



Synergistic effects of vermicompost and NPSZnB fertilizers on potato development and production

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Abstract

In Ethiopia, potato productivity is constrained by declining soil health and inconsistent fertilizer use. This study evaluated the effects of vermicompost (VC) and blended NPSZnB fertilizer on potato growth, yield, and economic returns in East Wollega during the 2022 main cropping season. A 4 × 4 factorial experiment was conducted using a randomized complete block design with three replications, testing four VC rates (0, 2.5, 5, and 7.5 t ha⁻¹) and four NPSZnB rates (0, 150, 195, and 240 kg ha⁻¹) with the Gudane variety. Soil analysis indicated that VC generally improved cation exchange capacity, organic carbon, and available phosphorus. Significant interactions between VC and NPSZnB affected maturity, plant height, tuber numbers, unmarketable yield, and tuber size distribution. The combination of 7.5 t ha⁻¹ VC and 240 kg ha⁻¹ NPSZnB produced the highest marketable tuber yield (19.4 t ha⁻¹), approximately 57% higher than the control, while reducing unmarketable tubers. PCA explained 85.7% of the total variation, revealing contributions to PCA and positive associations among major yield traits. Economically, this treatment generated a net benefit of 266,091 ETB ha⁻¹ and a marginal rate of return of 799%. Further studies across multiple locations and seasons are recommended to more validate these findings.

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INTRODUCTION

The cultivated potato (*Solanum tuberosum* L.) is classified within the genus *Solanum*, which falls under the family Solanaceae (Haward, 1969). Global potato production has to increase in order to support smallholder farmers in achieving food security, given the current rate of population growth (Kolech et al., 2019; Devaux et al., 2020). Potatoes have high nutritional value and are the leading crop in energy production per unit area. They provide a cheap human diet source compared to the primary cereal crops; potatoes produce more protein per hectare and dry matter (Górska-Warsewicz et al., 2021). Worldwide, potatoes are grown on 16,799,108 million hectares and yield 383,082,607

million tons annually, whereas in Ethiopia they cover roughly 74,817 hectares, producing 1.2 million tons per year with a productivity of 15.9 tons, which is about 6 tons/ha below the global average productivity (FAOSTAT, 2023). This implies the presence of a large gap. The primary causes of low potato yield in Ethiopia, which also add to its low productivity, are the use of low-yielding seed tubers and poor agronomic techniques (Zarzyńska et al., 2023). The continuous use of inappropriate rates of inorganic fertilizers by farmers is common in Ethiopia, causing problems in fertility management, environmental effects, and a decline in soil nutrients (Chanie et al., 2017).

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Increasing the amount of organic matter in the soil and applying fertilizer at the correct rate improves both the sustainability and the productivity of potatoes. Thus, according to a study, adding vermicompost (VC) to the soil and adding NPS fertilizers to boost its organic matter and nutrient content enhanced agricultural output (Emamu and Wakgari, 2021). Vermicompost (VC) is a peat-like material that possesses high levels of nutrition, microbiological activity, and buffering capacity—all crucial physicochemical properties for soil fertility and plant growth. Research reports also showed that VC has excellent water-holding capacity, aeration, and drainage (Pathma & Sakthive, 2012). In addition, the study found that VC improved bulk density, aeration, porosity, and water retention, and also enhanced chemical properties such as pH, electrical conductivity, and organic matter content, leading to higher crop yields (Lim et al. 2015). According to Satyanarayana et al. (2002), sustainable productivity cannot be achieved by using only organic sources or inorganic fertilizers. Due to its slow-release nutrient content, VC cannot be used alone as a substitute for inorganic fertilizer to sustain crop yield at a higher level unless combined with inorganic fertilizers (Fanuel & Gifole 2013).

Moreover, striking a balance between chemical and organic fertilizer use could enable higher agricultural productivity while maintaining soil fertility and health (Chivenge et al. 2011). The ongoing application of chemical fertilizers leads to an imbalance in nutrients and adversely impacts the biological and physicochemical characteristics of the soil. Potatoes require high potassium, phosphorus, and nitrogen as heavy nutrient feeders (Kumar et al., 2017), and the utilization of both mineral and organic fertilizers in combination, rather than in isolation, significantly enhances responsive and comprehensive yield, including the quantity and quality of potatoes (Banotra et al., 2022; Alemayehu et al., 2020).

According to EthioSIS (2015), the concept of the soil critical point suggested that most of Ethiopia's soil composition was deemed inadequate for a number of components, implying that

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applying fertilizer according to crop requirements and soil deficiencies will lessen nutrient imbalances in the soil, meet crop needs, increase crop yield, and lower poverty. Furthermore, the majority of the soil in western Ethiopia had turned acidic, which significantly reduced crop productivity. For the sustainable management of these soils, it is essential to correct low pH through the use of organic materials and/or liming, since low pH impacts the availability of nutrients, especially phosphorus and other macronutrients. (Takala, 2019).

Therefore, so far, in many potato-growing areas, including the study area (East Wallaga), farmers grow potatoes using inorganic fertilizer alone, without any recommended rate, and the integration effect with organic fertilizer like VC was not well known, as well as sustainable production is becoming one of the global current issues. Thus, this study set out to examine how applying VC together with NPSZnB fertilizer affects potato growth, yield, and economic profitability.

MATERIALS AND METHODS

The trial was conducted in East Wollega, Ethiopia's Leka Dullecha district. A farmer's field in 2022. It is located at 2,174 m.a.s.l, 33°29.59'99" E, 8°49'59.99" N and has three different agro-ecological zones, which are 9% (cool), 47 % mild climate, and 44% warm climate.

Study materials

The Gudane potato, developed and released by the Holeta Agricultural Research Center, served as the test subject. Gudane variety was recommended for production between 1600 and 2800 m.a.s.l. in elevation, and it produced 29.2 and 21 tons/ha total tuber production in research centers and farmer farms, respectively.

Fertilizer application

Vermicompost serves as an organic fertilizer and is applied 14 days before planting, while blended NPSZnB inorganic fertilizer is applied at the time of planting. The blend of NPSZnB fertilizers is

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made up of 17.8% N, 35.7% P₂O₅, 7% S, 2.2% Zn, and 0.1% B.

Experimental design and treatment combination

Using a factorial arrangement, the four NPSZnB levels (0, 150, 195, and 240 kg/ha) were combined with the four vermicompost levels (0, 2.5, 5, 7.5 t/ha) (Table 1) and put in an RCB design replicated three times. There were four rows in every plot, and there was between 30 and 75 cm between each plant. Each potato plot measured 1.5 by 3.75 m (1.5 * 3.75 m) in gross and 1.2 * 3 m (3.6 m²) in net. A single potato plant measured 0.75 m * 0.3 m², or 5.625 m². Each plot had four rows, with 30 cm separating each row and 75 cm between the plants. The net plot size of each potato plant was 1.2 * 3 m

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= 3.6 m², but the gross area was 1.5 m * 3.75 m (1.5 * 3.75 m). A single potato plant had an area of 0.75 m * 0.3 m², or 5.625 m². The corresponding VC and NPSZnB fertilizer rates per experimental plot were 0,1.4,2.8,4.2 kg and,84.375,109.6875 and 135 grams, respectively, and were assigned to experimental plots randomly. Plots were spaced 0.5 meters apart, whereas blocks were separated by 1 meter. Each plot had four rows and four plants/row, i.e., 16 plants per plot. During the main cropping season, medium-sized seed tubers with good sprouts were planted by hand in ridges set 30 cm apart. The outside two rows on each side and the 0.15 m space between each row's ends were used to define a plot's borders.

Table 1

Treatment combinations.

No.	Vermicompost levels (tha ⁻¹)	NPSZnB levels (kg ha ⁻¹)	Treatments combination
1	0	0	Control (0) fertilizer
2	0	150	150 kg ha ⁻¹ NPSZnB
3	0	195	195 kg ha ⁻¹ NPSZnB
4	0	240	240 kg ha ⁻¹ NPSZnB
5	2.5	0	2.5 tha ⁻¹ VC
6	2.5	150	2.5 t ha ⁻¹ VC +150 kg ha ⁻¹ NPSZnB
7	2.5	195	2.5 t ha ⁻¹ VC+ 195 kg ha ⁻¹ NPSZnB
8	2.5	240	2.5 t ha ⁻¹ VC+ 240 kg ha ⁻¹ NPSZnB
9	5	0	5 t ha ⁻¹ VC
10	5	150	5 t ha ⁻¹ VC+150 kg ha ⁻¹ NPSZnB
11	5	195	5 t ha ⁻¹ VC+195 kg ha ⁻¹ NPSZnB
12	5	240	5 t ha ⁻¹ VC+240 kg ha ⁻¹ NPSZnB
13	7.5	0	7.5 t ha ⁻¹ VC.
14	7.5	150	7.5 t ha ⁻¹ VC+150 kg ha ⁻¹ NPSZnB
15	7.5	195	7.5 t ha ⁻¹ VC+195 kg ha ⁻¹ NPSZnB
16	7.5	240	7.5 t ha ⁻¹ VC+240 kg ha ⁻¹ NPSZnB

NB: VC:Vermicompost, NPSZnB=NPS: Nitrogen-Phosphorus-Sulphur, Zn:Zinc, & B: Boron, and T:treatment

Soil test of the experimental site

Before sowing, soil samples were taken randomly across the site in a zigzag pattern at a depth of 0–20 cm, which were then combined into a single composite surface soil sample for the experimental field. Following a time of natural drying, and the blending of the prefabricated soil samples were blended into one sample. The samples were ground

in a mortar and then filtered through a 2 mm sieve. The sample underwent physical and chemical soil testing. Utilizing the Bouyoucos hydrometer method, the soil's texture was examined (Bouyoucos, 1962), and based on Van Reeuwijk (1992), the pH in water was found to be 1:2.5. The soil carbon content was measured following the procedure outlined by Walkley and Black (1934).

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Total nitrogen was measured using the Micro-Kjeldahl digestion method with sulfuric acid (Jackson, 1962). Available phosphorus was recorded with a spectrophotometer using Olsen's method (Bray & Kurtz, 1945). CEC was determined by saturating the sample with 1N ammonium acetate (NH₄OAc) and subsequently displacing it with 1N NaOAc.

Methods of vermicomposting

The vermicomposting facility was situated in a shaded, cool spot beneath a corrugated iron home. Three days after the extraction process, harmless dried leaves (for example, *cardio africana*) and grasses were chopped and mixed into the cow dung at a 3:1 ratio. The combination was then allowed to partially decompose for 15 to 20 days, and in 45 to 50 days, it was ready. A layer of dried leaves or grasses, around 15 to 20 centimeters long, was cut up and laid at the base of the bed to serve as bedding. Beds used for measuring partially decomposed material were built with dimensions of 182.88 cm by 60.96 cm × 60.96 cm; each bed held 1.5–2.0 g of raw material (cow dung, chopped dry broad leaves (*Cardio. U africana*), and grasses); the number of beds can be increased depending on requirements and the supply of raw material. Mature red earthworms (1–2000 in number, 3–5 months old, 0.8–10 cm in length, 0.5–0.6 grams in weight) were placed on the top layer of the bed, based on the assumption that ten earthworms break down one kilogram of leaves. Once the worms had been released, water was sprayed using a watering can. Polythene sheets were used to cover the beds, and frequent water misting was used to maintain a 60–70% moisture content. The bed was turned once every thirty days to ensure sufficient decomposition and aeration until the compost matured in 45–50 days.

Data collection

Days to 50% flowering: In each net plot, the number of days from planting was counted when half of the plants had flowered.

Days to 90% maturity: The number of days from planting until 90% of the plants in each net plot showed senescence

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Plant height (cm): At the physiological maturity stage, ten plants randomly selected from the middle rows had their heights measured with a tape measure, from the ground to the tips of their main stems.

Stems per hill: To establish the average number of stems per hill at the flowering stage, the total count of stems emerging from the ground was recorded for ten plants chosen at random from the net plot.

Marketable tuber number (per hill): At harvest, every tuber collected from the five hills within the net plot was counted and subsequently divided by five to establish the number of tubers free from diseases and insect pests, with average weights of 25 g.

Number of unmarketable tubers (per hill): After the plants in the net plot were harvested, a count was taken of tubers weighing less than 25 g that were diseased, damaged by disease, or damaged by insects.

Marketable tuber yield: The average weight of tubers that weighed 25 g or more and were free from diseases and insect pests was measured from the net plot and then converted into tons per hectare.

Unmarketable tuber yield: The average weight of tubers in the size class under 25 g, converted to t/ha from net plots that were affected by insect pests, disease, or both.

Total tuber yield (t/ha): To calculate the total tuber yield per hectare, the weights of marketable and unmarketable tubers were combined.

Tuber size distribution by count: This refers to the appropriate number of tuber size categories. Every tuber from five plants selected at random was sorted into four categories, very little (<25 g), little (25–39 g), medium (40–75 g), and enormous (>75 g). The share of each tuber category in terms of number was stated as percentages.

Methods for analyzing data

The gathered data underwent an analysis of variance (ANOVA), LSD test ($p < 5\%$), and PCA Biplot analysis using the R package (R Software 2022).

Profitability analysis

To determine the financial gain from applying different amounts of VC and NPSZnB fertilizer, a partial budget analysis was conducted using marketable tuber production data (CIMMYT, 1988). All expenses and advantages were assessed in Birr per hectare. The gross benefit per hectare (GFB ha⁻¹) was calculated by applying the adjusted average marketable tuber yield for each treatment, the field price of inputs (costs for blended NPSZnB fertilizer and seed tubers of the Gudane potato variety), along with a 10% reduction in mean marketable tuber yield for each treatment.

RESULTS AND DISCUSSION**Results****Soil properties prior to planting**

The percentages of clay, silt, and sand in the soil sample from the experimental site are 10%, 38%, and 52%, respectively, and the soil texture was loam. The soil's pH was 5.3, while the CEC was 39.38 cmol (+)/kg. Furthermore, the experimental field had an organic carbon content (OC) of 3.24%, and the total nitrogen content was 0.28%, as shown in Table 2.

Table 2

Physicochemical properties of the soil in the research area before planting.

Soil data recorded	result	range
Clay (%)	10	
Silt (%)	38	
Sand (%)	52	
Textural class	loam	
pH	5.3	Strongly Acidic
CEC cmol (+)/kg	39.38	High
Organic carbon (%)	3.24	High
Total nitrogen (%)	0.28	Moderate
Available P (mg/kg)	16.07	low
Organic matter (%)	5.59	High

Vermicompost and NPSZnB fertilizer use on soil properties

Vermicompost (VC) has tended to increase the CEC, phosphorus, organic carbon, and available P, while pH (%), OC (%), OM (%), and TN (%) were not significantly influenced, as expected. On the

other hand, except for OM (%), inorganic fertilizer treatment did not significantly change the values of the other soil chemical properties. The joint use of VC and inorganic fertilizer has led to an increase in the CEC (meq/100 gm soil) and Available P (ppm) properties (Table 3).

Table 3

Some soil chemical properties after planting.

Factors				Parameters			
VC(t/ha)	NPSZnB (kg/ha)	pH(1:2.5h2O)	OC (%)	OM (%)	TN (%)	CEC (cmol (+)/kg)	Available P (ppm)
0	0	5.25	3.13	5.39	0.27	39.5	16.13
0	150	5.21	3.09	5.33	0.27	39.34	17.24
0	195	5.3	2.98	5.14	0.26	40.88	15.02
0	240	5.15	2.99	5.16	0.26	40.94	16.13

Table 3 continues

2.5	0	5.38	3.23	5.56	0.28	41.34	20.58
2.5	150	5.33	3.3	5.69	0.28	41.38	17.24
2.5	195	5.29	3.34	5.76	0.29	42.22	21.69
2.5	240	5.35	3.33	5.74	0.29	41.06	19.47
5	0	5.52	3.42	5.9	0.29	43.34	27.24
5	150	5.48	3.34	5.76	0.29	44.34	25.02
5	195	5.45	3.38	5.83	0.29	45.34	26.13
5	240	5.39	3.42	5.9	0.29	42.22	23.91
7.5	0	5.75	3.58	6.17	0.31	48.52	30.58
7.5	150	5.7	3.62	6.23	0.31	46.56	26.13
7.5	195	5.65	3.53	6.08	0.3	44.04	27.24
7.5	240	5.45	3.56	6.14	0.31	47.58	25.02
Mean		5.42	3.33	5.74	0.29	43.1	22.17

Variance analysis

The interaction between VC and NPSZnB was found to significantly ($p < 0.01$) impact days to maturity, plant height, marketable and unmarketable tuber yield per hectare, marketable tuber count per hill, total tuber count per hill, and the sizes of large, medium, and small tubers per plant; however, the interaction of these treatments did not have a significant effect on flowering date, main stems per plant, marketable tuber yield, total tuber yield, or unmarketable tuber count per hill (Table 4).

Phenology and potato development

Days to 50% flowering: The longest flowering period (63 days) was achieved by applying 7.5

tons/ha of VC, while 240 kg/ha NPSZnB application caused about 60 days. The control treatment yielded the shortest duration for 50% flowering, which was 54 days (Table 5).

Days to 90% maturity: When 7.5 tons of VC and 240 kg of NPSZnB per hectare were applied together, the maximum amount of time needed to reach 90% maturity (114 days) was recorded. This was statistically equivalent to applying 7.5 tons of VC plus 195 kg of NPSZnB and 7.5 tons of VC and 150 kg of NPSZnB separately (Table 6). Conversely, the control group was the shortest, lasting only 90 days.

Table 4

The mean squared values for phenology, growth, yield, and yield components of potato in response to the application of VC and NPSZnB.

Sources of Variation	Df	Date of flowering	Date of maturity	Main stem per plant	Plant height	Marketable tuber yield ($t\ ha^{-1}$)	Unmarketable tuber yield ($t\ ha^{-1}$)	Total tuber yield ($t\ ha^{-1}$)
Rep	2	1.20	13.2	0.11	22.7	193.9	2.58	225.1
VC	3	181.3**	546.7**	7.7**	197.1**	169.9**	3.90**	123.6**
NPSZnB	3	15.98**	86.4**	20.2**	138.45**	167.3**	0.45**	151.4**
VC*NPSZnB	9	0.352 ^{ns}	25.0**	0.82 ^{ns}	14.3*	16.7 ^{ns}	0.10**	17.4 ^{ns}
Error	27	1.44	5.2	21.7	3.7	17.2	0.02	17.1
LSD (5%)		1.05	3.6	0.8	3.6	3.5	0.2	3.4
CV (%)		2.16	2.04	7.5	3.3	28.1	5.7	24.0

Table 4 continues

Sources of Variation	Df	Marketable tuber number per hill	Unmarketable tuber number per hill	Total tuber number per hill,	Large tuber size(>75 g,)	Medium size(,75 -.>25 g),	small tuber size(<25 g)
Rep	-	32.9	2.9	26.0	55.5	112.	1.2
VC	2	3569.8**	129.6**	2347.9**	2334.3**	12276.9**	77.0**
NPSZnB	3	2644.6*	55.38**	1974.3**	2121.1**	10104.5**	7.5ns
VC*NPSZnB	3	104.9**	5.3ns	144.7**	188.8**	451.8**	15.4**
Error	9	11.03	4.7	19.4	31.9	66.7	5.1
LSD (5%)	27	5.5	1.8	6.9	-	-	1.8
CV (%)	-	7.3	24.3	7.8	18.8	11.2	27.8

Means that letters sharing the same character(s) do not show a meaningful difference at the 5% significance level. * indicates significance, and ** indicates high significance, both evaluated at the 5% significance threshold. LSD = Least Significant Difference; CV = Coefficient of Variation (%). Df = Degrees of freedom.

Effect of VC and NPSZnB on potato growth response

Stem count per hill: As VC rates increased from 0 to 7.5 t/ha, the main potato stems increased from 10 to 12, while for NPSZnB rates applied from 0 to 240 kg/ha, the growth was from 10 to 13, demonstrating nearly the same effect (Table 5). In

general, the control group had the least number of main stems per hill, averaging about 10.

Plant height: The tallest plants (71.3 cm) were achieved from the treatment that combined 7.5 t/ha of VC with 240 kg/ha of NPSZnB fertilizer. In contrast, the control treatment exhibited the shortest plant height (47.7 cm) (Table 6).

Table 5

Main effect of the VC and NPSZnB factors on flowering duration in potatoes, stems per plant, marketable tuber yield, and overall tuber yield per hectare.

Factors VC(t/ha)	Days to flowering	Main stem per plant	Marketable tuber yield (t ha ⁻¹)	Total tuber yield (t ha ⁻¹)
0	54.17 ^d	10.23b	10.9c	14.1c
2.5	56.58 ^c	11.61a	12.8bc	15.3bc
5	59.33 ^b	11.73a	16.3ab	18.3ab
7.5	63.33 ^a	12.16a	19.4a	21.3a
LSD (5%)	1.1	0.7	3.4	3.4
NPSZnB (kg/ha)				
0	57.08 ^c	9.93 ^d	10.4c	10.4c
150	57.92 ^c	10.67 ^c	13.5bc	13.4bc
195	58.83 ^a	12.09 ^b	16.1ab	16.1ab
240	59.58 ^a	13.04 ^a	19.2a	19.2a
LSD (5%)	1.05	0.7	3.5	3.4
CV (%)	2.1	7.3	28.05	24.0

At the 5% significance level, means sharing the same letter(s) exhibit no significant differences.

Mean performance of potato yield components

Number of marketable tubers/hills: The peak number of tubers per hill (approximately 90) was

observed with the simultaneous application of 7.5 t/ha VC and 240 kg/ha NPSZnB, while the control treatments yielded the least (about 14) (Table 6).

Table 6

Interaction between vermicompost and NPSZnB fertilizer levels on days until maturity, height of plants, yield of tubers per plant, quantity of tubers per hill, and distributions of tuber sizes.

Treatments (Kg /ha)		Days to maturity	Plant height	Tuber numbers/hill			Unmarketable tuber yield (t ha ⁻¹)	Tuber size categories(g)		
VC	NPSZnB			MTN	UNTN	TTN		LG	MD	SM
0	0	90.3	47.7	13.67	18.00	31.67	3.8a	13.7	18.0	4.2
	150	92.7	55.8	21.00	11.00	32.00	3.3b	11.0	32.0	11.0
	195	101.3	56.7	28.67	9.67	38.33	2.9c	16.0	44.7	9.7
	240	104.7	57.3	35.00	10.00	45.00	2.8cd	23.0	58.0	10.0
2.5	0	101.7	55.0	21.33	13.67	35.00	2.7de	9.3	30.7	13.7
	150	103.7	58.6	32.67	11.00	43.67	2.6de	19.3	52.0	11.0
	195	106.3	60.0	45.00	9.33	54.33	2.53def	31.7	76.7	9.3
	240	107.0	60.6	51.00	8.00	59.00	2.5ef	41.5	92.5	8.0
5	0	108.0	57.7	30.67	10.33	41.00	2.37fg	18.0	48.7	10.3
	150	109.0	59.1	43.00	8.33	51.33	2.30fgh	27.3	70.3	8.3
	195	109.7	61.3	58.00	7.50	65.50	2.2ghi	37.5	95.5	7.5
	240	111.7	61.6	66.50	7.50	74.00	2.07hij	49.0	115.5	7.5
7.5	0	111.7	58.4	38.33	6.00	44.33	2.0ijk	20.0	58.3	6.0
	150	112.7	61.9	54.67	5.00	59.67	1.9jkl	39.7	94.3	5.0
	195	113.3	64.8	78.00	4.33	82.33	1.8kl	62.3	140.3	4.3
	240	114.0	71.3	90.33	3.00	93.33	1.7kl	73.0	163.3	3.0
LSD (5%)		3.62	3.6	2.73	1.80	3.48	0.24	9.8	7.1	1.8
CV (%)		2	3.6	7.9	24.47	8.38	5.7	19.7	11.9	27.9

MTN = number of marketable tubers per hill, UNTN = number of unmarketable tubers per hill, TTN = total number of tubers per hill.

Unmarketable tuber number/hill: The results showed that adding both VC and NPSZnB fertilizers at higher levels considerably reduced the number of unmarketable tubers per plant. Thus, applying vermicompost at the maximum rate of 7.5 t/ha together with 240 kg/ha of NPSZnB resulted in the lowest number of unmarketable tubers per plant (3), while the highest number of unmarketable tubers per plant (18) was recorded when both factors in the combination were at zero levels. Consequently, applying vermicompost at 7.5 t/ha together with 240 kg/ha of NPSZnB markedly lowered the number of unmarketable tubers per plant, reducing it by 66.3% relative to the average.

Total tuber numbers per plant: The highest number of tubers per plant (93) resulted from the interaction of 7.5 t/ha of VC with 240 kg/ha of NPSZnB fertilizer, while the lowest tuber number (32) came from the unfertilized plot (Table 6).

Marketable tuber yield (t/ha): Applying 7.5 t/ha of VC gave the highest value at 19.4 t/ha, while 240 kg/ha of NPSZnB produced 19.2 t/ha (Table 5), with no interaction effect detected. This indicated that the use of either fertilizer raised tuber yield by about 31% relative to the average.

Unmarketable tuber yield (t/ha): The greatest unmarketable tuber yield (3.8 t/ha) was observed in the control treatments, whereas the lowest

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unmarketable tuber yield (1.8 t/ha) occurred with the application of 7.5 t/ha of VC combined with 240 kg/ha of blended NPSZnB (Table 6), indicating a decline of nearly one ton per hectare in unmarketable tuber yield due to the fertilizers used.

Total tuber yield (t/ha): The maximum total tuber yield, 21.3 t/ha, was achieved with 240 kg/ha of blended NPSZnB fertilizer, whereas the 75 t/ha VC treatment yielded 19.2 t/ha (Table 5). This demonstrated that mixed NPSZnB had a more significant impact on overall tuber yield compared to VC.

Large tuber size/plant/ (g)/ (> 75 g): Applying 7.5 t ha⁻¹ of vermicompost together with 240 kg/ha NPSZnB significantly increased the yield of large tubers (668 g/hill), which reflects a large tuber size per plant (g) (> 75 g). Nevertheless, the largest tuber size (170.8) was achieved under the control treatment (182.7 g/hill) (Table 6).

Medium tuber size per plant (g/hill) (25- 75 g): The highest yield of medium-sized tubers (163.3/hill) was achieved by using 7.5 t/ha in combination with 240 kg/ha of mixed NPSZnB fertilizer, while the control group yielded the least (13.7/hill). The maximum quantity of medium-sized tubers was reached with 7.5 t/ha VC and 240 kg/ha of combined NPSZnB fertilizers; this result significantly differed from that obtained with the 7.5 t/ha VC and 195 kg/ha combined NPSZnB fertilizer treatment (Table 6)

Small tuber size /plant (g/hill)(< 25 g): Raising VC and NPSZnB from 0 to 7.5 t/ha × 240 kg/ha decreased the yield of small-sized tubers by 120.9%. The tiniest tuber size (3 g/hill) resulted from the mix of 7.5 t/ha VC and 240 kg/ha NPSZnB (Table 6).

PCA Biplot factor map

The PCA method was employed to condense and illustrate the essential details in the multivariate dataset. In the PCA factor maps, color gradients were used to enhance the visualization of relationships, clustering patterns, and variability among observations. The first two principal

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components, Dim1 and Dim2, together explained approximately 85.7% of the total variation in the dataset (Figures 1a and 2b), indicating that these dimensions captured most of the information contained in the original variables. In the PCA biplot, variables are represented as vectors (arrows) alongside individual observations. Longer vectors indicate variables with greater contributions to the principal components, while vectors oriented in similar directions suggest strong positive correlations among the corresponding variables. Thus, in this study, the nature of the relationship between variables and their contributions to the PCA can be elucidated. Hence, the variables TTY and MTY, NSPH and TTNO, as well as MTN and L, and DM and DF, exhibited strong positive correlations, as these variables were positioned on the same side of the PCA biplot and oriented in similar directions. In contrast, variables separated by larger obtuse angles demonstrated strong negative correlations. Accordingly, UNTY, UNTM, and S showed negative correlations with most of the other variables located on the right side of the y-axis. Furthermore, the variables TTY, MTY, UNTY, and UNTM were represented by relatively longer vectors, indicating that they contributed more strongly to the PCA and played a major role in explaining the observed variation in the dataset (Figure 1).

Moreover, the individual samples grouped under VC and represented by red-colored points (corresponding to the 7.5 t ha⁻¹ application rate) were predominantly distributed on the right side of the y-axis, followed by the grey-colored points representing the 5 t ha⁻¹ application rate (Figure 1a). The colored groups formed distinct clusters in the PCA plot (Figure 1b), indicating clear differences among the groups in terms of the variables influencing their distribution and positioning on the graph. Furthermore, the contribution of the clusters to the PCA increased progressively from the red-colored cluster, which showed the lowest contribution (6.5), to the light blue-colored cluster, which exhibited the highest contribution (8.5).

Comparative Multivariate Analysis: PCA Biplot a) vs. b)

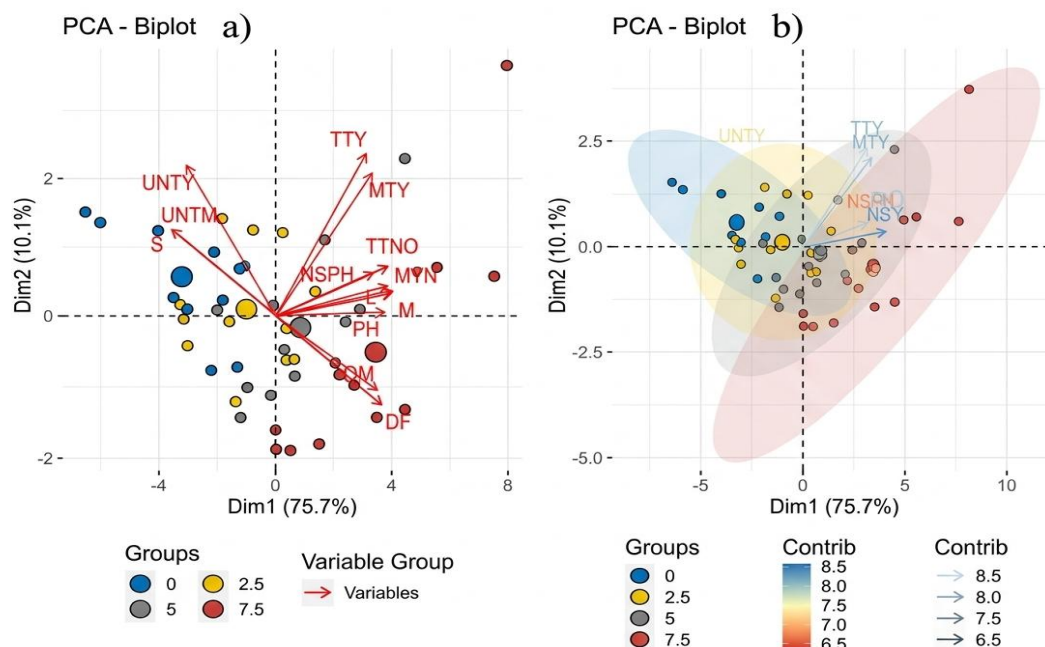


Figure 1. Principal component analysis (PCA) biplots illustrating the effects of VC levels on the distribution of individuals and variables: (a) PCA biplot showing colored individual samples and variable vectors according to VC treatment groups; (b) PCA plot displaying individuals grouped by VC levels (colored points) and variables colored according to their contributions to the PCA.

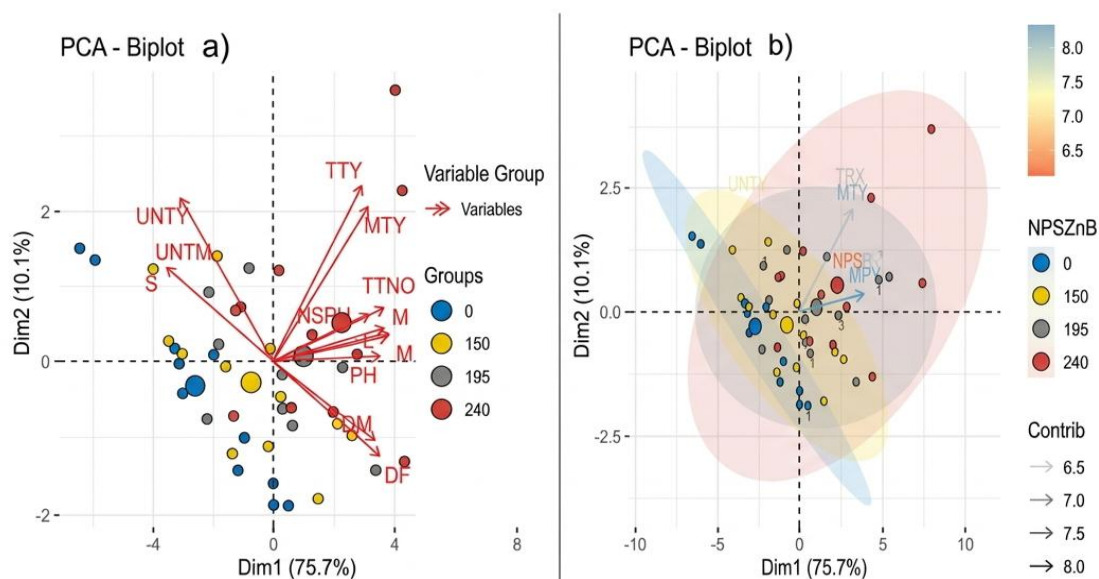


Figure 2. PCA biplots illustrating the effects of NPSZnB fertilizer levels on the distribution of individuals and variables: (a) PCA biplot showing individual samples and variable vectors grouped according to NPSZnB treatment levels; (b) PCA plot displaying individuals colored by NPSZnB treatment levels and variables colored according to their contributions to the principal components.

Individual samples grouped under the NPSZnB treatments and represented by red-colored points (corresponding to the 240 kg ha⁻¹ application rate) were predominantly located on the right side of the y-axis, whereas samples represented by grey-colored points (190 kg ha⁻¹ application rate) were more widely dispersed across the PCA biplot (Figure 2a). This distribution pattern differed slightly from that observed for the VC factor effect. In addition, the clusters formed distinct groupings, and their contributions to the PCA gradually increased from the red-colored cluster, which exhibited the lowest contribution (6.5), to the light

blue-colored cluster, which showed the highest contribution (8.0) (Figure 2b).

Profitability

A partial budget assessment was conducted to assess the financial viability. Analyses of dominance, marginal, and partial budgets were conducted. The total variable cost peaked at 110,402 ETB/ha when 240 kg/ha of NPSZnB was combined with 7.5 t/ha of VC. To determine the net benefit, gross revenues were decreased by all variable expenses. The highest net benefit (266,091 ETB per ha) and a 799% marginal rate of return were attained by using 7.5 t/ha of VC together with 240 kg/ha of NPSZnB fertilizers (Table 7).

Table 7

Analysis of the partial budget and marginal rate of return for potatoes in response to blended NPSZnB and vermicompost fertilizer ratios applied at Leka Dulecha (2022)

Treatments		Economic analysis		TVC	GR	Net benefit	MRR in %	Rank
VC(t/ha)	NPSZnB (kg/ha)	Unadjusted marketable tuber yield (kg/ha)	Adjusted marketable tuber yield (kg/ha)					
0	0	8,002	7,202	40,400	104,026	63,626	157	
0	150	10,488	9439	53,315	136,344	83,029	150	
0	195	12,000	10,800	55,337	156,000	100,663	872	
0	240	12,977.7	11,679.9	57,210	168,710	111,500	578.6	
2.5	0	10,088.8	1008.9	53,259	131,154	77,895	D	
2.5	150	12,444	11,199.5	66,312	161,772	95,460	134.6	
2.5	195	13,466	12,119	68,265	175,058	106,793	580	
2.5	240	14,755	13,279	70,248	191,815	121,567	745	
5	0	11,422	10,279	66,023	148,486	82,463	D	
5	150	14,444	12,999.6	79,281	187,772	108,491	196	
5	195	17,244	15,519.5	80,481	224,172	143,691	2,933	1
5	240	21,066	18,960	83,397	273,858	190,461	1603	2
7.5	0	12,887	11,040	78,819	167,531	88,712	D	
7.5	150	15,866.7	14,280	92,131	206,267	114,136	190.9	
7.5	195	21,555.5	19,399.9	100,132	280,221.5	184,015.5	873	
7.5	240	27,955	25,159.5	110,402	363,415	266,091	799	

VC=Vermicompost, NPSZnB=Nitrogen, Phosphorus, Sulphur, Zinc, Boron. TVC=Total variable costs, GR=Growth return, MTY=marketable tuber yield, vermicompost price/100 kg=500 ETB, NPSZnB/100kg=1900 ETB, Urea/100 kg=2000 ETB, farm gate price for potatoes in 2022 =13 ETB kg⁻¹, labor cost =150.00 ETB per man per day for fertilizer application at the study area.

Earlier research has demonstrated that potatoes thrive best in loose, well-drained sandy loam or loam soils, which permit unimpeded tuber growth, contain sufficient organic matter, and keep a slightly acidic to neutral soil reaction (pH 5.5–6.5). Thus, the physicochemical properties of the soil used in this experiment suggest that the study area is, on the whole, well suited to potato cultivation. Soil analyses conducted before planting and following harvest revealed no statistically significant changes in most soil chemical properties after the application of VC and NPSZnB fertilizers. Nonetheless, applying VC tended to enhance some soil fertility parameters, such as cation exchange capacity (CEC), organic carbon content, and available phosphorus (Table 3), even though the extent of these improvements was fairly modest. The limited response may be attributed to the balancing effects between VC and NPSZnB applications, possible nutrient interactions, or nutrient imbalances resulting from excess or overlapping nutrient supply.

These results align in part with Yimer's (2022) review, which found that applying organic manure together with lower doses of inorganic fertilizer markedly increased potato yield and improved soil fertility, while using inorganic fertilizer alone had minimal impact on sustaining soil fertility.

Although the integration of VC was expected to alleviate soil acidity problems, particularly aluminum (Al^{3+}) toxicity, its observed effect was relatively limited in the present study. Soil acidity has become an increasing threat to crop productivity in western Ethiopia, mainly due to factors such as high rainfall intensity, continuous nutrient depletion, and declining soil organic matter content (Takala, 2019). The application of VC may have contributed to slight improvements in soil conditions through the addition of organic matter and buffering effects against acidity; however, the magnitude of its influence remained low. This limited response could be associated with insufficient application rates, short-term experimental duration, or the persistence of

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strongly acidic soil conditions that require longer-term integrated soil management interventions to achieve substantial improvement.

The joint impact of VC and NPSZnB treatments was notable ($p < 0.01$) on days to maturity, plant height, both marketable and unmarketable tuber yield per hectare, marketable tuber count per hill, total tuber count per hill, and tuber size categories (large, medium, and small) (Table 4). In general, increasing VC and NPSZnB levels prolonged the flowering and maturity periods of potato plants (Tables 5 and 6). This delay may be attributed to the higher nutrient supply, which promoted vigorous vegetative growth before tuber development and maturity. Similarly, Alemayehu et al. (2020) reported that increased nitrogen application delayed tuber formation and crop maturity, extended the growing period by about 10 days. The highest tuber yield occurred with the application of 7.5 t ha^{-1} VC and 240 kg ha^{-1} NPSZnB, resulting in approximately 90 tubers per hill, while the control treatment yielded roughly 14 tubers per hill. The same combination of treatments also resulted in the highest yields of large tubers (73 g hill^{-1}) and medium tubers ($163.3 \text{ g hill}^{-1}$) (Table 6), demonstrating the positive effect of integrated nutrient use on potato yield and tuber quality.

In addition, applying 7.5 t ha^{-1} VC together with 240 kg ha^{-1} NPSZnB yielded roughly 19 t ha^{-1} of marketable tubers, which is about a 30% gain compared with the control treatment. Simultaneously, this treatment markedly lowered unmarketable tuber yield to 1.7 t ha^{-1} (Tables 5 and 6). The increase in marketable yield and the reduction of unmarketable tubers indicate the positive effect of integrated nutrient management on both tuber productivity and quality. These outcomes somewhat correspond with the results of Balemi (2012), which indicated that incorporating 7.5 t ha^{-1} of farmyard manure (FYM) along with 75% of the advised inorganic NP fertilizer boosted tuber output, achieving 41.6 t and 33.7 t/ha during the Belg and Meher seasons, respectively, and a marketable tuber yield of 32.23 t ha^{-1} . Likewise, Alam et al. (2007) in Bangladesh documented that applying 10 t ha^{-1} vermicompost along with 100%

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NPKS fertilizer produced the greatest potato growth and tuber yield. Abou El-Goud et al. (2021) noted a similar increase in total tuber yield, which improved from 27.11 t ha⁻¹ in the control to 37.95 t ha⁻¹ with the application of 7.5 t ha⁻¹ vermicompost alongside mineral fertilizers (103 kg P₂O₅ ha⁻¹ and 124 kg N ha⁻¹).

The Factoextra R package is widely used for visualizing multivariate data through PCA biplots based on the first two principal dimensions (Kassambara & Mundt, 2017). By assigning different colors to specific attributes such as qualitative groups, quality of representation, and variable contributions, the factor maps become more informative and easier to interpret. This approach improves the visualization of relationships among individuals and variables, enabling a clearer understanding of their associations with the principal components and with one another on the biplot. Even though the distribution patterns of individual samples and variables under the influence of VC and NPSZnB treatments looked broadly alike in Figure 1a and Figure 2a, the clustering patterns displayed in Figure 1b and Figure 2b were markedly different. This indicates that the two treatment factors affected the grouping and variability of the observations in distinct ways, suggesting differences in how much each contributed to the multivariate structure of the dataset.

CONCLUSIONS

Using 7.5 t ha⁻¹ VC along with 240 kg ha⁻¹ NPSZnB resulted in the highest marketable tuber yield (approximately 19 t ha⁻¹), while the untreated control yielded the least at about 10 t ha⁻¹. Significant interaction effects between VC and NPSZnB were observed for days to maturity, plant height, the number of marketable and unmarketable tubers per hill, total tuber number per hill, unmarketable tuber yield, and tuber size categories, indicating differing responses. The PCA biplot analysis explained 85.7% of the overall variation in the dataset, illustrating the significant explanatory capacity of the first two principal components. The

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variables total tuber yield (TTY), marketable tuber yield (MTY), unmarketable tuber yield (UNTY), and unmarketable tuber number (UNTM) exhibited extended vectors, signifying greater contributions to the overall variability. Moreover, the variables TTY and MTY, NSPH and TTNO, MTN and L, as well as DM and DF, exhibited strong positive correlations among the corresponding variables, as their vectors oriented in similar directions and the variables were positioned on the same side of the PCA biplot.

Recommendation

The results showed that using 7.5 t ha⁻¹ VC alongside 240 kg ha⁻¹ NPSZnB resulted in the highest marketable yield (19.2 t/ha) and was economically viable, generating a net profit of 266,091 ETB ha⁻¹ with a marginal rate of return (MRR) of 799%. Moreover, the weak response and absence of interaction effects observed in certain economic traits of potato in this study may call for further research involving additional sites and treatments in order to obtain more definitive results.

CRedit Author Statement

Wakjira Ejersso: Conceptualization, Investigation, Writing - Original Draft; **Zerihun Jalata:** Investigation, Formal analysis, Supervision. Writing - Review & Editing. **Kinde Lamessa:** Methodology, Validation. Visualization, Project administration

Declaration of Competing Interest

The authors declare that there are no institutional, financial, or personal conflicts of interest related to this study.

Ethical Approval

Not applicable

Data Availability Statement

All the information utilized in the preparation of this manuscript can be accessed freely in a Mendeley data repository at the link <https://data.mendeley.com/datasets/42ghfjh6ky/2>.

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