The potential of water hyacinth vermicompost as a sustainable alternative to nitrogen, phosphorous, and potassium fertilizer

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ABSTRACT

Excessive use of chemical fertilizers results in irreversible soil quality loss, food safety issues, and eutrophication concerns in aquatic ecosystems that promote the growth and spread of invasive weeds such as water hyacinth (*Pontederia crassipes* (Mart.) Solms) (Pontederiaceae). However, less attention has been given to mitigating wetland pollution and the direct biomass disposal of water hyacinth towards biomass vermicomposting for weed control and sustainable agriculture through integrated fertilizer management. An open-field lettuce (*Lactuca sativa* L.) growth experiment was conducted to enhance soil quality, promote growth, and manage aphid pests by substituting water hyacinth vermicompost (VC) for nitrogen, phosphorus, and potassium (NPS) (19N-38P_2O_5-7S) fertilizer. A completely randomized block design (RCBD) with three replications was employed, utilizing the recommended NPS fertilizer dose (F1), 2.5 t ha^{-1} VC (F2), 5 t ha^{-1} VC (F3), 2.5 t ha^{-1} VC + 50% NPS (F4), 5 t ha^{-1} VC + 50% NPS (F5), and unfertilized soil (F6, control). Maximum fresh weight (215–227%), vitamin C (82.1–94.8%), reduced nitrate content (21.1–23.3%), the highest marginal rate of return (157%), the lowest aphid population (52.8–86.6%), and leaf damage (52.9–92.3%) were observed in plants treated with F4 relative to F6. Moreover, F4 and F5 improved the soil quality characteristics (pH, electrical conductivity, total nitrogen, total available phosphorus, total potassium, total organic carbon, and carbon-to-nitrogen ratio) compared to F6. Based on the findings of this study, the use of F4 in similar agro-ecological zones for improved soil quality, pest control, and enhanced lettuce development is recommended. This work demonstrates how VC can be used sustainably to replace the widespread use of chemical fertilizers to enhance soil fertility, promote lettuce growth, reduce pests, and address wetland eutrophication challenges.

Keywords: Aphids; Biomass; Eutrophication; Fertilizer; NPS; Sustainability; Vermicompost; Water hyacinth
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INTRODUCTION

Mineral fertilizer application has been employed as a common practice to improve agricultural yield. Nevertheless, the overuse of chemical fertilizers can lead to the deterioration of soil health, chemical reliance, pest population development and resistance, and economic implications (Wei *et al*., 2024). Ecologically, the overuse of

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fertilizers, specifically nitrogen and phosphorus, has raised worries regarding eutrophication (Vogels *et al*., 2023), human health, nutrition, food security, and food safety (Qi *et al*., 2022). Eutrophication in freshwater environments is associated with fertilizer runoff, which results in nutrient enrichment and decline in water quality (Vogels *et al*., 2023). Eutrophication causes oxygen depletion, which produces hypoxic conditions that are harmful to aquatic life; fish populations decline, and widespread growth and invasion of hazardous aquatic invasive weeds, specifically water hyacinth (*Pontederia crassipes* (Mart.) Solms) (Pontederiaceae) occur (Ratnani *et al*., 2024).

Since its first appearance in Lake Tana, Ethiopia, in 2011, at the northern tip of the lake, it spread quickly over the next few years, covering about 2,126.9ha of water surface during the wet and 592.4 ha during the dry seasons by the end of 2019 causing irreversible social, economic, and environmental problems (Damtie *et al*., 2022). Water hyacinth is a noxious, invasive aquatic weed that can cause severe environmental disruption. It can have many negative impacts on the lake, including reduced phytoplankton productivity, reduced fish catches, increased mosquito larvae and leeches, and affected crop production and livestock feed availability. Its population growth, spread, and reproduction are influenced by water depth, quality, and spatial factors (Abebe *et al*., 2023). Furthermore, as the water hyacinth dies and decomposes, it releases nutrients such as nitrogen and phosphorus into the water, which can further exacerbate eutrophication and oxygen depletion, thereby reducing biodiversity (Melesse *et al*., 2020; Lakane *et al*., 2024). Also, water hyacinth invasion has diminished the lake's surface area by 0.5% (1603 ha) causing water loss through evaporation to increase from 5.14 mm/day in 2011 to 18.85 mm/day in 2019 (Abebe *et al*., 2023).

Water hyacinth removal in Lake Tana has only been attempted through mechanical harvesting that employs community mobilization and the aid of simple machines like boats and tractors, though it has been reported as less efficient (Dechassa., 2020). This mechanical removal efforts failed because the direct disposal of water hyacinth biomass on the lakeside after harvesting fosters seed regeneration and vegetative propagation (Karouach *et al*., 2022), creates continuous leachate flow that aggravates eutrophication (Otieno *et al*., 2022), and creates social problems such as the spread of malaria (Getahun and Kefale, 2023). The ever-growing environmental awareness regarding the excessive use of chemical fertilizers and their negative impacts on soil health, aquatic ecosystems, and human health has prompted an increasing demand for integrated nutrient management practice (Mohanty *et al*., 2023).

The integrated nutrient management approach combines the use of both chemical and organic fertilizer inputs that provide a balanced strategy to maximize both productivity and sustainability (Ramnarain *et al*., 2017). Chemical fertilizer application is generally more effective for immediate crop production and nutrient availability compared to solely organic methods. On the other hand, organic fertilizer promotes long-term soil health and sustainability. The choice between the two often depends on specific agricultural goals, environmental conditions, and economic considerations. Its application supplies nutrients and beneficial microorganisms, improves soil and plant health, and increases agricultural productivity sustainably (Choirunnisa *et al*., 2022). It also provides better resistance to various environmental stressors, promotes plant growth and yield, while reducing fertilizer doses and increasing income (Baroud *et al*., 2024). Furthermore, its use can reduce costs for the purchase and transport of chemical fertilizer, mitigate the ill effects of synthetic fertilizers on human health and food safety, and maintain sustainable agricultural ecosystems (Mohite *et al*., 2024). Vermicompost produced from water hyacinth biomass (VC) can be the best candidate for integrated nutrient management (Lim *et al*., 2014). Given the aforementioned benefits of VC, integrating it with synthetic fertilizers can help mitigate aquatic eutrophication and the decline in soil health, fertility, and related quality concerns, thereby improving agricultural yields (Balkrishna *et al*., 2024a).

In this study, lettuce (*Lactuca sativa* L.) was selected as a test crop due to its fast growth, sensitivity to fertilizer applications, and widespread cultivation in Ethiopian urban and peri-urban areas, including in the study area. Growing lettuce is one of the most economically profitable (Balkrishna *et al*., 2024a) and socially acceptable practice (Yang *et al*., 2022). Its widespread cultivation and demand as a fresh market vegetable makes integrated nutrient fertilizer trials practical for local farmers (Gonzaga *et al*., 2017). Lettuce is a low-calorie salad crop commonly consumed worldwide and is a good source of various nutrients, several minerals, and fiber. It is a good source of bioactive compounds such as folate, β-carotene, lutein, and phenolics (Yang *et al*., 2022). It also contains various natural health-promoting phytochemicals and vitamins, such as glycosylated flavonoids, hydroxycinnamic acids, sesquiterpene lactones, carotenoids, B vitamins, ascorbic acid, and tocopherols (Yang *et al*., 2022).

However, its fast growth, higher yields, chlorophyll content, vitamin A and C (ascorbic acid), and nitrogen-nitrate concentration, as well as sensory quality traits such as crispiness and bitterness, are influenced by the amount and type of fertilizer applied (Mulyono *et al*., 2018; Islam *et al*., 2021). Its responsiveness to macronutrients (nitrogen, phosphorus, potassium) and trace elements makes it a reliable indicator of vermicompost quality (Manzoor *et al*., 2024). Lettuce grown in phosphorus- and potassium-deficient vermicompost quickly shows reduced root growth and poor leaf quality (chlorosis) (Li *et al*., 2024). Furthermore, lettuce is a shallow-rooted plant that is highly sensitive to environmental factors such as soil quality, moisture availability, and temperature changes (Damerum *et al*., 2021). Damerum *et al*. (2021) reported that lettuce responded positively to compost application in terms of water use efficiency and tolerance to heat stress. Its environmental sensitivity justifies its selection as an ideal candidate for monitoring how well compost improves soil structure, water retention, and resilience to stress in this study. This study hypothesizes that the use of VC, compared to the sole use of NPS mineral fertilizer, improves lettuce growth, chlorophyll content, vitamin C, nitrate content, and aphid pest suppression. This study aimed to investigate the integrated use of VC with NPS on lettuce growth, quality, aphid reduction, and soil quality under field conditions.

MATERIALS AND METHODS

Experimental setup

The experiment was conducted in an open field at the Bahir Dar Institute of Technology, Ethiopia, from January to March 2023. During the study, the daytime relative humidity was 54%, with maximum and minimum temperatures of 28 °C and 11 °C, respectively (latitude: 11° 30′ 11″ to 11° 58′ 11″ N; longitude: 37° 2′ 2″ to 37° 29′ 4″ E) (Figures 1-2). Thirty-day-old lettuce seedlings, grown in a seedling tray (128 holes) using a soil and vermicompost (VC) mixture (3:1, w:w), were transplanted under field conditions according to a factorial randomized complete block design (RCBD). The RCBD is a widely used experimental design for its statistical reliability (Abu-Alsoud *et al*., 2024).

The land was divided into three blocks, each containing six plots (3 m × 2.4 m, with a total area of 7.2 m^2). There were six rows per plot and five plants per row, making 30 plants per plot. The space between blocks and plots was 0.5 and 1.0 m, respectively. The distances between rows and plants were about 50 cm and 40 cm, respectively (Moniruzzaman, 2006). The soil properties of the experimental field are shown in Table 1.

Table 1. Characteristics of soil and vermicompost

Characteristics	Soil	Vermicompost
Chemistry		
pH	5.23	7.47
EC (d Sm^{-1})	1.24	3.81
TOC (g kg^{-1})	125	50.00
TN (g kg^{-1})	8.27	20.00
TAP (g kg^{-1})	7.20	16.30
TK (g kg^{-1})	9.07	16.10
C/N	15.10	7.50
Texture		-
Silt (%)	15.00	-
Sand (%)	15.40	-
Clay (%)	69.60	-

pH, EC = electrical conductivity, TOC = total organic carbon, TN = total nitrogen, TAP = total available phosphorous, TK = total potassium, C/N = and carbon to nitrogen ratio

The treatments applied were as follows: F1 = recommended NPS fertilizer (19N-38P2O5-7S kg ha^{-1}), F2 = 2.5 t ha^{-1} VC, F3 = 5 t ha^{-1} VC, F4 = 2.5 t ha^{-1} VC + 50% of the recommended NPS rate, F5 = 5 t ha^{-1} VC + 50% NPS, and F6 = unfertilized soil (control) (Table 2). The average relative humidity, rainfall, and temperature during the field study period were conducive to lettuce production (Figure 2).

Table 2. Water hyacinth vermicompost (VC) and NPS doses in different treatments

Treatment	**Vermicompost dose**
F1	0% VC, 100% NPS (19N-38P_2O_5-7S)
F2	VC 2.5 t ha^{-1}
F3	VC 5 t ha^{-1}
F4	VC1 + 50% NPS
F5	VC2 + 50% NPS
F6	Control (unfertilized soil)

The fertilizer doses of recommended NPS (158 kg ha^{-1}) and VC (5 t ha^{-1}) were made based on Demir's (2019) recommendation, with NPS applied at transplanting time and VC applied 4 weeks before the transplanting (Alemayehu *et al*., 2020). All other soil and plant management practices were uniformly implemented across all plots as suggested by Yang *et al.* (2022) for lettuce production.

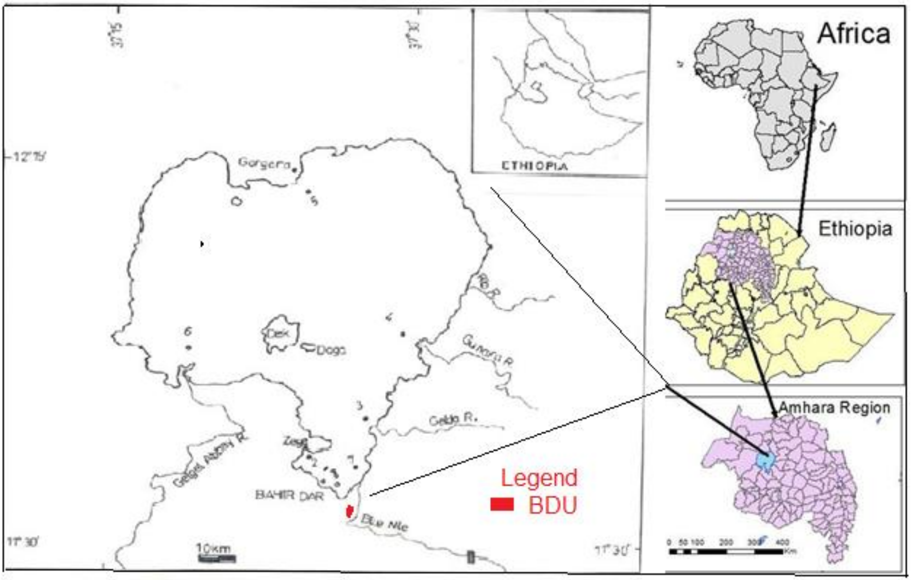

Figure 1. Study site location map

Lettuce growth measurements

At the end of 45 days after transplanting (DAP), various morphometric growth measurements were recorded, including plant height (cm), root length (cm), leaf length (cm), leaf width (cm), leaf number, head diameter (cm), leaf area (cm²), fresh and dry weight (g), chlorophyll content in the apical leaves, fresh leaf vitamin C levels, and leaf nitrate content (Figure 3). For these measurements, six plants were selected from the interior plots, ensuring they were free from pest infestations and damage. These growth parameters are vital indicators of the plant's health, productivity, and adaptability to environmental conditions, offering insights into the physiological, morphological, and biochemical status of the plants (Camen *et al.*, 2022).

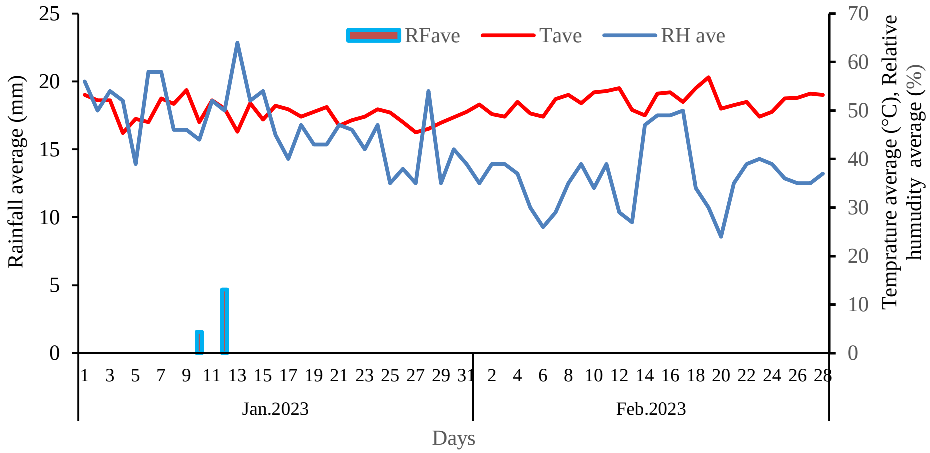

Figure 2. Average air temperature (Tave), relative humidity (RHave), and rainfall average of the study area during the study period in 2023 (Source: Ethiopian Metrological Agency, Bahir Dar)

Furthermore, numerous studies have validated these morphometric metrics, underscoring their significance in assessing and managing leafy vegetable growth (Camen *et al.*, 2022). Plant height was measured from the uppermost growing point of the leaf to the root tip, while root length was measured from the cotyledonary node to the root tip (Chen *et al.*, 2019). Head diameter was determined by measuring the distance between the two most distant leaves of each plant. Leaf area was calculated by multiplying leaf length by leaf width, using a ruler and a correction factor of 0.587 (Meskelu *et al.*, 2024).

The criteria for selecting marketable lettuce based on fresh weight (g plant^{-1}) included: 1) a minimum fresh weight of less than 150 grams per plant (Holsteijn Van, 1980), and 2) the removal of basal leaves that were not fully green or had aphid damage (Yadav *et al.*, 2020). The fresh yield of lettuce per plant per plot was recorded in grams, representing the total weight of the entire plant after harvest from each plot (2.0 m × 1.2 m). This weight was then converted to hectares to calculate the marketable yield per hectare, expressed in tons (Islam *et al.*, 2020). The total fresh weight measurement (g plant^{-1}) included both marketable and unmarketable leaves, including those that were basal or damaged by aphids. Dry biomass (g plant^{-1}) was determined by drying the plant tissue in an oven at 65 °C for 48 hours (Sarkar *et al.*, 2018). The marketable yield (t ha^{-1}) was calculated as shown in Equation 1 below.

$$\text{Marketable yield (t } ha^{-1}) = \frac{\text{Marketable weight} * \text{\% marketable weight} * \text{planting density}}{100} \quad \ldots(1)$$

Apogee leaf chlorophyll content determination

The relative leaf chlorophyll content of lettuce was assessed using a portable Apogee Chlorophyll Meter (Apogee Instruments, Logan, UT). After calibration, chlorophyll content (µmol m^2 s^{-1}) was measured three times near the margins of the three randomly selected, most recently matured, fully expanded leaves during midday (Zandvakili *et al.*, 2019).

Leaf vitamin C content determination

Vitamin C was measured using a titration method with the 2,6-dichloroindophenol staining method (Wu *et al.*, 2023). First, fresh leaf samples were cleaned and crushed, followed by extraction (5 g sample) with 25 mL of 2% oxalic acid solution, oxidized with 1 g of activated carbon, and filtered. A total of 5 mL of the extract and 5 mL of 2% thiourea solution were added and combined. About 2 mL of diluent and 0.5 mL of 2% 2, 4-dinitrophenylhydrazide colorimeter were added to a test tube and then incubated at 37 °C for 3 hours, followed by cooling to room temperature. Finally, after 2.5 mL of 85% sulfuric acid was added, the vitamin C absorbance measurement reading was made at 520 nm (Wu *et al.*, 2023). The vitamin C content (per 100 grams of fresh leaf (mg 100 g^{-1})) was determined as shown in Equation 2 below.

$$\text{Vitamin C (mg } 100\text{g}^{-1}) = \frac{(\text{As}-\text{Ab})}{\text{Astd}-\text{Abstd}} \times 10 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where, A_s is the absorbance of the sample, A_b is the absorbance of the blank, A_{std} is the absorbance of standard concentration (mL), A_{bstd} is the absorbance of the blank for standard, and 10 is the dilution factor.

Leaf nitrate content determination

About 5 g of fresh, clean, pest-free lettuce leaf samples were chopped and mixed. Then, distilled water was added to the mixture with 0.5 mL of hydrogen peroxide (H_2O_2) and centrifuged at 4000 rpm at 25 °C for 15 min, and the supernatant was separated and filtered through a filter paper. About 80 µL of 5% salicylic acid-sulfuric acid solution and 3 mL of NaOH (1.5 N) were added to 20 µL of extract. Then, the samples were allowed to cool at room temperature, and nitrate readings were made in a colorimetric reading of the microplates at 410 nm (Song *et al.*, 2020).

Aphid leaf infestation and damage

Aphid populations and the damage they caused were recorded at 15, 30, and 45 DAP. The number of aphids and damage was counted from all the leaves of the selected 6 plants and calculated as shown in Equations 3-4, respectively. Aphids are small, pear-shaped, soft-bodied insects that can be yellow, green, or dark in color. They typically feed in colonies on the undersides of tender terminal growth (Badar *et al.*, 2022). Aphids can also transmit plant viruses through the honeydew they secrete (Adenka *et al.*, 2021). Aphids damage lettuce leaves by sucking the sap from the leaves and stems, causing symptoms including wrinkled leaves, deformed shoots, and yellow or brown spots (Aguilera *et al.*, 2021).

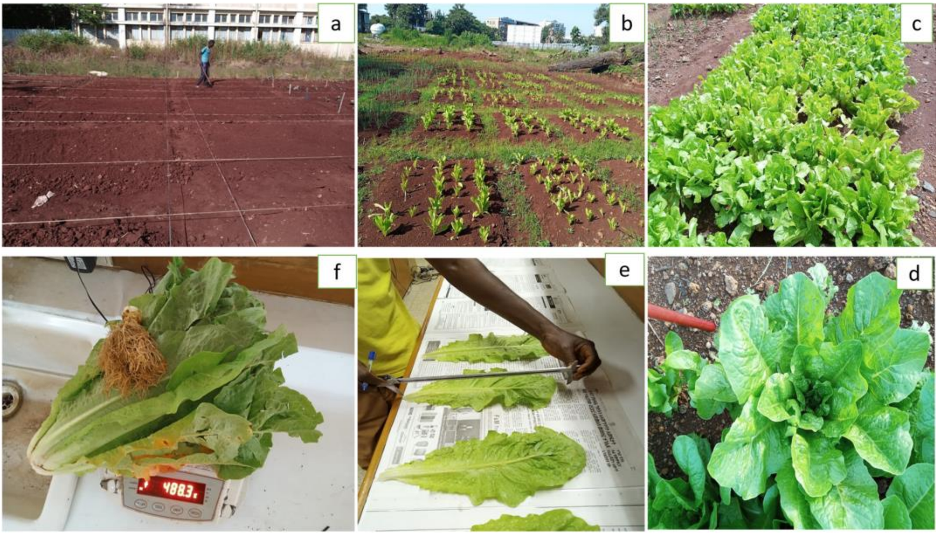

Figure 3. Displaying activities from the experimental field plot to the fresh weight measurements (a= field lay out before transplanting; b = lettuce planted; c = lettuce plot at the end of 45 days of transplanting; d = single lettuce plant at the end of 45 days of transplanting; e = lettuce leaf length measurement; f = total fresh lettuce weight measurement.

$$\text{Leaf infestation by aphids (\%)} = \frac{\text{Number of infested leaves}}{\text{Total number of leaves}} * 100 \ldots\ldots(3)$$

$$\text{Leaf damage by aphids (\%)} = \frac{\text{Number of leaves damaged per plant}}{\text{Total number of leaves per plant}} * 100 \ldots\ldots(4)$$

Soil sampling and analysis

A composite soil sample (0–20 cm soil depth) was collected with a soil auger in a zigzag pattern randomly from each block prior to transplanting for the determination of pH, electrical conductivity (EC), total nitrogen (TN), total available phosphorous (TAP), total potassium (TK), moisture content (MC), total organic carbon (TOC), and carbon to nitrogen ratio (C/N). These measurements provide valuable insights into the effectiveness of VC for integrated nutrient management in terms of soil nutrient balance, fertility, and overall health, which directly influence plant growth and productivity (Mengistu *et al*., 2017; Oyege and Balaji Bhaskar, 2023).

The pH and EC were measured using a calibrated pH meter and EC with a conductivity meter, respectively, after mixing 3 g of dried samples with 30 mL of distilled water in a

1:10 (w/v) ratio (Ahmed and Deka, 2022; Das *et al*., 2022). This mixture was then mechanically shaken for 2 hours, incubated, and then the extract was filtered for analysis (Devi and Khwairakpam, 2020).

TN and TAP were determined after a preliminary digesting of a 0.1 g sample treated with 98% (v/v) sulfuric acid and 30% (v/v) hydrogen peroxide. TN was measured based on the Kjeldahl method, and TAP was measured using the anti-Mo-Sb spectrophotometry method in a UV spectrophotometer (UV-1800, Shimadzu, Japan) as described by Gong *et al*. (Gong *et al*., 2021). TK was determined by flame photometry after digesting a 0.2 g air-dried, 0.2 mm sieved sample with 10 mL of H_2SO_4 and $HClO_4$ (5:1) at 300 °C for 2 hours. The C/N ratio was calculated from the values of total organic carbon and nitrogen content (Boruah *et al*., 2019), as shown in equation 1 below. The moisture content (MC) of the samples was calculated after a 100-gram fresh sample was dried for 24 hours at 105 °C on weighted crucible plates (Masin *et al*., 2020). The content of volatile solids was measured by igniting 5 g of ground, oven-dried samples at 550 °C for 2 hours in a muffle furnace. The calculations for MC, TOC, and volatile solids are outlined in Equations 1–3, with TOC determined through weight loss upon ignition, indicating the amount of volatile solids present.

$$\text{MC (\%)} = \frac{\text{Fresh weight } - \text{Dry weight}}{\text{Fresh weight}} \times 100 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (5)$$

$$\text{Total organic carbon (\%)} = \frac{\text{\% Volatile solid}}{1.8} * 100 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Partial budget analysis

A partial budget economic analysis was conducted to determine the economically optimal application rates for NPS fertilizer and vermicompost (VC) for marketable products. The analysis considered gross field benefit (GFB), total variable cost (TVC), and net benefit (NB). Prices for NPS was set at 15.50 ETB kg^{-1}, VC at 5.00 ETB kg^{-1}, lettuce seedlings at 0.10 ETB $seedling^{-1}$, and harvested lettuce at 5.00 ETB single $plant^{-1}$ based on local market rates at the time of transplanting and harvesting. The average daily labor cost for land preparation, transplanting, watering, and harvesting was approximately 75.00 ETB.TVC encompassed all costs, including seedling purchases and labor for land preparation, transplanting, watering, weed management, and fertilizer application, as well as transportation costs to the farm per hectare. GFB was calculated by multiplying the farm gate price of lettuce (in birr per kg) by the adjusted lettuce yield (in $kg \cdot ha^{-1}$). The average yield was adjusted downward by 10% to account for differences between experimental yields and those typically achieved by farmers. A dominance analysis was performed to identify the most profitable treatments, and the marginal rate of return (MRR) was calculated for the non-dominated treatments (CIMMYT, 1988). Net benefit was determined by subtracting TVC from GFB, as shown in Equation 6.

$$\text{Net benefit} = \text{Gross field benefit} - \text{Total variable cost} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (6)$$

The marginal rate of return (MRR) was calculated as the ratio of differences between the net benefits of preceding treatments to the difference between the TVC of successive treatments (Equation 7). The minimum acceptable MRR for developing countries, including Ethiopia, is 100%.

$$\text{Marginal rate of return (MRR \%)} = \frac{\text{Change in net benefit}}{\text{Change in total variable cost}} * 100 \ldots\ldots\ldots \ldots\ldots\ldots\ldots\ldots(7)$$

Statistical analysis

All data were evaluated for normality and homogeneity of variance. Then, they were subjected to statistical analysis with three replicates by analysis of variance (ANOVA) using the SAS statistical package (9.4 version) (SAS Institute Inc., 2000, Cary, NC, USA). Aphid pest suppression data was analyzed using 2-way repeated measures ANOVA, considering time as additional factor. Mean separation was done using the least significant differences (LSD) test at level $p \leq 0.05$. LSD tests were used due to their post-hoc comparisons, sensitivity to detect smaller differences between means, simplicity, flexibility, and less conservativeness.

RESULTS

Effect on lettuce growth

The assessment of lettuce plant height, root length, leaf length, leaf number, leaf area, head diameter, shoot fresh weight, total fresh weight, shoot dry weight, and marketable yield in response to various fertilizer treatments is presented in Figures 4A-D, 5D, and Table 3. Results indicated that all growth responses were significantly improved ($p < 0.05$) by the fertilizer applications compared to the control (F6). Notably, treatment F4 led to significant increases in plant height and leaf length, with enhancements of 226% and 86.8%, respectively, over the control. Additionally, F4 significantly increased root length, root fresh weight, and root dry weight by 150%, 267%, and 151%, respectively, compared to F6, showing results statistically similar to F5. For leaf number, the F1 treatment yielded significantly higher counts, comparable to F5 ($p < 0.05$). Head diameter and leaf area were also significantly greater with F4, increasing by 106% and 286% over the control, respectively, although no significant differences were observed with F1. Moreover, the F1 treatment resulted in a 198% increase (431 g) in shoot fresh weight (Figure 5C), which was statistically similar to F4. Among all treatments, F4 exhibited the highest total fresh weight, with a 227% increase (431 g), which was statistically comparable ($p<0.05$) to F1 when compared to F6 (control).

Table 3. Effect of integrated fertilizer application on lettuce head diameter, total dry weight, and marketable mass growth

Treatments	**Head diameter (cm plant $^{-1}$)**	**Leaf area (m^2 plant $^{-1}$)**	**Total dry weight (g plant^{-1})**	**Marketable weight (g plant $^{-1}$)**
F1	30.30^a	249.00^a	69.20^a	395^a
F2	22.50^c	130.00^c	37.10^d	153^d
F3	26.70^b	155.00^c	46.50^c	202^c
F4	31.00^a	275.00^a	70.40^a	405^a
F5	25.30^b	186.00^b	58.00^b	350^b
F6	15.30^d	71.20^d	25.30^e	71.0^e

Means followed by the same letter in each column are not significantly different at $p < 0.05$. F1 = NPS fertilizer (19N-38P_2O_5-7S); F2 = 2.5 t ha^{-1} VC; F3= 5 t ha^{-1} VC; F4= 2.5 t ha^{-1} VC + 50% NPS; F5= 5 t ha^{-1} VC + 50% NPS; F6 = unfertilized soil (control)

Effect on lettuce chlorophyll, vitamin C, and nitrate content

Compared to the control (F6), the quality parameter of lettuce, including leaf chlorophyll, vitamin C, and nitrate concentration, was significantly enhanced in all fertilizer treatments ($p < 0.05$, Figure 5A, B, C). Among these, the highest leaf chlorophyll content (73.8%) was observed in plants grown with F5, which was statistically similar to F1 when compared to F6. Additionally, treatments F2, F3, F4, and F5 showed the most significant reductions in nitrate concentrations, with declines ranging from 45.4% to 48.5% compared to F1 ($p < 0.05$). There was no significant difference in nitrate content between treatments F5 and F4 ($p > 0.05$). The lowest leaf nitrate values were recorded for the control (F6, 1216 mg kg^{-1}), while the highest values were found in the F1 treatment (100% NPS).

Effect on suppression of aphid infestation and damage

The number of aphids per plant and the resulting leaf damage—linked to fertilizer application, nutrient absorption, and plant vigor—were assessed biweekly (Table 4). Throughout the plant growth period, significantly ($p < 0.05$) lowest aphid counts and leaf damage were recorded at 15 days after transplanting (DAP), but a significant increase in infestation was noted toward the end of the growth period at 45 DAP (Table 4). At 15 DAP, the F4 treatment exhibited the highest reduction in aphid numbers (86.6%), which was statistically similar to F5. Additionally, at 30 DAP and 45 DAP, F4 showed a decrease of 74.4% and 52.8% in aphid counts, respectively, with results statistically comparable to F1. Leaf damage also demonstrated a significant reduction of 92.3% with F4 at 15 DAP, which was statistically similar to F5, followed by F1 and F3. Furthermore, at 30 and 45 DAP, leaf damage was significantly reduced by 92.3% and 52.9%, respectively, in the F4 treatment.

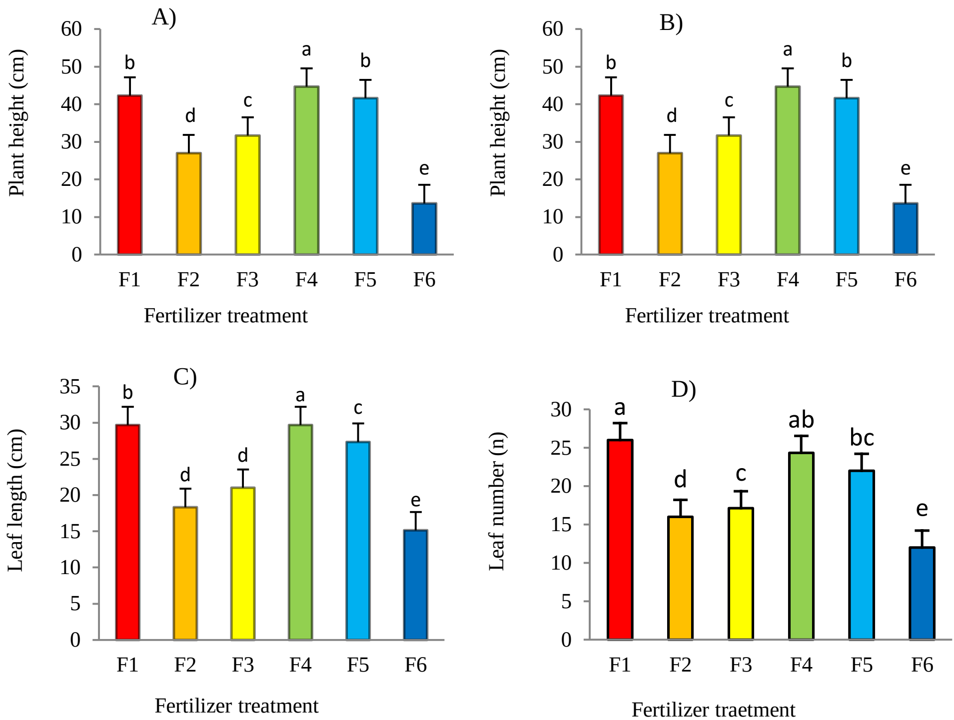

Figure 4. Effect of integrated fertilizer application on lettuce plant height (A), root length (B), leaf length (C), and leaf number (D). F1 = NPS fertilizer (19N-38P_2O_5-7S); F2 = 2.5 t ha^{-1} VC; F3= 5 t ha^{-1} VC; F4= 2.5 t ha^{-1} VC + 50% NPS; F5= 5 t ha^{-1} VC + 50% NPS; F6 = unfertilized soil (control)

Also, in terms of fertilization significantly ($p < 0.05$) highest aphid numbers were recorded for T6 at all-time points, especially at 45 DAP, reaching 20.50 plant^{-1} and the lowest count was observed in T4 and T5 (Table 4). Moreover, significantly ($p < 0.05$) highest leaf damage percentages were also observed in T6, where unfertilized plants experienced the most significant damage (47.20% at 45 DAP). T1 and T4 had the least leaf damage, particularly at 15 DAP, with T4 showing significant resistance throughout the study (Table 4).

Effect on soil chemical property

The application of single or combined fertilizer treatments significantly influenced soil pH, electrical conductivity (EC), total organic carbon (TOC), total nitrogen (TN), total available phosphorus (TAP), and the carbon-to-nitrogen (C: N) ratio immediately after application and before transplanting ($p < 0.05$) (Table 5).

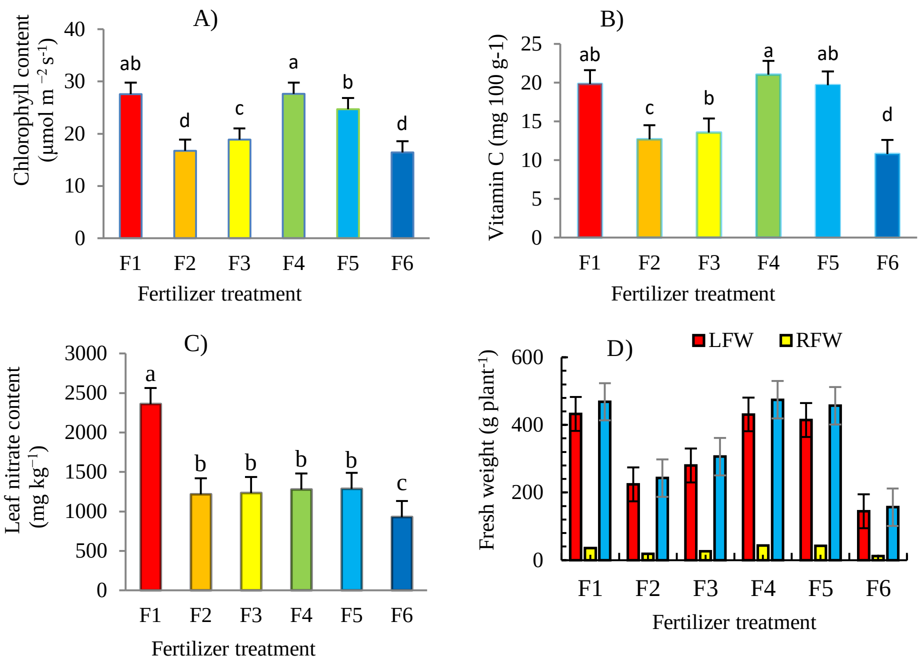

Figure 5. Effect of integrated fertilizer treatments on lettuce leaf chlorophyll (A), vitamin C (B), nitrate concentration, (C), and fresh weight (D); F1 = NPS fertilizer (19N-38P_2O_5-7S**)**; F2 = 2.5 t ha^{-1} VC; F3= 5 t ha^{-1} VC; F4= 2.5 t ha^{-1} VC + 50% NPS; F5= 5 t ha^{-1} VC + 50**%** NPS; F6 = unfertilized soil (control)

Among the treatments, the lowest values for these soil properties, excluding the C:N ratio, were observed in the control (F6). Specifically, soil pH, EC, TOC, and TK levels increased significantly in F5, showing enhancements of 223%, 30.8%, 39.2%, and 39.6%, respectively, compared to the control. Compared to F6, the greatest increments in TN and TAP were obtained in F4 and F5 by 67-70% and 55.6-59.7%, respectively. The most substantial reduction in the C:N ratio was achieved with F1, which declined by 27.7% compared to F6. Conversely, significant increases in the C:N ratio were observed in F2 and F6, although these changes were statistically ($p < 0.05$) similar to each other.

Partial budget analysis

The primary goal of fertilizer application to soil is to enhance the growth, quality, and yield of plants, thereby maximizing profit. The partial budget analysis showed that the F4 treatment yielded the highest net benefit of 122,840.00 Birr per hectare and a higher marginal rate of return of 156% (Tables 6-7).

Table 4. Effect of integrated fertilizer application on aphid numbers plant^{-1} and leaf damage plant $^{-1}$ due to aphid

Treatments	15 DAP		30 DAP		45 DAP	
	Aphid number plant^{-1}	Leaf damage (%)	Aphid number plant^{-1}	Leaf damage (%)	Aphid number plant^{-1}	Leaf damage (%)
F1	4.75^{c}	3.76c	8.10^{c}	9.80^{cd}	10.60^{cd}	15.50^{cd}
F2	6.67^{b}	16.70^{b}	10.50^{b}	24.60^{b}	16.00^{b}	31.00^{b}
F3	8.83^{a}	12.90^{c}	14.20^{a}	18.50^{bc}	12.7^{bc}	24.20^{bc}
F4	1.42^{d}	1.910^{d}	4.20^{d}	3.22^{d}	9.67^{d}	5.40^{d}
F5	1.58^{d}	2.13^{d}	8.42^{c}	5.97^{cd}	13.30^{bc}	9.23^{d}
F6	10.50^{a}	24.90^{a}	16.30^{a}	41.70^{a}	20.50^{a}	47.20^{a}

Means followed by the same letter in each column are not significantly different at p<0.05.
F1 = NPS fertilizer (19N-38P_2O_5-7S); F2 = 2.5 t ha^{-1} VC; F3= 5 t ha^{-1} VC; F4= 2.5 t ha^{-1} VC + 50% NPS; F5= 5 t ha^{-1} VC + 50% NPS; F6 = unfertilized soil (control)

Table 5. Characteristics of soil after fertilizer amendments

Treatments	pH	EC (d Sm^{-1})	TOC (g kg^{-1})	TN (g kg^{-1})	TAP (g kg^{-1})	TK (g kg^{-1})	C/N
F1	5.43^{e}	3.93^{ab}	154.00^{d}	14.00^{a}	11.20^{a}	11.50^{b}	11.00^{d}
F2	6.27^{d}	3.67^{c}	166.00^{c}	11.40^{c}	9.27^{c}	9.97^{c}	14.50^{b}
F3	6.53^{c}	3.94^{ab}	173.00^{b}	12.20^{b}	9.70^{b}	10.90^{b}	14.20^{b}
F4	6.80^{b}	3.94^{ab}	174.00^{b}	13.80^{a}	11.20^{a}	11.50^{b}	12.60^{c}
F5	7.17^{a}	4.07^{a}	182.00^{a}	14.10^{a}	11.50^{a}	12.70^{a}	13.00^{c}
F6	5.23^{f}	1.24^{d}	125.00^{e}	8.27^{d}	7.20^{d}	9.07^{d}	15.10^{a}

Means followed by the same letter in each column are not significantly different at $p < 0.05$. F1 = NPS fertilizer (19N-38P_2O_5-7S); F2 = 2.5 t ha^{-1} VC; F3= 5 t ha^{-1} VC; F4= 2.5 t ha^{-1} VC + 50% NPS; F5= 5 t ha^{-1} VC + 50% NPS; F6 = unfertilized soil (control), EC= Electrical conductivity, TOC= total organic carbon, TN= total nitrogen, TAP= total available phosphorous, TK=total potassium, and C/N =carbon to nitrogen ratio

Table 6. Marketable fresh yield, gross field benefit, total variable cost and net benefit as influenced by the combination of NPS fertilizer and VC

Treatments	Marketable fresh yield (t ha^{-1})	Adjusted marketable fresh yield (t ha^{-1})	Gross field benefit (ETB ha^{-1})	Total variable costs (ETB ha^{-1})	Net benefit (ETB ha^{-1})	Rank
F1	20.50	18.40	184,161.60	68,432.22	115,729	2
F2	10.70	9.67	96,768.00	26,666.67	70,101	4
F3	13.40	12.10	121,089.60	52,222.22	68,867	5
F4	20.30	18.30	183,168.00	60,327.22	122,840	1
F5	19.90	17.90	178,977.60	85,882.78	93,094	3
F6	0.69	0.62	6,220.80	12,222.22	-6,001	6

Means followed by the same letter in each column are not significantly different at $p < 0.05$.
F1 = NPS fertilizer (19N-38P_2O_5-7S); F2 = 2.5 t ha^{-1} VC; F3= 5 t ha^{-1} VC; F4= 2.5 t ha^{-1} VC + 50% NPS; F5= 5 t ha^{-1} VC + 50% NPS; F6 = unfertilized soil (control)

Table 7. Analysis of marginal rate of return

Treatments	Total variable costs (ETB ha^{-1})	Net benefit (ETB ha^{-1})	MRR (%)
F1	12,222.22	-6,001	
F2	26,666.67	70,101	
F3	52,222.22	68,867	D
F4	60,327.22	122,840	156
F5	68,432.22	115,729	D
F6	85,882.78	93,094	D

Means followed by the same letter in each column are not significantly different at $p < 0.05$. F1 = NPS fertilizer (19N-38P_2O_5-7S); F2 = 2.5 t ha^{-1} VC; F3= 5 t ha^{-1} VC; F4= 2.5 t ha^{-1} VC + 50% NPS; F5= 5 t ha^{-1} VC + 50% NPS; F6 = unfertilized soil (control). MRR = marginal rate of return; D = dominated treatments. Market price of lettuce = 10.00 ETB·kg^{-1}; cost of NPS =15.5 ETB·kg^{-1}; labor cost for fertilizer application and other management operations, including till harvest 4 persons ha^{-1}, each paid 75 ETB·day^{-1}; ETB = Ethiopian Birr, 1 USD = 56.91 Ethiopian Birr.

DISCUSSIONS

The significantly improved lettuce plant growth results due to the combined application of VC and NPS fertilizer, better than VC or NPS alone, are consistent with the earlier reports (Oyege and Balaji Bhaskar, 2023; Santiago *et al*., 2024). According to the work of Oyege and Balaji Bhaskar (2023) and Santiago *et al*. (2024), the mechanism of action for the improved performance of the plants was attributed to soil aggregation, soil structure, water retention, nutrient availability, and microbial diversity due to VC. As stated by Santiago *et al.* (2024), the integrated nutrient management encourages a healthy soil microbial community that promotes effective nutrient cycling, plant growth, and hence sustainable agricultural productivity. This integrated approach aligns with sustainable agricultural systems, reducing reliance on chemical fertilizers and promoting long-term soil fertility (Kharel *et al*., 2022).

Integrated fertilizer application enhances the overall plant growth better than the exclusive use of either chemical or organic fertilizers (Mohanty *et al*., 2023). As stated by Rehman *et al*. (2023) the improved plant growth from the use of VC with reduced chemical fertilizers can be attributed to reduced nutrient loss through leaching and a balanced soil nutrient supply. The increased tolerance to biotic and abiotic stress (Yatoo *et al*., 2021) and enhanced diversity and activity of beneficial biological communities in the soil rhizosphere, including nitrogen-fixing bacteria and arbuscular mycorrhizal fungi, are also reported to be responsible mechanisms. The superior leaf fresh weight, shoot dry weight, and total dry weight observed in F1 compared to other treatments could be linked to the immediate nitrogen effect from NPS, which significantly improved the vegetative growth (Mota *et al*., 2021). In contrast, Theourn *et al.* (2021) stated that 100% vermicompost (10 t ha^{-1}) increased lettuce leaf area, leaf count, and fresh weight per plant, showing statistically non-significant differences when combined with either 25% N + 75% vermicompost or 75% N + 25% vermicompost.

Additionally, Papathanasiou *et al.* (2012) reported that applying 10 to 20% vermicompost enhanced lettuce leaf count, leaf dry weight, root fresh weight, root dry weight, and yield to levels equal to or greater than those achieved with inorganic fertilizers. In summary, the combined application (i.e., F4) yields better lettuce growth traits and overall yields compared to the sole use of NPS. These findings indicate that the use of VC can partially replace NPS fertilizer, reduce agricultural production costs, enhance soil fertility, promote health, and mitigate the environmental impact of mineral fertilizers, particularly eutrophication (Ajibade *et al*., 2022). While vermicomposting water hyacinth biomass presents a practical and sustainable option for improving soil health in mixed farming systems, the sustainability of this practice lies on the biomass's availability. Communities better focus on how to eradicate this weed by diversifying alternative agricultural, municipal, weed biomass sources of organic wastes and adopting sustainable agricultural practices. By fostering resilience in their nutrient management strategies, these communities can continue to thrive even in the absence of water hyacinth.

The enhanced chlorophyll, vitamin C, and nitrate contents in fresh lettuce leaves observed in this study align with findings of Chatterjee *et al*. (2012), who reported that application of 75% of the recommended inorganic NPK (150:80:75 kg ha^{-1}) fertilizer along with 5 t ha^{-1} of vermicompost resulted in the highest vitamin C levels (44.62 mg 100 g^{-1}) and lowest nitrate content (217.17 mg kg^{-1}), compared to using 100% NPK fertilizer. Similarly, our results corroborate those of Zandvakili *et al.* (2019), who found maximum chlorophyll (Apogee), photosynthesis, and vitamin C levels at 49.4, 0.32 mg 100 g^{-1}, and 26 µmol m^{-2} s^{-1}, respectively, with values 13.5%, 150%, and 52% higher than the control treatments (NPK, 100:50:50 kg ha^{-1}). The superior chlorophyll levels in F4 and F5 can be attributed to higher levels of plant growth hormones, enhanced availability of potassium and nitrogen, beneficial microorganisms, and plant growth stimulants such as humic substances and hormones that promote photosynthesis following the integrated use of VC (Balkrishna *et al*., 2024b).

The strong correlation between leaf nitrate accumulation and the amount of fertilizer applied aligns with previous studies (Chatterjee *et al*., 2012), which demonstrated that lettuce amended with organic fertilizers had lower nitrate concentrations compared to conventionally grown varieties. Chatterjee *et al.* (2012) noted that leaf nitrate content increased in proportion to the level of mineral fertilizer used. Specifically, they reported that 100% NPK fertilizers resulted in the highest head nitrate content (282 mg kg^{-1}), while combining 75% NPK with 5 t ha^{-1} of vermicompost reduced head nitrate content by 28–30%.

The maximum nitrate content (175 to 361 mg kg^{-1}) is significantly below the acceptable levels (3000 mg kg^{-1}) set for lettuce grown in open fields by the European

Commission (Commission Regulation Nr 1258/2011) (European Commission, 2011). The reduction in nitrate levels associated with vermicompost can be attributed to its ability to alleviate stress (Rehman *et al*., 2023), lower nitrate load (DahPahlavan *et al*., 2023), enhance plant vigor, and promote improved chlorophyll formation, all of which contribute to increased photosynthesis.

Excessive nitrate levels in leafy vegetables can lead to serious health issues, particularly methemoglobinemia, which affects oxygen delivery in the blood, posing risks like headaches, dizziness, and even severe complications in infants (Kappel *et al*., 2021; Htwe *et al*., 2023). Htwe *et al.* (2023) indicated that consuming lettuce with lower nitrate levels improves blood pressure regulation, while higher vitamin C content boosts immunity, collagen synthesis, and antioxidant levels, reducing oxidative stress (Murray *et al*., 2023). Optimal organic fertilizer application can lower nitrate levels and enhance vitamin C in fresh vegetables, contributing to overall health benefits.

Increasing vitamin C in lettuce is particularly crucial for addressing dietary deficiencies in urban areas where fresh produce is scarce (Murray *et al*., 2023). The interaction between nitrate and vitamin C content is vital for optimizing lettuce's nutritional quality, offering significant public health benefits, such as improved nutrition, reduced disease burden, and enhanced food security (Yang *et al*., 2022). By focusing on agricultural practices that elevate the nutritional quality of vegetables, communities can foster better health outcomes and promote sustainable development (Bošković-Rakočević *et al*., 2023). Thus, while integrating vermicompost and fertilizers can enhance growth, careful management is essential to balance nutrient content for optimal health benefits (Htwe *et al*., 2023; Murray *et al*., 2023).

The results of this field study revealed the highest suppression of aphid pests (88.5–92.0%) and associated leaf damage (80.4–91.4%) in F4, compared to F6, in line with Yatoo *et al*. (2021), which showed that substituting NPK fertilizers with liquid vermicompost led to increased aphid mortality rates. Rehman *et al*. (2023) and Balkrishna *et al*. (2024b) attributed the pest-suppressing mechanisms of vermicompost and its derivatives to 1) enhancement of predatory insect populations, 2) increased host-plant resistance, 3) elevated levels of phenolic and anthocyanin compounds, as well as chitinase enzymes in plant tissues, and improved nutrient availability. These properties make plants less attractive to pests, thereby reducing pest populations and activity. Vermicompost deters pests, alters the feeding behavior, and reduces reproduction rates, resulting in decreased insect pest and pathogen populations (Yatoo *et al*., 2021). Yatoo *et al*. (2021) noted that incorporating vermicompost promotes the release of substances that inhibit pest growth and activity while enhancing plant growth. Thus, the combined application of vermicompost can effectively replace up to 50% of NPS and other inorganic fertilizers, improving lettuce growth and quality while suppressing aphid populations more effectively than solely using mineral fertilizers. Reducing reliance on chemical pesticides is critical for maintaining ecosystem balance and resilience against pest outbreaks through integrated sustainable pest management strategies (Zhou *et al*., 2024). Sustainable pest management involves using organic inputs that improve soil health and support crop growth (Mir *et al*., 2022). Educating farmers about pest biology, ecology, and management fosters informed decision-making and agricultural sustainability (Zhou *et al*., 2024). Vermicompost has been shown to induce systemic resistance in plants to both abiotic and biotic stresses, further reducing pest infestations and damage. The mechanisms behind this defense involve complex interactions between nutrients and beneficial microorganisms, promoting increased nutrient availability and microbial activity (Yatoo *et al*., 2021). Additionally, the production of secondary metabolites and the activation of defense pathways contribute to enhanced systemic resistance, underscoring vermicompost's potential as a sustainable input for pest management in agriculture (Yatoo *et al*., 2021; Rehman *et al*., 2023).

The significant effect of the integrated application of VC and NPS treatments observed in F4 and F5 on pH, EC, TOC, TN, TAP, TK, and C/N ratio was more pronounced than individual treatments (F1, F2, and F3) (Table 5) and was also supported by Rehman *et al.* (2023). According to Rehman *et al.* (2023) and Santiago *et al*. (2024), vermicompost releases substantial amounts of carbon, increases the level of macro- and micronutrients, and increases soil-dwelling organisms, which enhance TOC and lower C/N ratios. Mohite *et al.* (2024) observed that the addition of vermicompost increases soil carbon levels, leading to nitrogen enrichment that boosts soil fertility and agricultural productivity. Santiago *et al.* (2024) attributed the reduction in the soil C/N ratio following VC application to increased mineralized nitrogen, decreased carbon emissions as CO_2, carbon utilization by microorganisms or earthworms for energy, and conversion of some organic carbon in the substrate into soil-dwelling organisms.

The combined application of VC with reduced NPS fertilizer significantly improves nutrient levels compared to those treated solely with inorganic fertilizers (Terefe *et al*., 2024). The near-neutral to alkaline properties of VC further enhance nutrient release in the soil root zone use (Lim *et al*., 2014). Overall, treatments (either separate or combined) resulted in optimal soil conditions for plant growth, with a pH of 6.0–7.0, EC below 4.0 dSm^{-1}, and increased nutrient availability. Therefore, the use of VC as an organic amendment significantly benefits long-term soil structure and nutrient availability (Santiago *et al*., 2024). The ability of vermicompost to enhance soil aggregation, water retention, and microbial diversity supports a more sustainable agricultural system (Oyege and Balaji Bhaskar, 2023), playing a crucial role in promoting plant growth and agricultural productivity (Santiago *et al*., 2024). The ultimate aim of this study was to focus on improving the growth, quality, and yield of vegetables, specifically to optimize lettuce income. The market price and increasing demand for quality and safe-to-consume lettuce are important factors to consider. As a result, F4 treatment showed the highest adjusted marketable yield of 18.3 t ha^{-1} and net benefit of 122,840 Birr ha^{-1}, with a 156% MRR (Tables 6–7). Therefore, F4 demonstrated the best fertilizer to apply for growing lettuce and managing aphid pests, resulting in an optimum income.

CONCLUSION AND RECOMMENDATION

This study revealed that the integrated application of VC with NPS (i.e., F4) significantly enhances lettuce growth (fresh weight 197%), improves vitamin C content (21.0%), reduces nitrate (45.4–48.5%), suppresses aphid pest number (88.6–92.0%), and improves soil characteristics. Further, F4 results also in the highest marketable fresh yield of 20.3 t ha^{-1} with the highest net economic benefit of 122,840.00 Birr ha^{-1} and an MRR of 156%. Despite its invasive and allelopathic traits, vermicomposting water hyacinth produces a high-quality organic fertilizer (i.e., VC) important for soil fertility restoration and quality vegetable production, in addition to reducing the ill effects of direct WH waste biomass disposal on the lakeside that leads to eutrophication. This study suggests that VC could offer a viable alternative to partially replace NPS, lower vegetable production costs, improve soil fertility, and mitigate the environmental impacts of mineral fertilizers. The F4 application was statistically comparable to F1, indicating that the combined application can effectively improve lettuce growth in this experiment. Integrating vermicompost as a biofertilizer into traditional farming practices offers significant multiple benefits, particularly in regions that are heavily affected by such invasive species. Vermicompost plays a vital role in sustainable agriculture for its enhancing soil health and crop resilience to pest and disease, nutrient cycling, and environmental sustainability benefits. Given the above VC benefits and potential limitations, the experiment was held only for a single-time application due to financial and personal limitations. However, for wider VC applicability, key takeaways in the Lake Tana watershed and other similar agroecologies that suffer from WH invasion, and with high chemical fertilizer use and supply constraints, long-term field studies on the environmental impact of VC in different crops would be advisable as an instrument for sustainable agriculture. Future research should aim at the long-term impacts on soil microbiota and crop performance, ensuring that farmers are aware of how to manage and convert invasive species effectively through nutrient dynamics and recovery management techniques.

Data availability

The experimental data used to support this study are provided within the article.

Conflict of interests

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

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Author’s contribution

SGB designed the concept, undertook the experiment, collected and analyzed the data, wrote the text, edited, and submitted the manuscript; GYL, AS, and BAT designed the concept, supervised, reviewed, and edited the manuscript.

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