high ratio, which was a result of a nutrient release pattern that optimised the partitioning of assimilates. The mix not only made nutrients available immediately for establishment but also provided a gradual supply of 5 t ha⁻¹ compost with 50% nutrients that kept leaf nitrogen levels and rhizosphere health good during the fruit-filling period. This system increased the activity of sucrose synthase and cellulose biosynthesis, thus directing more photosynthates to structural dry matter and less to water accumulation (Ropokis et al., 2018; Tian et al., 2024). On the other hand, the 200 kg ha⁻¹ NPSB 100% application in Merakofana led to a low ratio, which was mainly due to physiological disruption. The mineral nitrogen supplied in large amounts facilitated uptake of water and increased fresh weight, but this was done at the cost of structural biomass, which in turn reduced the activity of sucrose synthase and the biosynthesis of lignin. The lack of compost matter may have caused the plants to suffer from a deficiency of micronutrients (boron) that affected the development of cell walls, thereby limiting dry matter accumulation even more (Alemu et al., 2016).

Where

DFWPP = Dry fruit weight plant^{-1}, DFWPP/FFWPP % =Dry to fresh fruits weight ratio per plant, Compost100%(10 t ha^{-1}), Compost 75%(7.5 t ha^{-1}) + NPSB25%(50 kg ha^{-1}), Compost 50%(5 t ha^{-1}) + NPSB50%(100 kg ha^{-1}), Compost 25%(2.5 t ha^{-1}) +NPSB75%(150 kg ha^{-1}), NPSB100% (200 kg ha^{-1}).

Figure 4: Effect of hot pepper varieties and integrated application of municipal-waste compost and NPSB fertilizer on dry fruit weight per plant (DFWPP, g) and dry-to-fresh fruit weight ratio per plant (DFWPP/FFWPP, %).

3.3.9. Number of seeds fruit^{-1} (NSPF)

The Number of Seeds Fruit-1 (NSPF) showed significant variation because the two main factors of variety and integrated application management (compost + NPSB) affected the results. The Merakofana variety produced the highest NSPF value of 104.5, while the 10 t ha⁻¹ compost 100% treatment produced 103.69 NSPF. The Melkshote variety recorded its lowest NSPF value of 77.41, while the 7.5 t ha⁻¹ compost 75% + 50 kg ha⁻¹ NPSB 25% treatment produced 75.77 NSPF (Table 5). The best performance was achieved by Merakofana, with 10 t ha⁻¹ compost 100%, because its growth was enhanced by both physiological and soil properties. The gradual nutrient release matched its reproductive development while keeping soil C: N ratios and pH (6.2–6.5) and water retention at their ideal levels. Mycorrhizal colonisation at 65–70% doubles the phosphorus uptake, which results in 25–30% better pollen viability, 20% less ovule abortion, and 15–20% faster seed filling, according to Singh *et al*., (2019). Melkshote showed low NSPF results because high inorganic fertilisation (2.5 t ha⁻¹ compost 25% + 150 kg ha⁻¹ NPSB 75%) created a situation where the local conditions matched neither the testing criteria nor the plant characteristics. The process of nitrogen mineralisation occurred at a rapid pace, which led to increased vegetative growth while it decreased reproductive development and resulted in a 40 per cent decrease in flower production. The adoption of organic inputs proved ineffective because it did not provide enough volume to sustain arbuscular mycorrhizal networks, which resulted in a 60% decrease in mycorrhizal colonisation while it reduced the ability to absorb phosphorus. The treatment caused plants to develop deficiencies in micronutrients, which resulted in ovule development and seed filling problems that matched the research results presented by Singh et al. (2025).

3.3.10. Seeds to dry fruit weight ratio (DFWPP %)

The Seed to Dry Fruit Weight Percentage (SDFWP %) varied significantly due to the main effects of variety selection and integrated application management (Compost + NPSB). The Halaba local variety produced the highest SDFWP value at 10.06% and under the 7.5 t ha⁻¹ compost 75% + 50 kg ha⁻¹ NPSB 25% treatment, which achieved a 7.24% SDFWP. The Merakofana variety exhibited the lowest SDFWP at 3.59%, while the 5 t ha⁻¹ compost 50% + 100 kg ha⁻¹ NPSB50% treatment produced an SDFWP of 4.78% (Table 5). The Halaba local variety demonstrates better results when treated with 7.5 t ha⁻¹ compost 75% + 50 kg ha⁻¹ NPSB 25% because its different physical and internal body systems, together with its chemical processes, create beneficial effects. The variety shows broad root systems, which develop

multiple branches to increase its ability to take in nutrients from the surrounding area. The combination of this characteristic with higher nutrient transporter activity results in improved absorption of nitrogen, phosphorus, sulphur and boron from the combined nutrient source. The treatment delivers continuous nutrient discharge, which maintains essential enzymatic functions during element absorption while stopping nitrogen-related reproductive destruction. The biochemical system increases the genetic expression of genes responsible for carbohydrate processing and transportation, which results in improved photosynthates distribution to fruits and causes better source-sink balance as demonstrated by an increased fruit-to-seed biomass ratio (Singh *et al*., 2019). The extremely low percentage of dry fruit weight for the Merakofana variety, which underwent 5 t ha^{-1} compost 50% + 100 kg ha^{-1} NPSB 50% treatment, showed a genetic-environmental combination that failed to perform correctly. The variety's natural ability to absorb nutrients suffered additional harm because the nutrient ratio used for their growth did not match their required biological needs, which resulted in restricted nutrient intake. The root architectural pattern that people genetically inherited through their ancestry restricted their ability to absorb phosphorus and sulphur. The process induced a decline in photosynthesis, which reduced the movement of carbohydrates to the fruits, and this process reduced the amount of plant material needed for fruit growth (Nehore, 2025). The adverse effects of soil environmental conditions, together with moisture shortages in vertisol, created more difficulties because they restricted nutrient movement and damaged root operations, which together produced the low DFWP results (Bonsa, 2019; Chernet, 2019).

3.3.11. Hundred seeds weight (HSW_g)

The main factors of variety and integrated applications (Compost + NPSB) showed significant effects on the Hundred Seed Weight (HSW) results. The Melkshote variety reached maximum (HSW) (19.57 g), and the 7.5 t ha^{-1} compost 75% + 50 kg ha^{-1} NPSB25% treatment produced 20.76 g. While the Halaba local variety achieved the lowest performance (19.19 g), the 10 t ha^{-1} compost 100% treatment produced 16.35 g (Table 5). The maximum (HSW) for Melkshote and the balanced integrated treatment resulted from a synergistic nutrient supply. The 50 kg ha^{-1} NPSB 25% provided instant nitrogen and phosphorus availability for vital seed development and protein production, while the 7.5 t ha^{-1} Compost 75% delivered continuous micronutrient output together with enhanced soil properties to support ongoing nutrient absorption throughout the development process. The combination established a C: N ratio, which enabled seed carbon distribution and enhanced soil water retention while eliminating shortages that resulted in increased starch and protein production (Belay et al., 2020). The minimum (HSW) requirement for Halaba Local, together with the 10 t ha^{-1} Compost100% value, shows that this variety has an insufficient nutrient balance needed for seed-filling development. The release of nutrients through gradual processes created a nitrogen and phosphorus shortage because these elements were needed during important seed development periods. The treatment failed to create enough mycorrhizal activity while also limiting access to essential micronutrients, which included boron and zinc. Halaba local requires specific nutrient levels because it needs nutrients during its reproductive period, as shown by Bekele, (2022).

Table 5
Main effects of hot pepper varieties and integrated application of municipal-waste compost and NPSB fertilizer on number of seeds per fruit (NSPF), seed-to-dry-fruit weight ratio (SDFWP, %), and hundred-seed weight (HSW, g).

Varieties	**NSPF**	**S/DFWPP(%)**	**HSW(g)**
Halaba local	80.74^{b}	10.06^{a}	14.99^{b}
Melkshote	77.41^{c}	5.67^{b}	19.57^{a}
Merakofana	104.51^{a}	3.59^{c}	19.83^{a}
$LSD_{(0.05)}$	1.59	0.48	0.89
Integrated application			
Compost100%	103.69^{a}	6.65^{ab}	16.35^{b}
Compost75%+NPSB25%	75.77^{d}	7.24^{a}	20.76^{a}
Compost50%+NPSB50%	73.64^{e}	4.78^{c}	14.17^{c}
Compost25%+NPSB75%	89.01^{c}	7.22^{a}	19.73^{a}
NPSB100%	95.64^{b}	6.29^{b}	19.63^{a}
$LSD_{(0.05)}$	2.05	0.62	1.16
C.V.	2.43	10.10	6.62

Where: LSD(0.05) = least of significance difference, CV= coefficient variation,, DFWPP = Dry fruit weight per plant (g), DFWPP/FFWPP (%) = Dry to fresh fruits weight ratio per plant (%), NSPF = Number of seeds per fruit, Seed/DFWPP (%) = Seeds to dry fruit weight ratio (%), HSW(g) = Hundred seeds weight (g), Compost100%(10 t ha^{-1}), Compost 75%(7.5 t ha^{-1}) + NPSB25%(50 kg ha^{-1}), Compost 50%(5 t ha^{-1}) + NPSB50%(100 kg ha^{-1}), Compost 25%(2.5 t ha^{-1}) +NPSB75%(150 kg ha^{-1}), NPSB100% (200 kg ha^{-1})

3.4. Yield Responses

3.4.1. Total fresh yield (TFY.t ha^{-1})

Total fresh yield (TFY t ha⁻¹) was significantly influenced by the interaction between varieties and integrated nutrient management (compost + NPSB). The Merakofana variety achieved the highest TFY of 11.41 t ha⁻¹ because it received 10 t ha⁻¹ Compost 100% treatment, while the Halaba Local variety obtained the lowest yield of 5.08 t ha⁻¹ from 7.5 t ha⁻¹ Compost 75% + 50 kg ha⁻¹ NPSB 25% (Fig. 5). The higher organic compost performance of Merakofana during complete organic fertilizer application results from its unique combination of genetic traits and environmental factors. The 10 t ha^{-1}compost 100% soil enhancement properties enabled the plant to develop its genetic capacity for efficient nutrient

uptake, which might include increased expression of transporter genes such as OsNPF and PHT1. The amendment improved cation exchange capacity and humic acid content, establishing a system that delivers nutrients according to the needs of plants throughout their growth cycle (Assefa et al., 2020). It confirmed that the system developed a useful microbiome in the rhizosphere, which improved phytohormones production and nutrient solubilization and optimized the plant's distribution of resources between fruit development and photosynthesis (Kumar et al., 2018). Nevertheless, the treatment at Halaba Local, which used partially integrated methods, produced lower yield results because the method interrupted the plant's natural growth process, which required minimal resources. The diminished organic material input to the system prevented adequate maintenance of soil organic carbon levels and mycorrhizal networks, which resulted in lower phosphorus availability (Kumar et al., 2018). The use of an unbalanced NPK ratio, which combined 4 parts nitrogen with 1 part potassium and 0.5 parts phosphorus from the inorganic materials, created ammonium toxicity, which showed leaf chlorosis and reduced nitrate reductase activity, which affected the plant's developed capability to use nutrients. The system experienced microbial nutrient cycling constraints because of insufficient labile carbon, which redirected resources to support root survival instead of enabling reproductive processes. The study demonstrates that partial integration creates instability in the co-evolved soil-plant systems that develop with landraces (Shilpa *et al*., 2024).

3.4.2. Marketable dry yield (MDY t ha^{-1})

The marketable dry yield (MDY t ha⁻¹) showed significant effects from the combined effect of different varieties and integrated application methods (compost + NPSB). The highest MDY was achieved by Merakofana (3.46 t ha⁻¹) under the 7.5 t ha⁻¹ Compost 75% + 50 kg ha⁻¹ NPSB 25% treatment, whereas the lowest yield was recorded for the same variety (1.33 t ha⁻¹) under the 100 kg ha⁻¹ NPSB 100% treatment (Fig. 5). Merakofana achieved its best performance when integrated systems used its improved ability to use nutrients from both organic and inorganic materials. The 7.5 t ha⁻¹ compost 75% created better soil structure, which increased microbial activity to provide continuous nutrient release according to plant growth needs, while the 50 kg ha⁻¹ NPSB 25% content delivered essential macronutrients needed for plant growth and fruit development. The combination of these elements enabled plants to move carbohydrates to their fruits, which resulted in increased dry matter production and crop yield, according to Simon and Tesfaye, (2014) and Mossie *et al*. ,(2024). The yield reduction, which occurs with the 200 ha⁻¹ NPSB 100%, shows that Merakofana requires organic soil processes for its growth. The absence of organic matter limited humic acid fractions and disrupted microbial networks because it resulted in two effects, which included suppressed nitrate assimilation, hormonal imbalances, and a failure to meet the variety's complex physiological requirements. The created situation established a phytohormones desert syndrome, which produced severe damage to fruit set and dry matter allocation. The results of this study support the findings of Mensa et al., (2021) and Muhie et al., (2023) because Merakofana elite varieties need integrated nutrition to maintain metabolic stability and reach their maximum yield potential.

3.4.3. Unmarketable dry yield (UMDY t ha^{-1})

The interaction effects of varieties and integrated application (Compost + NPSB) methods showed a significant effect on unmarketable dry yield (UMDY, t ha⁻¹). The Melkshote variety achieved its highest UMDY value of 0.82 t ha⁻¹ with the 2.5 t ha⁻¹ Compost 25% + 15014.68 kg ha⁻¹ NPSB75% treatment, while its lowest value of 0.17 t ha⁻¹ occurred with the 10 t ha⁻¹ Compost100% treatment (Fig. 5). The highest UMDY of Melkshote under the highest 150 kg ha⁻¹ NPSB75% treatment resulted from a mismatch between its genetic makeup and the environmental conditions. The abnormal nutrient ratio, which contained high minerals N and P without enough organic carbon, created conflicting biochemical signals that interrupted the normal process of fruit development (Simon and Tesfaye, 2014). The plant activated stress-response pathways, which resulted in resource misallocation, pathological lignification, and premature senescence due to the maladaptive nutrient ratio paradox, forcing the plant to sacrifice the quality of its fruit to survive. The research shows that specific nutrient combinations create a danger that triggers harmful physical reactions, according to Ateka et al. (2024). However, the 10 t ha⁻¹ Compost 100% amendment testing showed the lowest UMDY results, which confirm that exclusive organic nutrition supports Melkshote's evolutionary development. The treatment maintained stable nutrient release to match the developmental schedule of the variety while keeping the necessary hormonal levels for fruit growth. The treatment created a positive rhizosphere microbiome, which reduced stress reactions while enabling normal cell wall building and dry weight development, and the treatment probably maintained positive epigenetic regulation over fruit-quality genes, which mineral fertilization disrupts (Reyes Pérez et al., 2017).

3.4.4. Total dry yield (TDY t ha^{-1})

Total Dry Yield (TDY) was significantly influenced by the interaction of varieties and integrated application (Compost + NPSB). The maximum (TDY) was recorded by Merakofana at 4.04 t ha⁻¹ when it received the 7.5 t ha⁻¹ compost 75% + 50 kg ha⁻¹ NPSB 25% treatment. The lowest yield was observed for Halaba Local, which produced 1.71 t ha⁻¹ under the 2.5 t ha⁻¹ compost 25% + 150 kg ha⁻¹ NPSB 75% treatment (Fig. 5). The balanced integrated treatment of Merakofana produced its highest yield through combined physiological and soil optimization advantages. The 7.5 t ha⁻¹ Compost 75% + 50 kg ha⁻¹ NPSB 25% created an ideal rhizosphere, where the organic material was used for soil structure improvement and increased microbial activity, while the mineral component provided essential nutrients needed during vital growth periods. The process created favourable conditions for microbial growth, which led to better phosphorus solubilization, and the process enabled better distribution of dry matter to fruit. The treatment protected plants from stress while preventing them from growing excessively through the use of lower mineral inputs (Mensa et al., 2023; Muhie et al., 2023). The low yield in Halaba Local under high-150 kg ha⁻¹ NPSB 75% conditions occurred because the plant genetics did not match the environmental conditions. The plant developed excessive vegetative growth because the 150 kg ha⁻¹ NPSB 75% nitrogen application generated ammonium toxicity, which prevented normal reproductive development. The system depended on organic inputs, which could not provide enough resources to maintain essential microbial networks that support nutrient cycling, especially phosphorus mobilization. Physiological stress from the imbalance caused changes in photosynthetic distribution and soil properties, which created conditions that conflicted with the variety's ability to thrive in a low-input

agricultural system, and the traditional varieties need organic nutrition according to their evolutionary adaptation, which shows the requirement for genotype-specific fertilization methods (Muhie et al., 2023).

Where

LSD (0.05) = least of significance difference, t ha-1 = Tone per hectare, TFY = Total fresh yield, MDY = Marketable dry yield, UMDY = Unmarketable dry yield, TDY = Total dry yield., Compost100%(10 t ha^{-1}), Compost 75%(7.5 t ha^{-1}) + NPSB25%(50 kg ha^{-1}), Compost 50%(5 t ha^{-1}) + NPSB50%(100 kg ha^{-1}), Compost 25%(2.5 t ha^{-1}) +NPSB75%(150 kg ha^{-1}), NPSB100% (200 kg ha^{-1}).

Figure 5: Effects of hot pepper varieties and integrated application of municipal-waste compost and NPSB fertilizer on yield traits: total fresh yield (TFY, t ha^{-1}), marketable dry yield (MDY, t ha^{-1}), unmarketable dry yield (UMDY, t ha^{-1}), and total dry yield (TDY, t ha^{-1})

3.5. Correlation Analysis

The correlation matrix shows (Fig. 6) that plant height (PH) positively correlates with marketable yield, total dry yield (TDY), and the number of fruits per plant, while showing mixed results. The single fruit weight and fruit diameter (FD) show a negative correlation with these two variables. The trade-off between vegetative growth and fruit development leads to delayed flowering. The two canopy diameter (CD) links with architectural and floral traits, which include fruit diameter (FD: r = 0.36*), number of branches per plant (NBPP: r = 0.336*), and number of flowers per plant (NFPP: r = 0.331*). The (DFM: r = -0.313*) results show that the direct relations between yield components show weaker results because TDY and HSW show non-significant relations with the yield components (r = 0.256). The research shows that reproductive phenology demonstrates strong internal coherence because 50% flowering day (Day50%Fl) shows close tracking with D50%FS (r = 0.782*) and DFM (r = 0.417*). The negative relationship between Day50%Fl and harvest duration (DH) shows a correlation of -0.573, proving that later flowering results in shorter harvest periods. Pod and seed development demonstrate a strong connection between seed set and dry matter because the number of seeds per fruit (NSF) shows an extremely strong relationship with the dry-to-fresh fruit weight ratio per plant (DFWPP/FFWPP%: r = 0.993*). The total fresh yield (TFY) depends on dry fruit weight per plant (DFWPP: r = 0.908*) and fruit length (FL: r = 0.536*), while marketable dry yield (MDY) maintains a close relationship with total dry yield (TDY) through a high correlation (r = 0.937*) that faces strong limitations from the time needed to complete harvest (DH shows a correlation of -0.558*). The findings show that higher PH increases yield potential at the expense of later flowering, while larger CD causes specific floral and architectural characteristics to grow but decreases harvest time and leads to slight yield reductions, and early flowering helps plants escape drought conditions while it restricts their branching ability and several yield factors (Shumbulo et al., 2017).

Where

*= significant, ns = none significant, PH = plant height, CD = canopy diameter, NBPP = number of branches plant^{-1}, D50%Fl = Days to 50% flowering, D50%FS = Days to 50% fruit set, DFM = Days to fruit maturity, DH = Duration of harvest, NFPP = Number of fruits plant^{-1}, FL = Fruit length, FD = Fruit diameter, FPT = Fruit pericarp thickness .SFW = single fruit weight, FFWPP = Fresh fruit weight plant^{-1}, DFWPP = Dry fruit weight plant^{-1} (g), DFWPP/FFWPP (%) = Dry to fresh fruits weight ratio plant^{-1} (%), NSPF = Number of seeds fruit^{-1}, Seed/DFWPP (%) = Seeds to dry fruit weight ratio (%), HSW(g) = Hundred seeds weight (g), t ha^{-1} = Tone per hectare, TFY=Total fresh yield, MDY = Marketable dry yield, UMDY = Unmarketable dry yield, TDY=Total dry yield.

Figure 6: Pearson correlation coefficients (r) among phenological, growth, fruit, and yield parameters of hot pepper (*Capsicum annuum L*.) varieties as influenced by integrated application of municipal-waste compost and NPSB fertilizer.

4. CONCLUSION AND RECOMMENDATIONS

The integrated application of NPSB fertilizer and municipal-waste compost significantly enhanced the growth, yield, and yield-related traits of hot pepper varieties, with responses being highly variety-specific. The balanced treatment of 5 t ha⁻¹ compost 50% + 100 kg ha⁻¹ NPSB 50% consistently produced superior vegetative growth and fruit quality parameters, particularly for improved varieties like Mareko Fana and Melka Shote. However, the optimal nutrient management strategy varied with the specific production objective: Mareko Fana under mineral-dominated conditions (2.5 t ha⁻¹ compost 25% + 150 kg ha⁻¹ NPSB 75%) was best for maximizing fresh fruit weight and single fruit weight, while the same variety under sole compost achieved the highest total fresh yield. For dry matter production, the 7.5 t ha⁻¹ compost 75% + 50 kg ha⁻¹ NPSB 25% treatment optimized marketable and total dry yields in Mareko Fana, suggesting this combination is most suitable for commercial dried pepper production. The Halaba Local variety consistently performed poorly across all treatments, confirming its unsuitability for intensive integrated nutrient management systems. The significant improvements in soil chemical properties under treatments with higher compost proportions highlight the sustainability benefits of integrating organic amendments, particularly for long-term soil fertility maintenance.

The delayed phonological development observed under organic-dominant treatments suggests that while sole compost supports sustainable production, it may not be optimal for early maturation or where early harvest is desired. The varying responses of different varieties to nutrient management strategies emphasize the critical need for genotype-specific fertilizer recommendations rather than the current uniform approach. The economic implications are significant: the 7.5 t ha⁻¹ compost 75% + 50 kg ha⁻¹ NPSB 25% treatment for Mareko Fana maximizes dry yield (4.04 t ha⁻¹), which could substantially increase farmer income in the dried pepper market, while the 5 t ha⁻¹ compost 50% + 100 kg ha⁻¹ NPSB 50% treatment optimizes fresh fruit quality attributes (fruit size, pericarp thickness) for premium fresh market segments. The use of municipal solid waste compost in integrated systems also addresses

urban waste management challenges while improving agricultural productivity, representing a circular economy approach with environmental and economic co-benefits.

The study recommends the adoption of integrated nutrient management strategies incorporating both NPSB and municipal compost, with specific emphasis on matching nutrient application rates to variety-specific physiological requirements. For Mareko Fana and Melka Shote, the 5 t ha^{-1} compost 50% + 100 kg ha^{-1} NPSB 50% treatment is recommended for balanced growth and quality, while the 7.5 t ha^{-1} compost 75% + 50 kg ha^{-1} NPSB 25% treatment is suggested for maximizing dry matter yields. Halaba Local is not recommended for intensive integrated nutrient management systems, and farmers should be encouraged to adopt improved varieties with better responsiveness to nutrient inputs. Future research should focus on long-term soil fertility dynamics under continuous integrated nutrient management, economic optimization through partial budget analysis, and validation of these findings across different agro-ecological zones and seasons. Additionally, research on the effects of integrated nutrient management on capsaicin content, oleoresin quality, and post-harvest characteristics would provide comprehensive insights for both fresh and processing markets.

Declarations

Ethics, Consent to Participate, and Consent to publish declarations

Ethics approval and consent to participate:

Not applicable. This study did not involve human participants, human tissue, or animal subjects. It was a field experiment conducted on hot pepper (*Capsicum annuum L.*) varieties using municipal-waste compost and NPSB fertilizer at Arba Minch, Ethiopia.

Consent for publication:

Not applicable. This manuscript does not contain any individual person’s data in any form (including individual details, images, or videos).

Consent to participate:

Not applicable.

Conflicts of Interest

The authors declare no conflicts of interest.

Funding

declaration

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Author Contribution

Author Contributions StatementAuthor Contributions: G.H. Gebremedhin conceptualized the study, developed the methodology, carried out field experimentation, sample collection, and laboratory analyses, and performed formal data analysis and visualization. K.J. Bedadi and K. Kassa contributed to the conceptualization and methodology, supervised the research, provided administrative and resource support, and validated the findings. M.B. Andualem participated in validation and formal evaluation of the experimental design and data interpretation. G.H. Gebremedhin prepared the initial manuscript draft, and all authors critically revised and approved the final manuscript for submission.

Acknowledgement

The authors would like to express their sincere gratitude to the Gamo Development Association Farm Experts for their valuable technical support and facilitation during the field implementation of the study. Special thanks are extended to the Melkassa Agricultural Research Centres for providing the hot pepper seed materials used in the experiment. The authors are also deeply grateful to the Arba Minch RUNRES project and Jinka University for financial support and institutional assistance that made this research possible.

Data Availability

Data Availability Statement Data are available from the corresponding author on request

References

1. Abate TM, Dessie AB, Mekie TM. Technical efficiency of smallholder farmers in red pepper production in North Gondar zone, Amhara regional state, Ethiopia. J Economic Struct. 2019;8(1):18. https://doi.org/10.1186/s40008-019-0150-6.
2. Abdelkhalik A, El-Mageed TAA, Mohamed I, Semida W, Al-Elwany OA, Ibrahim IM, Hemida K, El-Saadony M, AbuQamar SF, El-Tarabily KA, Gyushi MAH. Soil application of effective microorganisms and nitrogen alleviates salt stress in hot pepper (Capsicum annum L.) plants. Front Plant Sci. 2023;13. https://doi.org/10.3389/fpls.2022.1079260.

3. Abdeta A, Chala G, Tamiru T. Growth and Yield Response of Hot Pepper (*Capsicum annuum L*.) to Varieties in Buno Bedele and Ilubabor Zone, Southwestern, Ethiopia. Cell Biology. 2024;12(1):1–7. 10.11648/cb.20241201.11. https://www.sciencepg.com/article/.
4. Abegaz BP, Fininsa P, Seid AP, Meressa H. B. P. (2020). Management of Meloidogyne incognita and M. Javanica populations using host resistance, botanicals, and organic amendments on hot pepper (*Capsicum annum* and *c. frutescens*) genotypes in Ethiopia (Doctoral dissertation, Haramaya University). http://ir.haramaya.edu.et/hru/handle/123456789/6677
5. Adugna-Chimdessa Duressa. Growth and yield response of hot pepper (Capsicum annuum L.) to different rate of NPS blended fertilizer and cattle manure at Bako, West Oromia, Ethiopia. Agric Forestry Fisheries. 2023;12(3):79–85. https://doi.org/10.11648/j.aff.20231203.13.
6. Ahmed MA, Abdelkader MAI. Enhancing growth, yield components and chemical constituents of chilli (*Capsicum annuum L*.) plants by using different NPK fertilization levels and nano-micronutrients rates. Asian J Soil Sci Plant Nutr. 2020;6(2):17–29. https://doi.org/10.9734/ajsspn/2020/v6i230083.
7. Alemu A, Wodajo A, Chuntal K. Performance evaluation of elite hot pepper (*Capsicum annuum L*.) varieties for yield and yield components at Derashea, South-Eastern Ethiopia. Int J Res - Granthaalayah. 2016;4(12):95–100. https://doi.org/10.29121/granthaalayah.v4.i12.2016.2397.
8. Al-Harbi AR, Obadi A, Al-Omran AM, Abdel-Razzak H. Sweet peppers yield and quality as affected by biochar and compost as soil amendments under partial root irrigation. J Saudi Soc Agricultural Sci. 2020;19(7):452–60. https://doi.org/10.1016/j.jssas.2020.08.002.
9. Aliyi I. Contribution of hot pepper production to household food security: The case of Gursum district, Oromia regional state, Ethiopia. Food Sci Qual Manage. 2018;81:44–53. https://www.iiste.org/Journals/index.php/FSQM/article/viewFile/47426/48969.
10. Asadu CO, Ezema CA, Ekwueme BN, Onu CE, Onoh IM, Adejoh T, Emmanuel UO. Enhanced efficiency fertilizers: Overview of production methods, materials used, nutrient release mechanisms, benefits, and considerations. Environ Pollution Manage. 2024;1(1):32–48. https://doi.org/10.1016/j.epm.2024.07.002.
11. Asatov S, Abdiyev Z. (2023). High-yielding pepper and hot pepper hybrids for greenhouse production. In A. Muratov and S. Igumnov, editors, *Fundamental and Applied Scientific Research in the Development of Agriculture in the Far East* (Vol. 1, pp. 1359–1366). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-36960-5_146
12. Asmare D, Woldeselassie A. Fruit yield and oleoresin content of pepper (*Capsicum annuum L*.) varieties as influenced by seedling ages in Humbo District, South Ethiopia [Preprint]. Res Square. 2026. https://doi.org/10.21203/rs.3.rs-8591252/v1.
13. Asrat U, Minuye M, Woldegiorgis E. Physicochemical properties of pepper cultivars (Capsicum annuum L.) grown at different locations in Ethiopia. Int J Vegetable Sci. 2025;31(3):352–75. https://doi.org/10.1080/19315260.2025.2475827.

14. Assefa G, Deresa S, Bersisa H, Girma S. Assessment and distribution of major hot pepper (*Capsicum annuum L*.) pests in West Hararghe Zone, Eastern Ethiopia. Adv Crop Sci Technol. 2024;12(3). Article 1000676. https://doi.org/10.4172/2329-8863.1000676.
15. Assefa G, Girma S, Deresa D. Response of hot pepper (*Capsicum annuum L*.) as affected by np fertilizer and planting method on yield and yield-related traits in West Hararghe zone, Eastern Ethiopia. Am J BioScience. 2020;8(4):113–22. https://doi.org/10.11648/j.ajbio.20200804.13.
16. Ateka B, Alemayehu M, Adgo E, Assefa F, Mengist Y. Effects of eco-green and inorganic nitrogen fertilizer rates on growth and green pod yield of hot pepper (*Capsicum annuum L*.) in Bahir Dar Zuria District of Amhara Region, Ethiopia. Discover Sustain. 2024;5(1). https://doi.org/10.1007/s43621-024-00311-5. Article 127.
17. Bekele D. Opportunities and potential of hot pepper (*Capsicum annuum L*.) production in Ethiopia. Eur J Agric Forestry Res. 2022;10(2):14–20. https://doi.org/10.37745/ejafr.2013/vol10n21420.
18. Belay F, Abate B, Tsehaye Y. Genetic variability and character association of hot pepper (Capsicum annuum L.) genotypes tested under irrigation in Northern Ethiopia. Agric Sci. 2020;2(1):289. https://doi.org/10.30560/as.v2n1p289.
19. Biratu W, Belew D, Ettissa E. Evaluation of hot pepper (*Capsicum annuum L*.) cultivars for growth and dry pod yields against different blended fertilizer and nitrogen rates in Raya Azebo, Southern Tigray. Int J Res Agron. 2021;4(2):15–22. https://doi.org/10.33545/2618060X.2021.v4.i2a.79.
20. Bonsa T. (2019). Response of hot pepper (Capsicum annuum L.) varieties to different rates of NPS fertilizer at Guder [Unpublished master's thesis]. Ambo University. Ambo University Institutional Repository. https://irlib.ambou.edu.et/xmlui/handle/123456789/1035
21. Central Statistical Agency of Ethiopia. CSAE. (2023). Report on Area and Production of Major Crops (Private Peasant Holdings, Meher Season). Agricultural Sample Survey 2022/2023. Volume I, Statistical Bulletin 586. Addis Ababa, Ethiopia.
22. Chatzistathis T, Tsaniklidis G, Papaioannou A, Giannakoula A, Koukounaras A. (2022). Comparative approach on the effects of soil amendments and controlled-release fertilizer application on the growth, nutrient uptake, physiological performance, and fruit quality of pepper (*Capsicum annuum L*.) plants. *Agronomy*, 12(8), Article 1935. https://doi.org/10.3390/agronomy12081935
23. Chernet S, Zibelo H. Evaluation of hot pepper (*Capsicum annuum L*.) varieties for green pod yield and yield components in Western Tigray, Northern Ethiopia. J Plant Breed Crop Sci. 2019;11(9):260–4. https://doi.org/10.5897/JPBCS2019.0812.
24. Chimdessa A, Bekele M, Obsa C. Growth and yield response of hot pepper (*Capsicum annuum L*.) to NPSB blended fertilizers and farm yard manure: a review. Int J Agric Agribusiness. 2019;5(2):88–97.
25. Da Silva MPS, Freitas MMM, Santos PC, De Carvalho AJC, Jorge TS. Capsicum annuum var. annuum under macronutrients and boron deficiencies: Leaf content and visual symptoms. J Plant Nutr. 2019;42(4):417–27. https://doi.org/10.1080/01904167.2018.1544255.
26. Damtew DTDTL, Megersa AHG. (2022). Growth and Yield Performance Evaluation of Hot Pepper Varieties for Green Pod Purpose under Wondo Genet Agro-ecology. Growth, *12*(22).

27. Debele AD, Fereja WM. (2024). Municipal solid waste challenges in Ethiopia and valorizing the potential of the organic waste fraction for composting and bioenergy. *International Journal of Chemical Engineering*, 2024, Article 7999719. https://doi.org/10.1155/2024/7999719
28. Doldt J, Yilma K, Ellis-Jones J, Schulz S, Thomson A, Barahona C. The role of integrated soil fertility management in improving crop yields in the Ethiopian Highlands. Exp Agric. 2023;59:e24. https://doi.org/10.1017/s0014479723000212.
29. Ejigu W, Selassie G, Elias Y, E., and, Damte M. Integrated fertilizer application improves soil properties and maize (*Zea mays L*.) yield on Nitisols in Northwestern Ethiopia. Heliyon. 2021;7(1). https://doi.org/10.1016/j.heliyon.2021.e06074. Article e06074.
30. Fufa N, Abera G. Effects of blended fertilizer types and rates on fruit yield and nutrient use efficiencies of hot pepper (*Capsicum annuum L*.) at Asossa, Western Ethiopia. Afr J Agric Res. 2019;14(33):1737–48. https://doi.org/10.5897/AJAR2019.14193.
31. Fufa N, Abera G, Etissa E. Agronomic and economic performance of hot pepper (*Capsicum annuum L*.) in response to blended fertilizer supply at Asossa, Western Ethiopia. Int J Plant Soil Sci. 2018;26(2):1–11. https://doi.org/10.9734/IJPSS/2018/45667.
32. Garrigues MM, Garrigues RB. Sweet pepper (*Capsicum annuum L*.) under organic nutrient management -A comparative study of agronomic and economic outcomes. Int J Res Innov Appl Sci. 2025;10(7):1348–63. https://doi.org/10.51584/ijrias.2025.100700122.
33. Gebrekidan TK, Gebremedhin GG, Weldemariam AK, Teferi MK. Municipal solid waste management in Ethiopia physical and chemical compositions and generation rate: Systematic review. J Air Waste Manag Assoc. 2024;74(12):861–83. https://doi.org/10.1080/10962247.2024.2393356.
34. Gelu G, Dane C, Ayza A, Habtewold M. Optimal agricultural water allocation for enhanced productivity of hot pepper (Capsicum annuum L.) and economic gain: An experimental study from Southern Ethiopia. Cogent Food Agric. 2024;10(1). https://doi.org/10.1080/23311932.2024.2313045. Article 2313045.
35. Gobie W. A seminar review on red pepper (*Capsicum annum L*.) production and marketing in Ethiopia. Cogent Food Agric. 2019;5(1):1647593.
36. Haydar MS, Ghosh D, Roy S. Slow and controlled release nanofertilizers as an efficient tool for sustainable agriculture: Recent understanding and concerns. Plant Nano Biology. 2024;7., Article 100058. https://doi.org/10.1016/j.plana.2024.100058.
37. Hemida K, Eloufey AZA, Hassan G, Rady M, El-Sadek A, Abdelfattah MA. Integrative NPK soil and foliar application improves growth, yield, antioxidant, and nutritional status of *Capsicum annuum L*. in sandy soils under semi-arid condition. J Plant Nutr. 2023;46(5):1091–107. https://doi.org/10.1080/01904167.2022.2046060.
38. Hunde N. Yield response and nutrient use efficiencies of hot pepper (Capsicum annuum L.) to inorganic fertilizers in Ethiopia: A review article. Int J Res Agron. 2020;3(1):1–6. https://doi.org/10.33545/2618060x.2020.v3.i1a.27.

39. Jibril T, Bekele G. (2022). Effect of coffee husk compost and NPSB fertilizers on selected soil chemical properties of potato field in Chora District, South West Ethiopia. *Applied and Environmental Soil Science*, 2022, Article 7397872. https://doi.org/10.1155/2022/7397872
40. Kahsay Y. Evaluation of hot pepper varieties (*Capsicum species*) for growth, dry pod yield, and quality at M/Lehke District, Tigray, Ethiopia. Int J Eng Dev Res. 2017;5(3):144–52.
41. Kassa Melese WM, Hadgu G. Response of hot pepper *(Capsicum annuum L*.) as affected by NP fertilizer and farmyard manure combined application in Raya Azebo district, Northern Ethiopia. Int J Life Sci. 2018;6(4):831–48.
42. Kazan K, Lyons R. The link between flowering time and stress tolerance. J Exp Bot. 2016;67(1):47–60. https://doi.org/10.1093/jxb/erv441.
43. Kebede T, Berhe DT, Zergaw Y. (2023). Effects of biochar and compost application on soil properties and on the growth and yield of hot pepper (*Capsicum annuum L*.). *Applied and Environmental Soil Science*, 2023, Article 8546135. https://doi.org/10.1155/2023/8546135
44. Kena K, Latera A. Effect of NPS and nitrogen fertilizer application rates for small pod hot pepper production (*Capsicum annuum L*.) variety at Kellem and West Wollega Zones. Agricultural Reviews. 2024;45(1):170–6. https://doi.org/10.18805/ag.RF-296.
45. Kitila C, Abraham A, Shuma S, Rufe H. Growth and pod yield of hot pepper (*Capsicum annuum L*.) as influenced by farmyard manure and NPS fertilizer at Dambi Dollo, Western Ethiopia. Food Sci Technology: An Int Journal. 2021;1(3):1–9.
46. Kumar A, Elad Y, Tsechansky L, Abrol V, Lew B, Offenbach R, Graber ER. Biochar potential in intensive cultivation of Capsicum annuum L. (sweet pepper): Crop yield and plant protection. J Sci Food Agric. 2018;98(2):495–503. https://doi.org/10.1002/jsfa.8481.
47. Li L, Wu T, Li Y, Hu X, Wang Z, Liu J, Ashraf U. Deep fertilization improves rice productivity and reduces ammonia emissions from rice fields in China: A meta-analysis. Field Crops Res. 2022;289:108704. https://doi.org/10.1016/j.fcr.2022.108704.
48. Li S. Is auxin the key to improving crop nitrogen use efficiency for greener agriculture? New Phytol. 2024;244(6):2170–5. https://doi.org/10.1111/nph.20140.
49. Mada MM, Lebiso TM. Response of hot pepper (*Capsicum annuum L*.) to deficit irrigation in Bennatsemay Woreda, Southern Ethiopia. World. 2021;8(2):305–11. https://doi.org/10.22158/wjm.v8n2p305.
50. Mali SS, Naik SK, Jha BK, Singh AK, Bhatt BP. Planting geometry and growth stage linked fertigation patterns: Impact on yield, nutrient uptake, and water productivity of chilli pepper in hot and sub-humid climate. Sci Hort. 2019;249:289–98. https://doi.org/10.1016/j.scienta.2019.01.045.
51. Mamo M, Kassa H, Ingale L, Dondeyne S. Evaluation of compost quality from municipal solid waste integrated with organic additive in Mizan-Aman town, Southwest Ethiopia. BMC Chem. 2021;15(1). https://doi.org/10.1186/s13065-021-00768-3. Article 43.
52. Mandal M, Singh Lodhi R, Chourasia S, Das S, Das P. A review on sustainable slow-release N, P, K fertilizer hydrogels for smart agriculture. ChemPlusChem. 2025;90(3).

https://doi.org/10.1002/cplu.202400643. Article e202400643.

53. McIntyre KE, Bush DR, Argueso CT. Cytokinin regulation of source-sink relationships in plant-pathogen interactions. Front Plant Sci. 2021;12., Article 677585. https://doi.org/10.3389/fpls.2021.677585.
54. Mekonnen SA. (2020). Genetic diversity of Ethiopian Capsicum spp. and molecular mapping of the Up gene in pepper (*Capsicum spp*.) [Doctoral dissertation, Seoul National University]. S-Space Institutional Repository. https://s-space.snu.ac.kr/handle/10371/168434
55. Meneses-Lazo R, Garruña R, Echevarría-Machado I, Alvarado-López C, Villanueva-Couoh E, García-Maldonado JQ, Cristóbal-Alejo J. Growth, chlorophyll fluorescence, and gas exchange of pepper (*Capsicum chinense Jacq*.) plants in response to uptake and partitioning of nutrients. Chil J agricultural Res. 2020;80(4):585–97.
56. Mensa A, Mohammed W, Woldetsadik K. Effect of blended NPS fertilizer rates on dry fruit yield and yield components of hot pepper (*Capsicum annuum L*.) varieties at Arba Minch, Southern Ethiopia. Adv Biochem. 2021;9(3):59–68. https://doi.org/10.11648/j.ab.20210903.16.
57. Mensa A, Mohammed W, Woldetsadik K, Wube T, Feyso A. Partial budget analysis of on-farm hot pepper (*Capsicum annuum L*.) production under varying rates of NPS fertilizer application and improved varieties: The case of Arba Minch Zuria District, Southern Ethiopia. Int J Sci Res Archive. 2023;9(1):519–27. https://doi.org/10.30574/ijsra.2023.9.1.0367.
58. Mohammed B, Ahmed B, Abdulsalam Z. Technical efficiency of chilli pepper production in Kaduna state, Nigeria. Am J Experimental Agric. 2015;9(5):1–9. https://doi.org/10.9734/AJEA/2015/20298.
59. Mohidin H, Abdullah S. (2022). The effect of empty fruit bunch (EFB) compost and Trichoderma biofertilizer on growth and yield performance of chili (*Capsicum annuum L. var. Kulai*). IOP Conference Series: *Earth and Environmental Science*, 1114(1), Article 012070. https://doi.org/10.1088/1755-1315/1114/1/012070
60. Mossie BA, Sheferie MB, Abebe TD, Abedalla MK. Effect of blended NPS fertilizer and cattle manure on soil property and hot pepper productivity in Jabi Tehnan. Ethiopia Heliyon. 2024;10(16). https://doi.org/10.1016/j.heliyon.2024.e35504. Article e35504.
61. Muhie S, Amare S, Masrie B. Effects of blended (NPSB) and urea fertilizer on growth and green pod yield of hot pepper (*Capsicum annuum L*.) under irrigation in Raya-Kobo district, North Wollo, Ethiopia. J Plant Nutr. 2023;46(15):3810–23. https://doi.org/10.1080/01904167.2023.2211622.
62. Munda D, Shumbulo A. Growth, pod yield, and quality of hot pepper (Capsicum annuum L.) as affected by variety and rates of nitrogen fertilizer in Wolaita, Southern Ethiopia. Global J Sci Frontier Research: D Agric Veterinary. 2020;20(1):1–10. https://doi.org/10.34257/gjsfrdvol20is1pg1.
63. Mweta AP, Nnungu SI. Productivity and phytochemical potential of selected hot pepper (*Capsicum annuum L*.) varieties cultivated in Tanzania. Agro Bali: Agricultural J. 2024;7(2):449–56. https://doi.org/10.37637/ab.v7i2.1581.
64. Nehore TT. Adaptation of improved hot pepper (*Capsicum annuum L*.) varieties at Humbo and Bombe districts of Wolaita Zone, Southern Ethiopia. Eur J Innovative Stud Sustain. 2025;1(1).

https://doi.org/10.59324/ejiss.2025.1(1).01. Article 01.

65. Nigussie G, Zewdia I. Research Achievements of Hot Pepper (Capsicum Species) and Its Agro-Ecological Requirements in Ethiopia: A Review. J Farming. 2023;2(1):11–8.
66. Paillat L, Cannavo P, Barraud F, Huché-Thélier L, Guénon R. (2020). Growing medium type affects organic fertilizer mineralization and CNPS microbial enzyme activities. Agronomy, 10(12), Article 1955. https://doi.org/10.3390/agronomy10121955
67. Pérez-García LA, Sáenz-Mata J, Fortis-Hernández M, Navarro-Muñoz CE, Palacio-Rodríguez R, Preciado-Rangel P. Plant-growth-promoting rhizobacteria improve germination and bioactive compounds in cucumber seedlings. Agronomy. 2023;13(2). Article 315. https://doi.org/10.3390/agronomy13020315.
68. Ramadan MMA, Bardisi SA. Effect of mineral and organic nitrogen and some natural substances on productivity and fruit quality of sweet pepper. J Plant Prod. 2020;11(3):223–31. https://doi.org/10.21608/jpp.2020.91689.
69. Reyes Pérez JJ, Murillo L, Bermeo RAR, Burgos M, D., Vázquez Morán VF. (2017). Fertilización con abonos orgánicos en el pimiento (*Capsicum annuum L*.) y su impacto en el rendimiento y sus componentes. *Centro Agrícola*, 44(4), 88–94. http://scielo.sld.cu/pdf/cag/v44n4/cag13417.pd
70. Ropokis A, Ntatsi G, Kittas C, Katsoulas N, Savvas D. Impact of cultivar and grafting on nutrient and water uptake by sweet pepper (*Capsicum annuum L*.) grown hydroponically under Mediterranean climatic conditions. Front Plant Sci. 2018;9:1244. https://doi.org/10.3389/fpls.2018.01244.
71. Salma U, Alam M, Khanam M, Solaiman A, Zakaria M, Rahman G, Rahman M. Effect of organic manures and mineral fertilizers on soil properties and yield of sweet pepper (*Capsicum annuum L*). Asian J Soil Sci Plant Nutr. 2022;8(2):32–43. https://doi.org/10.9734/ajsspn/2022/v8i230137.
72. Schmitter PS, Tegegne D, Adie A, Baudron F, Blümmel M, Lefore N, Barron J. (2016). Evaluation of suitable water lifting and on-farm water management technologies for the irrigation of vegetables and fodder in Lemo district, Ethiopia (*Africa RISING Research Report). International Livestock Research Institute*. https://hdl.handle.net/10568/82714.
73. Shamil A, Merga J. Evaluation of hot pepper (*Capsicum annuum L*.) varieties for green pod yield and quality under rain fed production at Teppi, South Western Ethiopia. Int J Hortic Sci. 2022;28:45–50. https://doi.org/10.31421/ijhs/28/2022/10419.
74. Shumbulo A, Nigussie M, Alamerew S. Correlation and path coefficient analysis of hot pepper (Capsicum annuum L.) genotypes for yield and its components in Ethiopia. Adv Crop Sci Technol. 2017;5(3). Article 280. https://doi.org/10.4172/2329-8863.1000280.
75. Sibhatu B, Tekle G, Harfe M. Hot pepper varietal evaluation for growth, dry pod yield, and yield-related parameters at Kolla-Tembien District, Northern Ethiopia. Res J Agric Environ Manage Vol. 2016;5(4):126–31.
76. Simon T, Tesfaye B. (2014). Growth and productivity of hot pepper (*Capsicum annuum L*.) as affected by variety, nitrogen, and phosphorus at Jinka, Southern Ethiopia. Growth, *4*(17).

77. Singh A, Singh NB, Afzal S, Singh T, Hussain I. Zinc oxide nanoparticles: A review of their biological synthesis, antimicrobial activity, uptake, translocation and biotransformation in plants. J Mater Sci. 2018;53(1):185–201. https://doi.org/10.1007/s10853-017-1544-1.

78. Singh K, Singh BK, Singh AK, Rathour A, Pandey SR, Singh S, Singh R. Chilli Performance under Integrated Organic and Inorganic Nutrient Management. J Sci Res Rep. 2025;31(12):505–14. https://doi.org/10.9734/jsrr/2025/v31i123793.

79. Sirba HY, Begna T, Gojam M. Adaptability evaluation of recently released hot pepper (*Capsicum annuum L*.) varieties at highland areas of West Hararghe, Ethiopia. Int J Res Agron. 2021;4(2):87–93. https://doi.org/10.33545/2618060X.2021.v4.i2a.116.

80. Soresa DN. (2023). Effects of blended NPSB fertilizers and farm yard manure rates on yield and yield components of hot pepper (*Capsicum annuum L*.) in Jima Genet District, Western Ethiopia. Cambridge Open Engage. https://doi.org/10.33774/coe-2023-9r7ll

81. Sran TS, Jindal SK, Sharma A, Bhatia D. LCVD resistance breeding in heat-tolerant bell pepper: Combined phenotypic and marker-assisted backcrossing for introgression of LCVD resistance from hot pepper. Euphytica. 2023;219(5). https://doi.org/10.1007/s10681-023-03173-0. Article 50.

82. Stoleru V, Mangalagiu I, Amăriucăi-Mantu D, Teliban G, Cojocaru A, Rusu O, Burducea M, Mihalache G, Roșca M, Caruso G, Sękara A, Jitareanu G. Enhancing the nutritional value of sweet pepper through sustainable fertilization management. Front Nutr. 2023;10., Article 1264999. https://doi.org/10.3389/fnut.2023.1264999.

83. Sufiyan A. Genetic variability analysis of hot pepper (*Capsicum annuum L*.) at Haramaya University, Eastern Ethiopia. Indian J Adv Bot. 2025;5(1):19–24. https://doi.org/10.54105/ijab.A1044.05010425.

84. Tian Y, Wang J, Chen J, Yu D, Zeng Z, Fu J, Liang T. Effects of integrated management strategies on pepper yield and quality: A study of cultivation and nutrient management practices. Agronomy. 2024;14(12). https://doi.org/10.3390/agronomy14122754. Article 2754.

85. Tilahun T, Abate S, Bezie Y, Gebreamanule B, Taye M. Screening Ethiopian hot pepper accessions for resistance to Fusarium wilt (Fusarium oxysporum) under greenhouse conditions. J Phytopathol. 2025;173(5). https://doi.org/10.1111/jph.170185. Article e70185.

86. Vadillo JM, Campillo C, González V, Prieto H. Assessing nitrogen fertilization in processing pepper: Critical nitrogen curve, yield response, and crop development. Horticulturae. 2024;10(11). Article 1141. https://doi.org/10.3390/horticulturae10111141.

87. Valenzuela-García AA, Figueroa-Viramontes U, Salazar-Sosa E, Orona-Castillo I, Gallegos-Robles MÁ, García-Hernández JL, Troyo-Diéguez E. Effect of organic and inorganic fertilizers on the yield and quality of Jalapeño pepper fruit (*Capsicum annuum L*). Agriculture. 2019;9(10). https://doi.org/10.3390/agriculture9100208. Article 208.

88. Wang J, Gao Z, Sun T, Huang W, Jia Y, Li X, Zhang Z, Hu X. Preharvest reduction in nutrient solution supply of pepper (*Capsicum annuum L*.) contributes to improving fruit quality and fertilizer efficiency while stabilising yields. Agronomy. 2022;12(12):3004. https://doi.org/10.3390/agronomy12123004.

89. Wassie WA, Andualem AM, Molla AE, Tarekegn ZG, Aragaw MW, Ayana MT. Growth, physiological, and biochemical responses of Ethiopian red pepper (Capsicum annuum L.) cultivars to drought stress. Sci World J. 2023;2023(1):4374318. https://doi.org/10.1155/2023/4374318.
90. Woldeamanuel AA, Tarekegn MM, Balakrishina RM. Production and application of organic waste compost for urban agriculture in emerging cities. Int J Agricultural Biosystems Eng. 2022;16(4):39–47. https://doi.org/10.5281/zenodo.6471852.
91. Worku A, Tesfaye W. Effect of integrated application of compost and NPS fertilizer on selected soil physicochemical properties and yield of barley (*Hordeum vulgare L.*) at Welmera, Ethiopia. Int J Appl Agricultural Sci. 2021;7(6):298–310. https://doi.org/10.11648/j.ijaas.20210706.18.
92. Zhang J, Lv J, Dawuda MM, Xie J, Yu J, Li J, Zhang X, Tang C, Wang C, Gan Y. Appropriate ammonium-nitrate ratio improves nutrient accumulation and fruit quality in pepper (*Capsicum annuum L*). Agronomy. 2019;9(11):683. https://doi.org/10.3390/agronomy9110683.
93. Zhang J, Lv J, Xie J, Gan Y, Coulter JA, Yu J, Zhang X. Nitrogen source affects the composition of metabolites in pepper (Capsicum annuum L.) and regulates the synthesis of capsaicinoids through the GOGAT-GS pathway. Foods. 2020;9(2):150. https://doi.org/10.3390/foods9020150.
94. Zhang Y, Liu B, Kong F, Chen L. Nutrient-mediated modulation of flowering time. Front Plant Sci. 2023;14:1101611. https://doi.org/10.3389/fpls.2023.1101611.

Figures

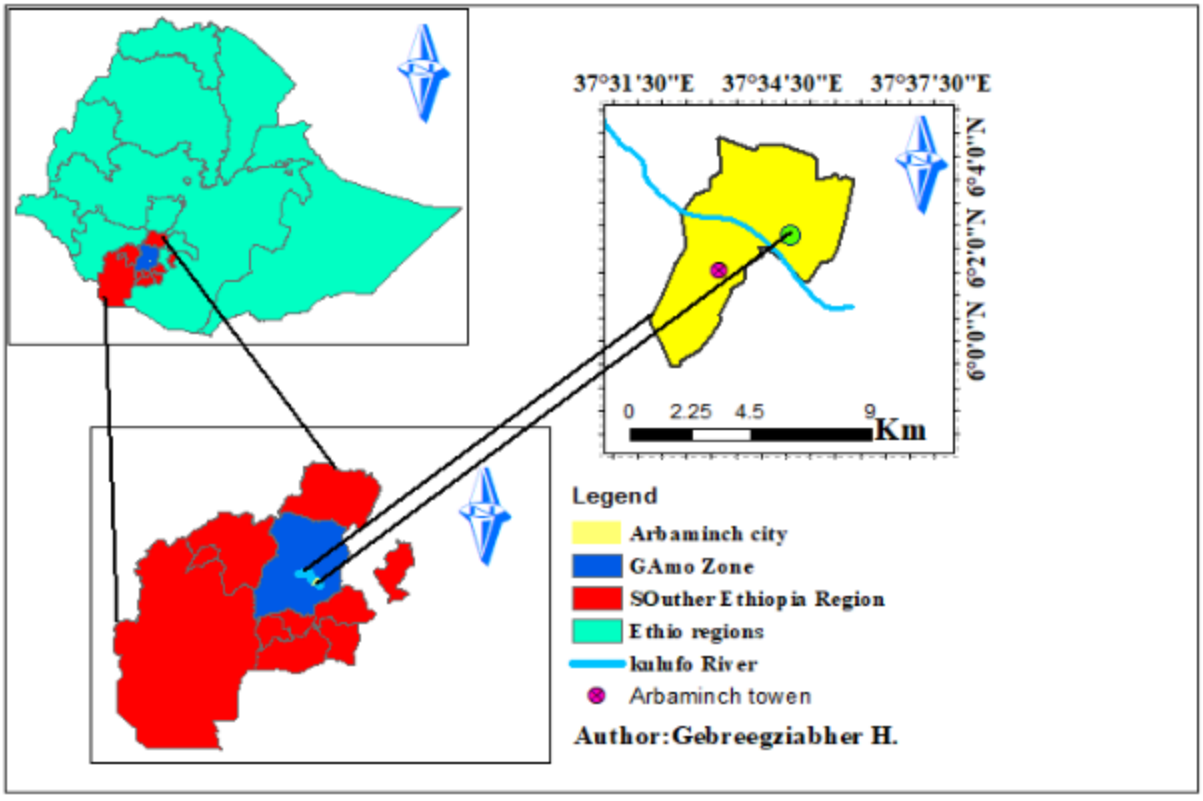


Figure 1

Map of the study area showing Arba Minch, southern Ethiopia.

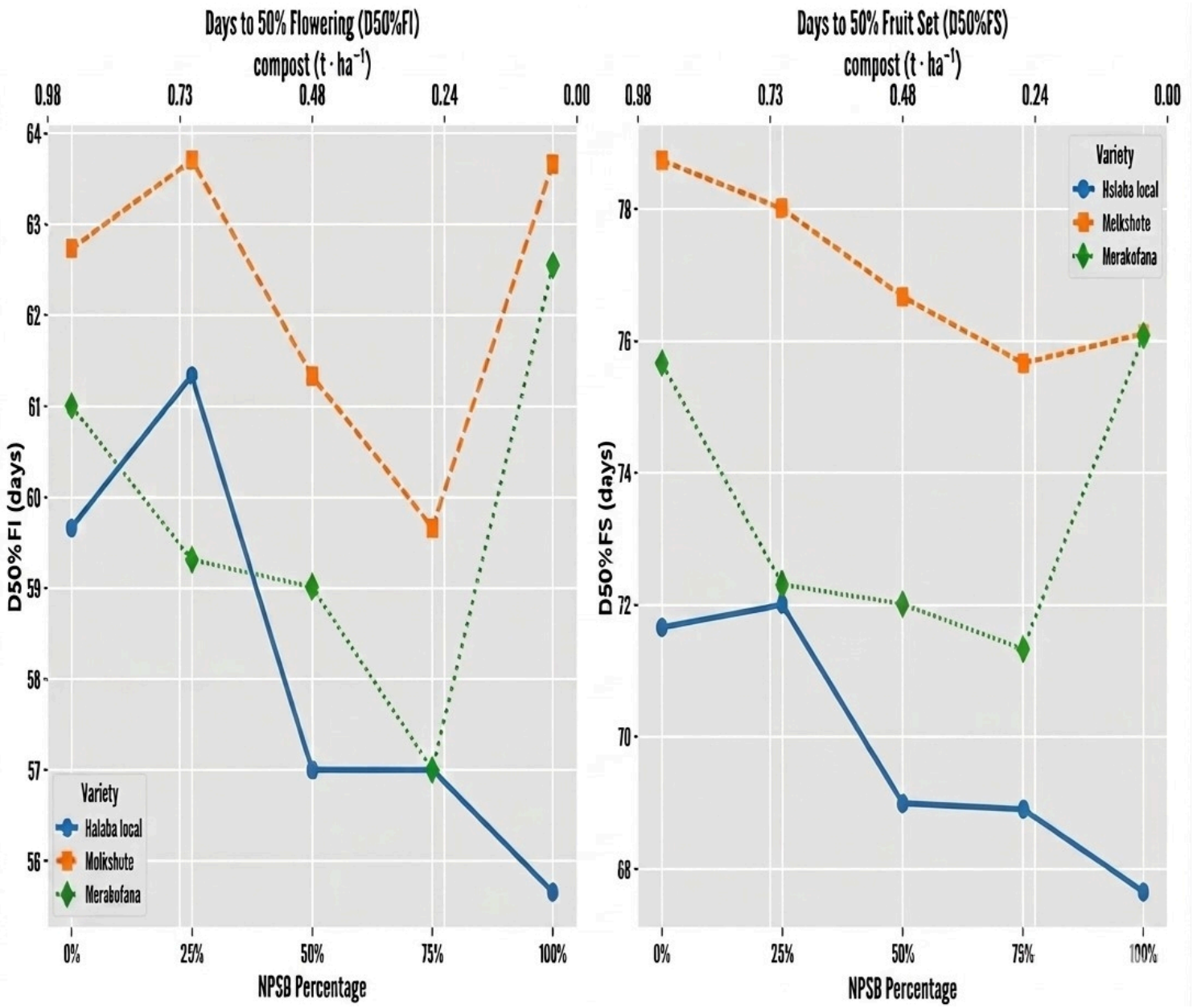


Figure 2

Effects of variety and integrated application of compost and NPSB fertilizer on days to 50% flowering and days to 50% fruit set of hot pepper.

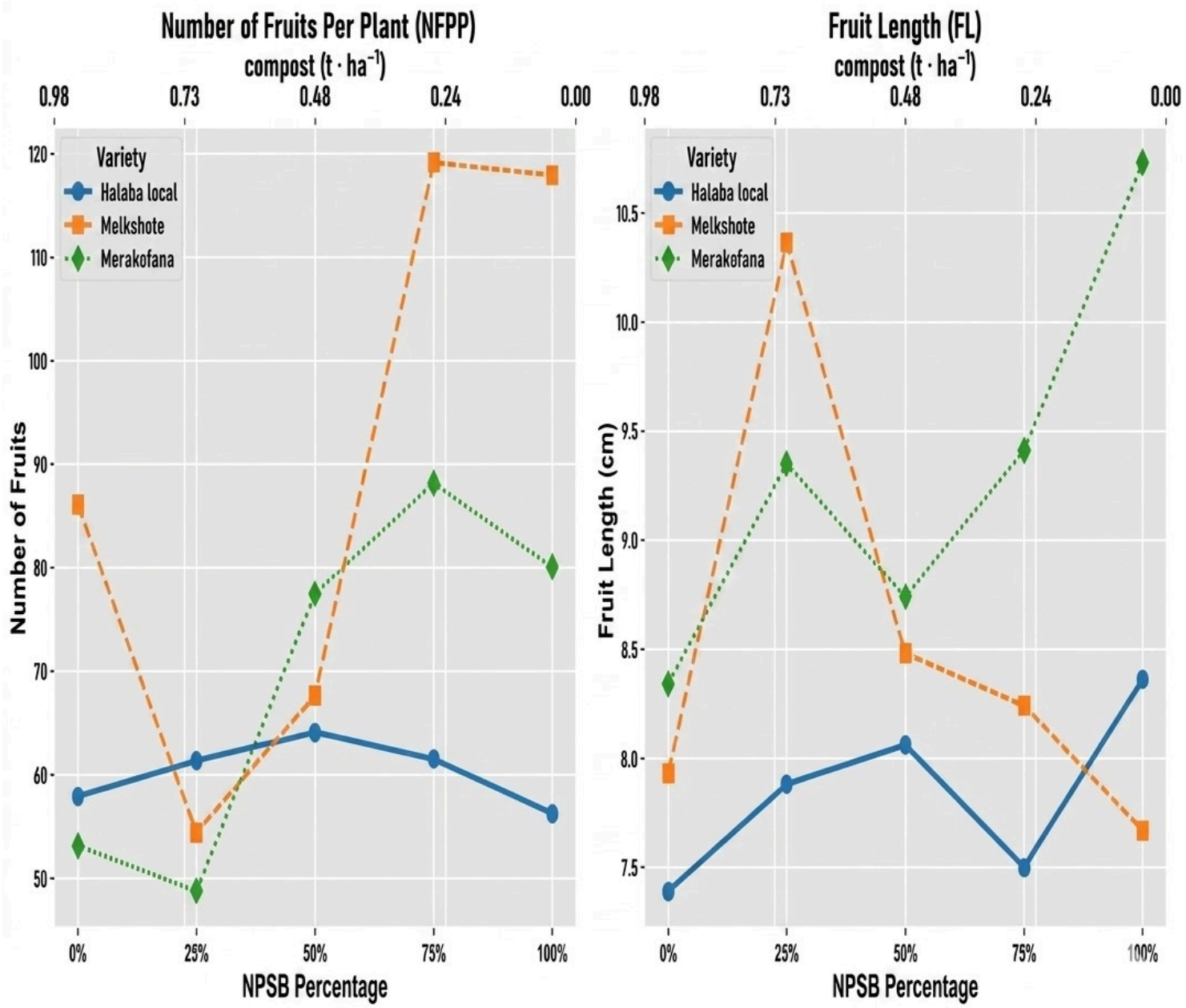


Figure 3

Effect of hot pepper varieties and integrated application of municipal-waste compost and NPSB fertilizer on number of fruits per plant (NFPP) and fruit length (FL, cm).

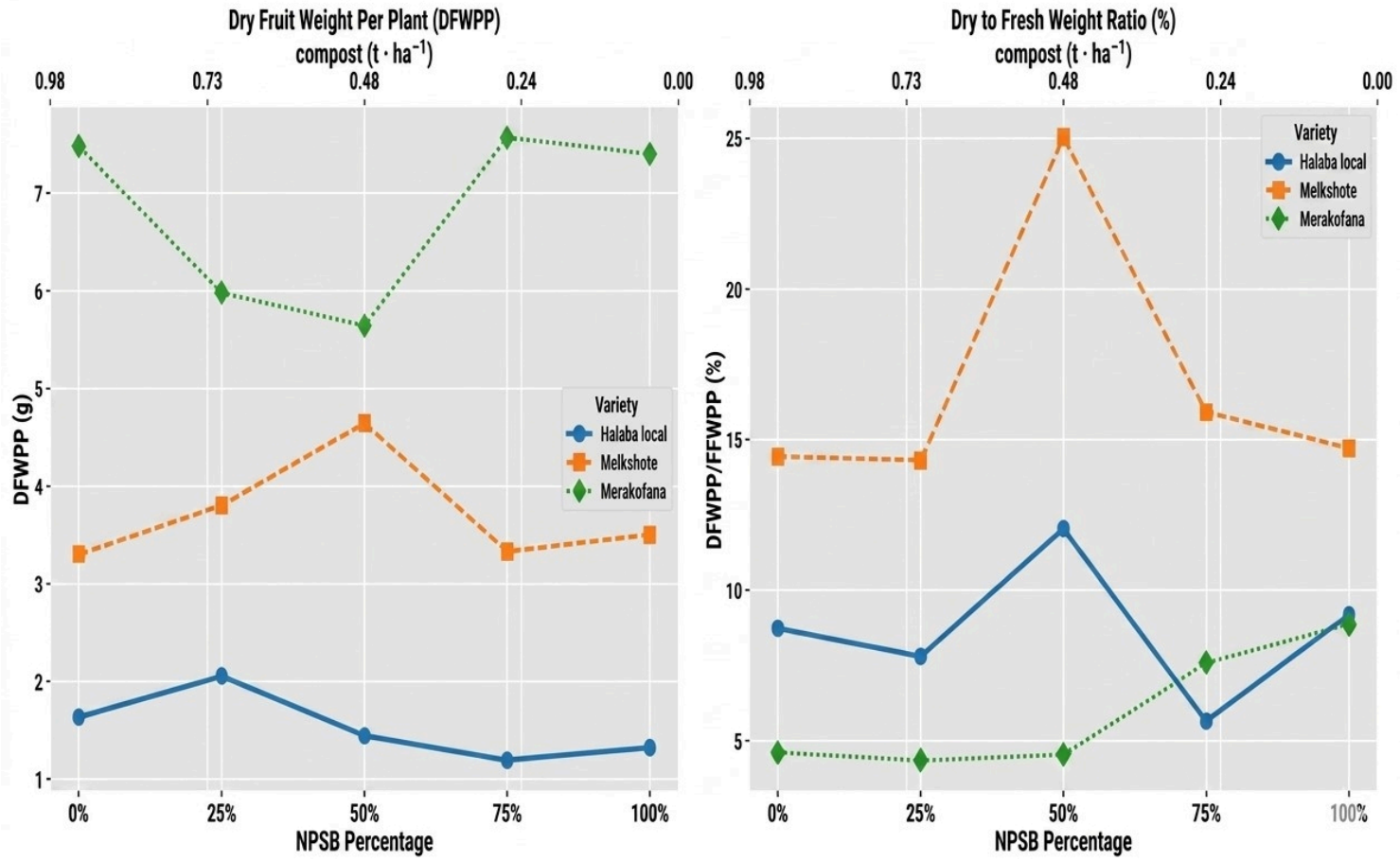


Figure 4

Effect of hot pepper varieties and integrated application of municipal-waste compost and NPSB fertilizer on dry fruit weight per plant (DFWPP, g) and dry-to-fresh fruit weight ratio per plant (DFWPP/FFWPP, %).

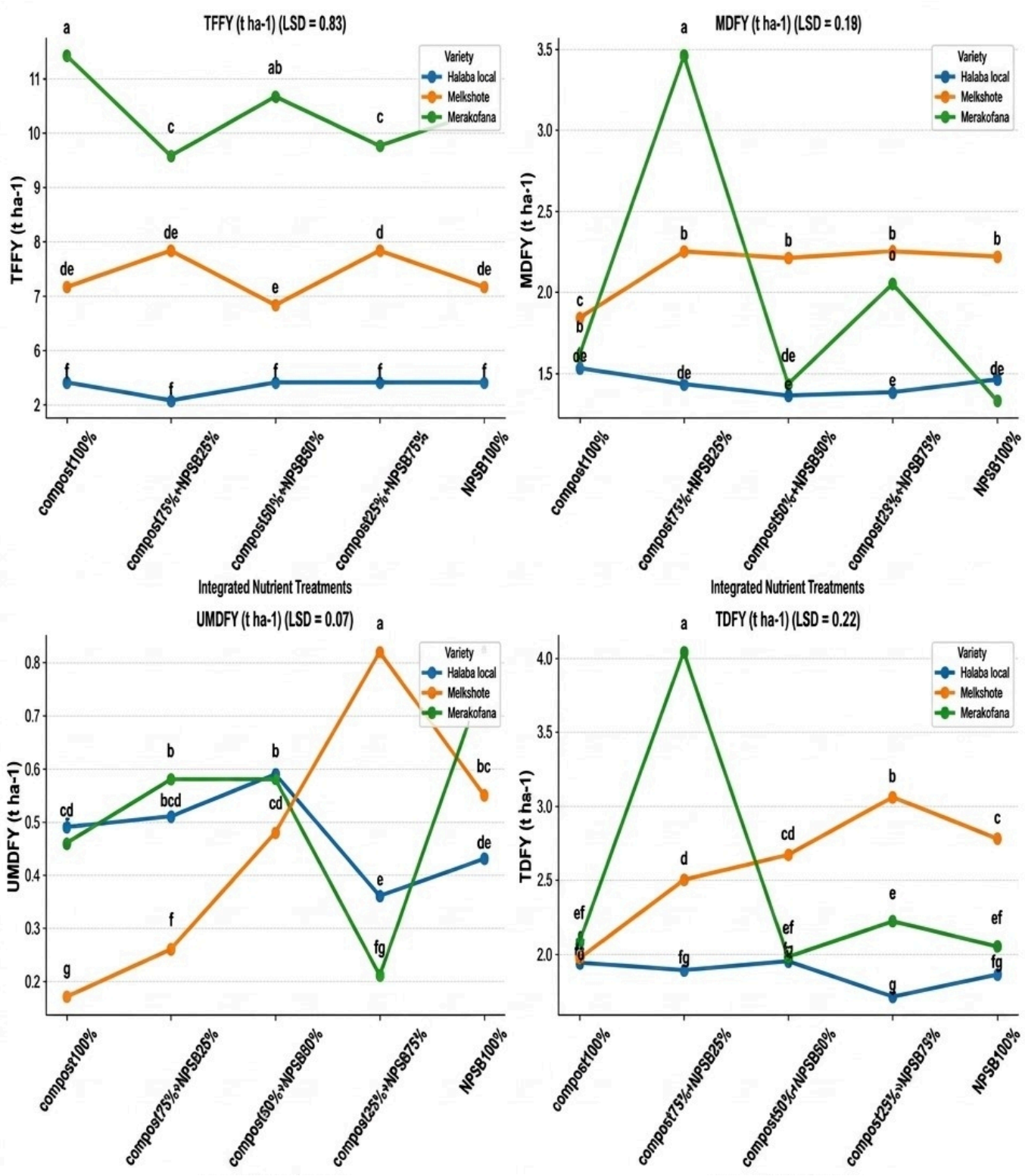


Figure 5

Effects of hot pepper varieties and integrated application of municipal-waste compost and NPSB fertilizer on yield traits: total fresh yield (TFY, t ha⁻¹), marketable dry yield (MDY, t ha⁻¹), unmarketable dry yield (UMDY, t ha⁻¹), and total dry yield (TDY, t ha⁻¹)

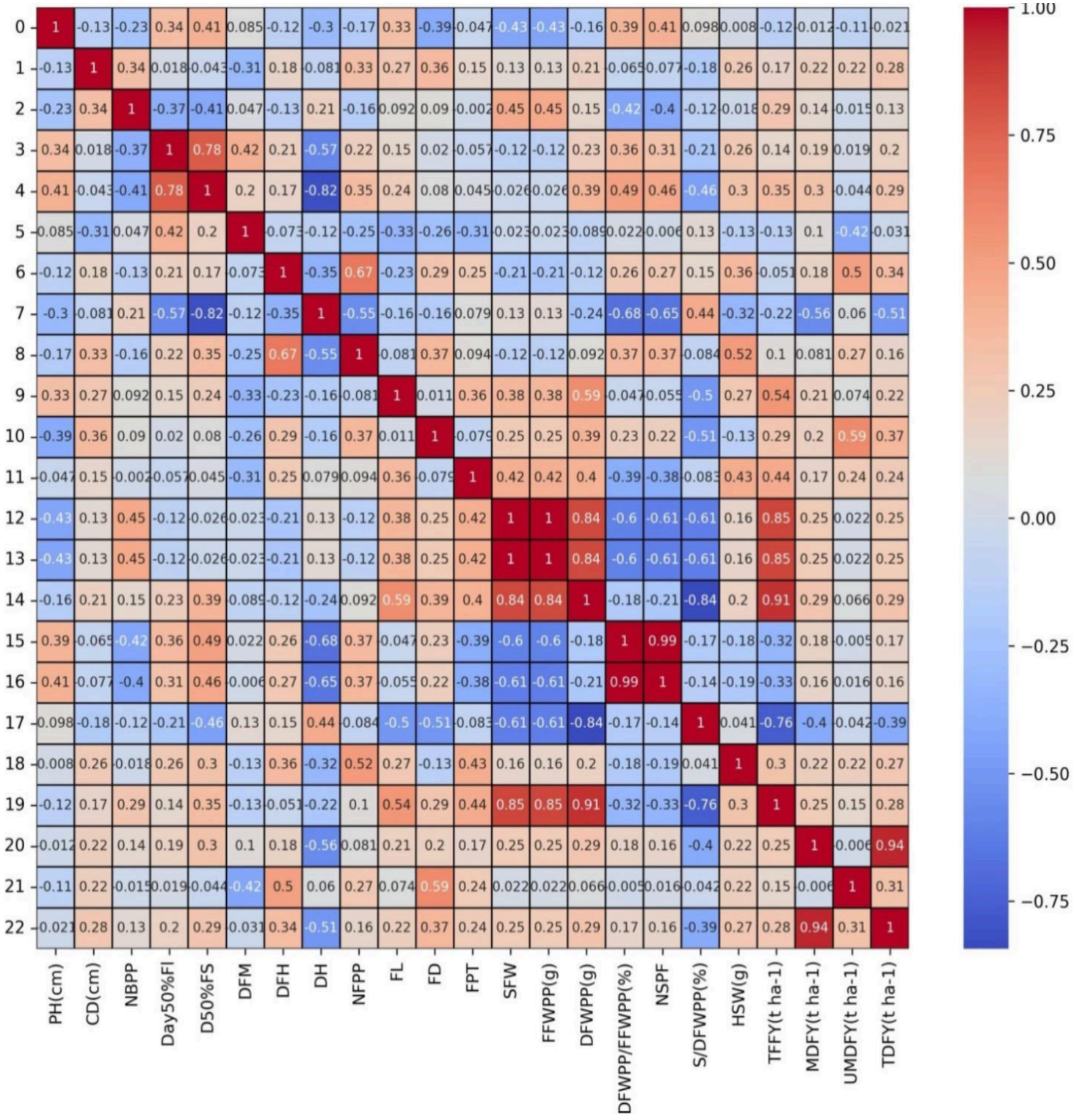


Figure 6

Pearson correlation coefficients (r) among phenological, growth, fruit, and yield parameters of hot pepper (*Capsicum annuum L.*) varieties as influenced by integrated application of municipal-waste compost and NPSB fertilizer.