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Long-Term Impact of the Continuous Use of Organic Manures on Crop and Soil Productivity under Maize–Potato–Onion Cropping Systems

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Abstract: The scarcity of fertilizers and their rising costs are significant barriers to crop production, as the current agricultural situation in India has shown. In maize–potato–onion cropping systems, the impact of various organic treatments on crop yields and soil parameters has shown that organic treatments increased maize, potato and onion yields compared to chemical treatment (recommended dose of fertilizers) alone. Treatments with applications of different organic sources, each equivalent to 1/3 of the recommended N, along with intercropping of soybeans in maize, radishes in potatoes and coriander in onions, gave the highest yield of maize crops, and significant positive yield trends were observed in four treatments (T1, T2, T4 and T6). Interestingly, all treatments showed a positive effect on potato and onion yields, clearly summarizing potatoes and onions as being more stable crops than maize. Further, the best soil characteristics, viz., bulk density and soil resistance under organic treatment, were lower than those found in integrated and chemical treatments. In contrast, the soil's water-holding capacity, stable aggregate and infiltration rate followed a reverse trend. The treatment (T3), in which soybeans were grown as an inter-row crop in maize, radishes in potatoes and coriander in onions, showed the highest energy-use efficiency, energy output efficiency and energy productivity.

Keywords: yield trends; bulk density; soil resistance; water stable aggregate; water infiltration rate; organic carbon; quality parameters; energy productivity; energy output efficiency; energy-use efficiency

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1. Introduction

The quality and availability of natural resources such as soil and water determine sustainable agricultural productivity. Agricultural growth can be sustained by promoting the conservation and sustainable use of these scarce natural resources. The substantially increased productivity of modern agriculture frequently comes at the expense of sustainable agricultural growth [1]. This is because modern agriculture can have a negative impact on biodiversity, which is a significant element that affects the health and function of agroecosystems [2]. The predominant agricultural system is rice (*Oryza sativa*) and wheat (*Triticum sativum*). Because of the rice–wheat system's stability, high productivity, and low risk, it has gained widespread adoption. Even though the system has endured for years, yields have stagnated since the 1990s [3]. This stagnation may be brought on by system monotony, the emergence of resilient weeds, an increase in insect/pest infestations and diseases, deterioration of the physical characteristics of the soil, the formation of hard pan beneath the plough layer, the exhausting nature of the cereal–cereal system, etc. To meet the water needs of the crops, rice crops have severely overexploited underground water resources, leading to lowering of the water table (74 cm/year in central Punjab), which is now a serious issue. To make Indian agriculture competitive, improve soil health and productivity, increase farm net incomes, and ensure economic security, diversification has been proposed as a new strategy. Adding crops such as oilseeds, vegetables, and pulses will enhance the farmers' economic situations due to better prices and more significant volumes of their primary and by-products [4].

Crop diversification with crops such as cereals, pulses, vegetables, and oilseeds, offers significant potential for addressing these issues, in addition to accomplishing basic food needs, regulating farm incomes, enduring weather anomalies, controlling price fluctuations, ensuring a balanced food supply, conserving natural resources, lowering the use of chemical fertilizers and pesticides, ensuring environmental safety, and generating employment opportunities [5]. Crop diversification has been acknowledged as a successful technique for accomplishing the goals of food security, nutritional security, income enhancement, poverty reduction, employment generation, rational use of water and land resources, sustainable agricultural development, and environmental conservation [6].

According to several agricultural studies, intercropping can improve biodiversity by boosting plant diversity in space and time [7]. Additionally, intercropping systems show clear advantages over monocultures regarding ecosystem services, including optimal resource utilization and yield advantages [8]. Therefore, having a proper understanding of how intercropping management affects the growth of plants and the soil ecology can help to advance the creation of new sustainable agriculture practices. Cropping systems that incorporate soil health management techniques, such as longer rotations, disease-suppressing crops, less tillage, and/or organic amendments, may change the soil microbiome, lessen the spread of soil-borne potato diseases, and boost yields.

After rice and wheat, maize is the third-most significant food crop in India. It is primarily grown during the kharif season on 9.03 m ha (2018–2019), which covers 80% of the area [9]. In addition, it creates over 100 million person-days of employment at the farm and in the downstream agricultural and industrial sectors, contributing over 9% to the national food supply and more than INR 100 million to the agricultural GDP at current rates [10]. In light of the shifting resource base under the present farming scenario, switching from traditional crops and cropping sequences to maize-based systems is becoming increasingly crucial. Several maize-based cropping systems have emerged due to the development of high-yielding maize varieties and hybrids, as well as efficient resource-use production techniques that are competitive with rice and wheat regarding farm profitability and are effective under a variety of soil, season, and climatic conditions.

To take advantage of economic opportunities and environmental constraints [11] and to ensure balanced farm growth at the regional level [12], a flexible cropping system is beneficial. Hence, the component crops must be carefully selected to ensure adequate resource utilization and maximize productivity [13]. Thus, keeping in view the deteriorating soil health (nutritional disorder, degradation of soil physical—properties, etc.), climate change, the excessive use of water, and the appearance of new biotypes, further coupled with the dynamics in soil physical, chemical, and biological properties, have led to the initiation of this long-term study of the maize–potato–onion system using an integrated nutrient management approach.

2. Materials and Methods

2.1. Experimental Site and Treatments

A long-term organic field experiment on maize–potato–onion cropping systems was set up from *kharif* 2003-2004 to 2017–2018, and it has now gone through fifteen crop cycles. There were eight treatments with different sources of organic manures on typic ustocrept soil of the research farm of the Punjab Agricultural University, Ludhiana, situated at 30°56′ N latitude and 75°52′ E longitude, with a mean elevation of 247 m above mean sea level. The experimental site is located in the trans-Gangetic plains region, which has scorching summers, cool winters, and high rainfall during the monsoon season. The experimental site experiences 705 mm of annual rainfall on average, with 80% of that falling during the monsoon season (from June to September). The experimental site's soil had a loamy sand texture with an EC of 0.32 dsm^{-1}, a naturally alkaline pH of 8.15, a low organic carbon content of 0.39 percent, a low available N content of 179.4 kg/ha, a medium available P content of 22.3 kg/ha, and a low available K content of 135.8 kg/ha. Each treatment's plot measured 100 square metres. The maize crop (cv. PMH 1) was sown with an intraplant spacing of 22 cm and a row spacing of 60 cm. In one treatment, soybeans were grown as an inter-row crop with maize, radishes were grown with potatoes, and coriander was grown with onions. The unreplicated high-value-based maize–potato–onion cropping system was chosen in this experiment. It comprises eight treatments, including pure inorganic, integrated, and six organic treatments.

The experiment included eight different treatment combinations, as shown in Table 1. The chemical treatment T7 was used as a control. High-value crops, viz., maize, potatoes, and onions, were chosen for the study. During the second year, a comparable yield of root crops was obtained for organically grown crops compared to chemically grown crops, whereas, in in the fourth year, a comparable yield of cereals was obtained. In high-value crops, different organic manures were applied, which had been obtained from distinct sources. These included applying nitrogen, phosphorus, and potassium fertilizers separately and combining these nutrients with various organic sources to replace from 25 to 50 percent of nitrogen (N) through FYM, 25% through vermicompost, and 25% through the nonedible cake. For maize, 125, 60, and 30 kg/ha of NO_3, P_2O_5, and K_2O were recommended, respectively. When sowing, all the phosphorus and potassium and one-third of of the nitrogen were drilled. At the knee-high stage, the top dress one-third nitrogen, and the final one-third at the pretasselling stage.

Table 1. Different treatment combinations applied in high-value-based experiment.

Treatments	Fertilizer Use (% of Recommended NPK)
T1	50% recommended NPK + 50% N as FYM/crop residues/composts/other organic sources–inorganic sources of micronutrients as per soil test report
T2	Different organic sources, each equivalent to 1/3 of recommended N (FYM + vermicompost + nonedible oil cake)
T3	T2 + intercropping or trap crop (location specific in each season)
T4	T2 + agronomic practices from weed and pest control (no chemicals, pesticides, and herbicides)
T5	50% N as FYM/other organic sources + biofertilizer for N + rock phosphate to substitute the P requirement of crops + phosphate solubilizing bacterial cultures (PSB)
T6	T2 + biofertilizer containing N and P carriers
T7	100% NPK + secondary and micronutrients based on the soil test report
T8	Dummy plot (T2)

Soil samples were taken from 0 to 15 cm from each plot. The soil samples were air-dried, processed, and kept in polythene bags for further analysis. The amounts of organic carbon [14], available N [15], available P [16], and available K [17] in the soil samples were examined. Issac and Kerber's atomic absorption spectrophotometry method (Issac and Kerber 1971) [18] was used to calculate the concentration (ppm) of Fe, Mn, Zn, and Cu. Similarly, the number of nutrients in the soil was calculated using micro-Kjeldhal's distillation and a spectrophotometer at 420 nm, as explained in [17], for N and P uptake, and a flame photometer, as in [19], for K uptake.

2.2. Soil Biological Properties

Infiltration rate: The infiltration rate of the soil is determined using the decline in water level. A double-ring infiltrometer of 29 cm diameter and 34 cm height was used to determine the infiltration rate [20].

Soil strength: A cone penetrometer [21] was used to measure soil strength. A hand-held digital cone penetrometer (CP40II; Rimik electronics, RFM, Queensland, Australia) was used to test penetration resistance at two randomly selected locations within a plot. Readings for soil penetration resistance were down to a depth of 25 cm. The measurement was made at the end of the experiment. The measurement was made from all the treatments at two randomly selected sites at field capacity.

Water content: Using a pressure-plate apparatus, soil water retention was calculated at 0.3, 3, and 15 bars and expressed as percent.

Bulk density: The sampling method [22] was used to measure the in situ bulk density of the soil profile. The metallic cores of known internal volumes (Vt) (internal diameter 7 cm × depth 4.5 cm) were used at various depths of 15 cm, with increments of 5 cm to obtain the samples of undisturbed soil. For 24 h, the undisturbed soil cores were oven-dried at 105 °C to determine the dry weight of the soil (Ws). The bulk density (Db) was calculated as the ratio of Ws and Vt and was expressed in g cm^{-3}.

Aggregate size distribution: The wet-sieving method [23] was used to measure the size distribution of aggregates by using a nest of sieves with diameters of 2.0, 1.0, 0.5, 0.25, and 0.1 mm.

Moreover, dehydrogenase enzyme activity, urease enzyme activity, phosphatase enzyme activity, and $KMnO_4$ oxidizable organic carbon were measured as described in [24–27], respectively. The standard calibration curve was used to determine the concentration of $KMnO_4$ from the sample and blanks. The amount of labile carbon in the sample was determined through oxidation using 0.033 M $KMnO_4$.

The instrument INFRATECTM 1241 GRAIN ANALYZER was also used to determine the quality parameters of maize, potatoes, and onions through a nondestructive method.

Enumeration of microbes in soil samples: The serial dilution spread-plate technique [28] was used to enumerate bacteria, fungi, and actinomycetes on the nutritional agar medium and glucose/yeast-extract medium. The medium was prepared and sterilized for 20 min at 121 °C and 15 psi pressure in an autoclave. Ten grammes of fresh soil (sample collected with auger) were added to a 150 mL Erlenmeyer flask with 90 mL of sterile distilled water, and the mixture was agitated at 120 rpm for 15 min to create a homogeneous solution. Serial dilutions (up to 10-8) were made by pipetting 1 mL of the soil suspension into 9 mL of sterile water blank. Hence, a uniform 0.1 mL aliquot of the diluted soil suspension was applied to solidified Petri plates with the appropriate medium using a sterilized spreader. The Petri plates were incubated in an inverted position at 28 ± 2 °C for 2 to 6 days. The number of colonies on dilution plates was counted after incubation to find the number of cells per gram of soil sample.

$$\text{CFU/g soil} = \text{Number (average of 4 replicates) of colonies} \times \text{dilution factor}$$

2.3. Data Analyses

The trends (slopes) of grain yields over time were determined using linear regression analyses. The observed changes were tested using *p*-values and t-statistics on the slopes to see if they differed significantly from 0 ($p < 0.05$). To lessen the impact of unexpectedly high or low yields in the experiment's first year, the initial yield was calculated as the average yield throughout the first three years. The correlation analysis was carried out among different variables, viz., maize, potato, and onion average yields; soil fertility status after *rabi* 2017–2018 for organic carbon, nitrogen, phosphorus, and potassium; and soil micronutrient status by using the SAS software (9.4 model).

The equivalent energy values of various inputs and outputs, as suggested in [29], are used for computing the total energy input and energy output of a cropping system. The energy input and output were computed as megajoules (MJ). For a particular treatment, the energy input was calculated as the summation of the energy requirements for human, animal, machinery, diesel, seed, herbicide, FYM, chemical fertilizers, and pesticides used in that system. Similarly, the energy output for a particular treatment was calculated as the summation of the energy output from the main product and by-products in that system. For onion and potato production, outputs include yields of the bulbs (onion) and tubers (potato), which are converted to megajoules. The energy-use efficiency, energy output efficiency (MJ/ha/day), and energy productivity (kg REY/MJ) were calculated using the following formulas.

$$Energy\ use\ efficiency = \frac{Energy\ output\ (\mathrm{MJ/ha})}{Energy\ input\ (\mathrm{MJ/ha}))}$$

$$Energy\ output\ efficiency = \frac{Energy\ output\ (\mathrm{MJ/ha})}{Duration\ of\ the\ system\ (\mathrm{days})}$$

$$Energy\ productivity = \frac{Maize\ Equivalent\ Yield\ (\mathrm{Kg/ha})}{Energy\ input\ (\mathrm{MJ/ha})}$$

3. Results and Discussion

3.1. Productivity

In a field experiment initiated in 2003 on loamy sand soils in the Indo-Gangetic plains of India, 50% and 25% of the recommended doses of nitrogen in T1, T2, T5, and T6, were substituted through different organics, viz., farmyard manure, vermicompost, and nonedible oil cake, along with the biofertilizer containing NPK carriers. Moreover, rock phosphate, along with phosphate-solubilizing bacterial cultures (PSBs), were used to substitute the P requirement of the crop. Based on the aggregated data, the inorganic treatment (T7) gave the lowest yield in maize, whereas T5, viz., 50% N as FYM, along with biofertilizer, rock phosphate, and phosphate-solubilizing bacteria, gave the lowest yields in the cases of potatoes and onions. The treatment (T3) with the application of different organic sources, each equivalent to 1/3 of the recommended N, along with intercropping of soybeans with maize, radishes with potatoes, and coriander with onions, gave the highest yield of maize crops (Table 2). The results of the maize crops revealed that the organic manure treatments produced maize grain yields in the range of 40.68 to 56.05 q/ha, which was about 9.4 percent more than the chemical farming treatment (51.19 q/ha). The results conform with the findings of Onduru et al. [30]. Organic fertilizers were found to consistently increase grain output over a long period of time [31]. A high value of maize of 40.68 q/ha was obtained in the treatment receiving only 50% N through FYM, which was 21.50% less than the chemical farming treatment. The yield of the partially organic treatment, which received 50% NPK fertilizers + 50% nitrogen from organic sources (farmyard manure), was 55.72 q/ha, which was 2.79% more than the yield of the organic treatment (T2), which received 1/3 N each from farmyard manure (FYM), vermicompost (VC), and nonedible cake, along with biofertilizers containing N and P carriers (Table 2). It was concluded that adding organic matter increased soil water retention and improved root growth, resulting in high yields of maize [32]. According to Gaur et al. [33], the application of 100% RDF NPK + FYM at 25 t/ha resulted in higher cob (11.21 and 11.07 kg/plot), grain (7.61 and 7.91 kg/plot), and biological yields (14.70 and 15.80 kg/plot), during 2017–2018 and 2018–2019 compared to other treatments, including the control. This may be because FYM's favourable effects helped to increase the availability of different macro- and micronutrients in soil, and the combined impact of FYM and fertilizers on balanced nutrients may be to blame [34]. FYM distributes nitrogen, phosphorous, and potassium through biological enzymatic reactions to the plants in available forms, in the right proportions, and uniformly for a longer time, along with micronutrients, resulting in higher yields.

Table 2. Grain yields of maize, potatoes, and onions, as influenced by various treatments (Average 15 years).

Treatments	Economic Yield (q/ha)			Maize Equivalent Yield (q/ha)
	Maize	Potato	Onion	
T1	55.7 ^{a}	210 ^{b}	213 ^{a}	209
T2	54.2 ^{ab}	204 ^{bc}	209 ^{ab}	205
T3	56.0 ^{a}	387 ^{a}	192 ^{c}	345
T4	52.6 ^{cd}	198 ^{c}	205 ^{ab}	202
T5	40.7 ^{e}	135 ^{e}	140 ^{e}	122
T6	54.6 ^{ab}	205 ^{bc}	210 ^{ab}	205
T7	51.2 ^{d}	175 ^{d}	182 ^{d}	162
T8	52.8 ^{bc}	199 ^{c}	203 ^{b}	200
CD (p = 0.05)	2.6	9.5	9.4	-
SE (±)	0.867	3.167	3.133	-

Note: Means within columns followed by the same letter are not significantly different (CD at p = 0.05).

In potatoes, the integrated treatment receiving 50 percent recommended NPK + 50 percent N as FYM gave the highest potato yield of 209.67 q/ha, which was 19.79 percent more than chemical treatment alone (175.02 q/ha). The potato yield for organic farming treatments varied from 204.96 to 135.37 q/ha. The highest tuber yield (204.96 q/ha) amongst organic farming treatments was obtained in the treatment receiving 1/3rd N through each of FYM, vermicompost, and nonedible cake, along with a biofertilizer containing NPK carriers (Table 2). In contrast, a 198.52 q/ha tuber yield was obtained in the treatment receiving 1/3rd N through each of FYM, vermicompost, and nonedible cake (no chemical pesticide or herbicide through agronomic practices). It was found that, compared to other treatments, 100% RDF NPK+ FYM at 25 t/ha recorded maximum biological yields in potatoes, measured at 64.95 and 75.90 t/ha during 2017–2018 and 2018–2019, respectively [33]. Using rice straw compost with Azotobacter and PSB produces better results than using rice straw alone [35]. Here, Azotobacter enhanced root development, seed germination, and plant growth in general. Onion crops produced similar outcomes. The intercropping of maize with soybeans, potatoes with radishes, and onions with coriander proved to be beneficial options with good yields.

The maize equivalent yield showed that organic sources produced economic yields that were higher than the chemical fertilizer treatment. The equivalent maize yield was the highest (344.90 q/ha/annum) in the treatment which received N from organic sources, along with intercropping of different crops in different seasons. Moreover, the maize equivalent yield in the case of the integrated nutrient management was 208.77 q/ha/annum, which was 27.72 percent more than the chemical fertilizer treatment; so, the data amply purported the 50 percent saving of NPK fertilizers in the maize–potato–onion cropping system.

3.2. Trends of Maize, Potato, and Onion Yields

A discernible change in the annual yields of maize, potatoes, and onions was observed in all the treatments after 15 years of maize–potato–onion cultivation. Figure 1 clearly describes the positive role of organic and balanced fertilizers. Negligible yield trends were observed in three out of eight treatments, mainly attributed to the absence of organic manures and low levels of chemical fertilizers. These insignificant trends were observed in treatments with average yields ranging from 0.245 q/ha in T7 to 0.610 q/ha in T3, indicating that the yields improved with each increment of fertilizer dose. The high initial yields and lower doses of fertilizer have contributed to negligible trend formation. Lower yield trends at lower N levels over the years may indicate the diminishing reservoir of nutrients in the soil [36].

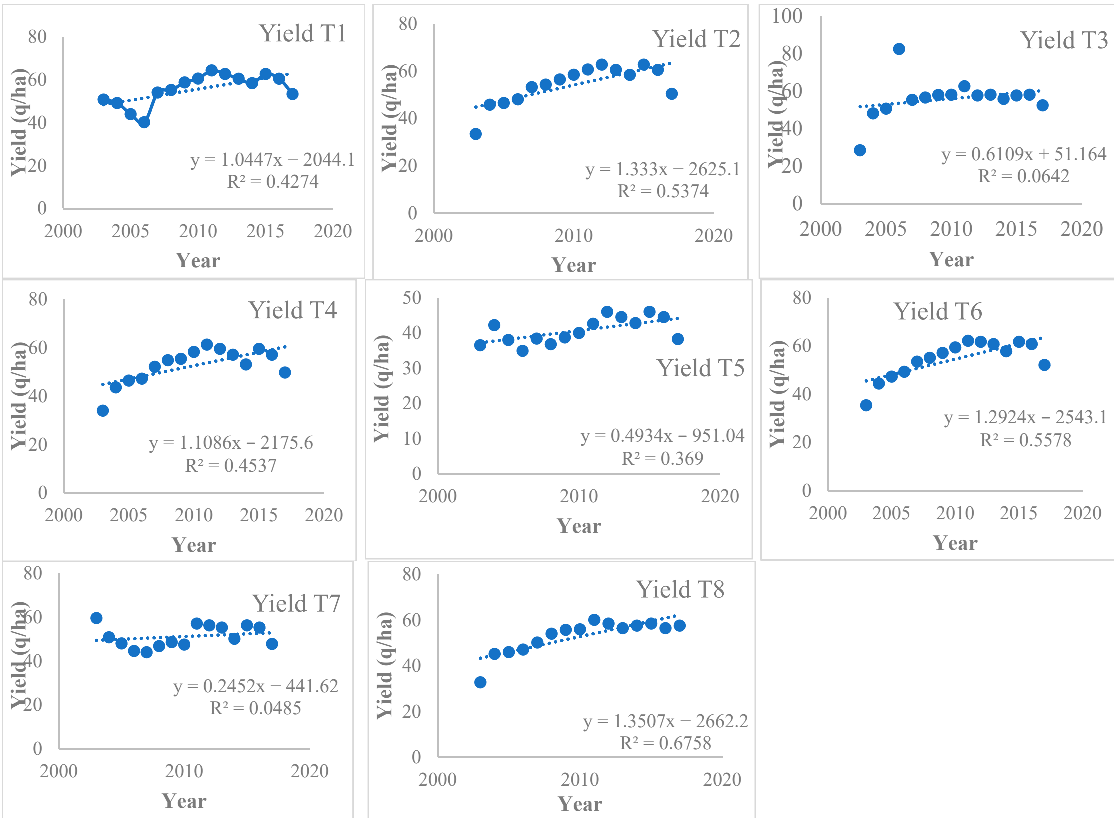

Figure 1. Grain-yield trends of maize in maize–potato–onion LTEs.

On the other hand, significant positive trends were observed in four treatments, T1, T2, T4, and T6. This indicates that the treatments receiving FYM and other organic sources of nutrients, such as vermicompost and nonedible oil cake, showed positive yield trends, mainly because of a lower C:N ratio. Hence, applying FYM and other organic sources of nutrition produced synergistic behaviour and boosted crop yields. In T2 (1.332 q/ha), the maize yield was higher and showed significant positive yield trends, followed by T6 (1.292 q/ha) and T4 (1.108 q/ha). The minimum yields were obtained in T5 (40.68 q/ha) and T7 (51.19 q/ha) (Table 3). Thus, it is clear that the soil medium would have been exhausted more when inorganic nutrients were applied along with an organic source of nutrients, and the crop surpassed the yield recommended level when supplemented with organic manures or biofertilizers. A gradual increase in grain yield was observed with the use of organic fertilizers over a period of time [31].

In potatoes, the rate of annual yield change ranged from 12.329 q/ha per year in T3 to 5.285 q/ha per year in T5 after 15 years of maize–potato–onion cultivation (Table 4, Figure 2). All eight treatments showed positive yield trends; thereby, potato yields appear to be more stable than maize yields. This is because vegetables are highly responsive to organic sources of nutrients and are profitable to farmers. Because potatoes are tuber crops with deep root systems, over a more extended period of time, the nutrients leached during maize cultivation might have been available to potatoes, resulting in greater yields in all treatments. The positive yield trend was observed in all the treatments, but T2 showed significant positive trends, followed by T1, T4, and T6. Tomato crops yielded the most when vermicompost was applied at 15 kg per square metre [37]. The application of vermicompost boosted the microbial activities in chilli plants (*Capsicum annum* L.), as per [38].

Table 3. Yield trends of maize in maize–potato–onion LTEs.

Treatments	Annual Yield Change			Average Grain Yield (q/ha)
	Rate (q/ha per Year)	t-Statistics	*p*-Value	
T1	1.044	3.114	0.008	55.7
T2	1.332	3.886	0.001	54.2
T3	0.610	0.944	0.362	56.0
T4	1.108	3.286	0.005	52.6
T5	0.493	2.757	0.016	40.7
T6	1.292	4.049	0.001	54.6
T7	0.245	0.814	0.430	51.2
T8	1.350	5.205	0.0001	52.83

Table 4. Yield trends of potato in maize–potato–onion LTEs.

Treatments	Annual Yield Change			Average Grain Yield (q/ha)
	Rate (q/ha per Year)	t-Statistics	*p*-Value	
T1	9.019	3.989	0.001	210
T2	9.088	4.317	0.0008	204
T3	12.329	1.480	0.162	387
T4	8.810	4.195	0.001	198
T5	5.285	4.258	0.0009	135
T6	8.146	3.640	0.002	2085
T7	6.293	3.394	0.004	175
T8	9.368	4.443	0.0006	199

Moreover, vermicompost improves crop performance due to increased branches and fruits [34]. The highest average yield was obtained in T3, measured at 387.04 q/ha, followed by T1 (209.67 q/ha), T6 (204.96 q/ha), and T2 (203.89 q/ha). However, in the case of onions, significant positive yield trends were observed in almost all the treatments, except T5 and T7, wherein, yields did not vary over time (Table 5, Figure 3). Similar results were reported by Yadav et al. [39].

The analysis of yield trends of LTEs suggests that a significant positive yield trend is widespread; however, yields of maize are stagnant in a few of the LTEs (T1, T3, T5, and T7), whereas potatoes (T1, T2, T4, and T6,) and onions (T1, T2, T3, T4, and T6) showed significant positive trends in almost all the treatments except the treatments that received only recommended doses of fertilizers and bacterial cultures. The findings support numerous other studies that suggested that, in addition to providing N, P, and K, these organic sources also convert unavailable sources of elemental nitrogen, bound phosphates, micronutrients, and decomposed plant residues into forms that are available to the plants so that they can more easily absorb the nutrients [40]. Mycorrhizae and other beneficial organisms in the soil improved and became more active due to the application of organic sources, which also helps to address the rising incidence of secondary and micronutrient deficiencies and can support healthy soil and high crop productivity [41]. Additionally, low crop yields in maize–potato–onion cropping systems were observed with the long-term use of the recommended dose of NPK in treatments that either received chemical treatment or lower levels of organic sources of nutrition [42,43]. This could be because other essential nutrients are not available in these treatments.

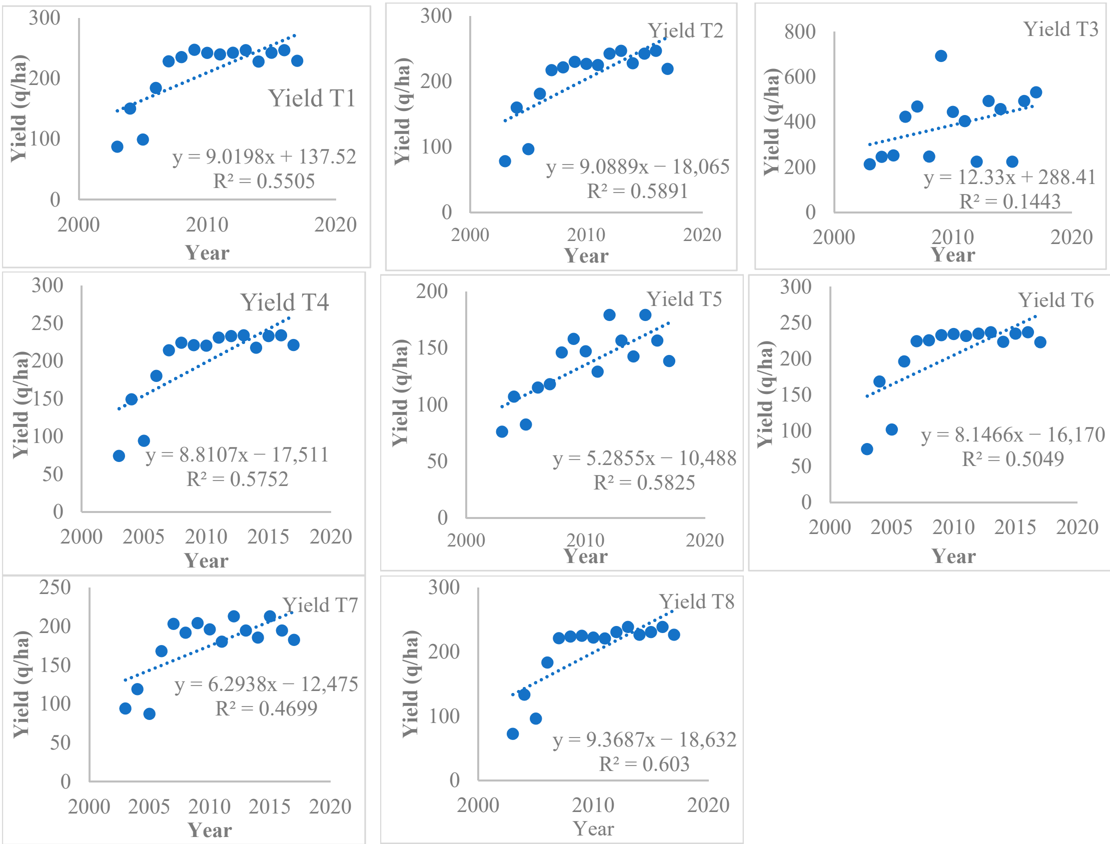

Figure 2. Grain-yield trends of potato in maize–potato–onion LTEs.

Table 5. Yield trends of onions in maize–potato–onion LTEs.

Treatments	Annual Yield Change			Average Grain Yield (q/ha)
	Rate (q/ha per Year)	t-Statistics	*p*-Value	
T1	5.394	3.510	0.003	213
T2	4.718	3.200	0.006	209
T3	4.045	3.830	0.002	192
T4	4.378	2.803	0.014	205
T5	1.438	1.515	0.153	140
T6	4.161	2.977	0.010	210
T7	3.633	4.125	0.001	182
T8	4.300	3.124	0.008	203

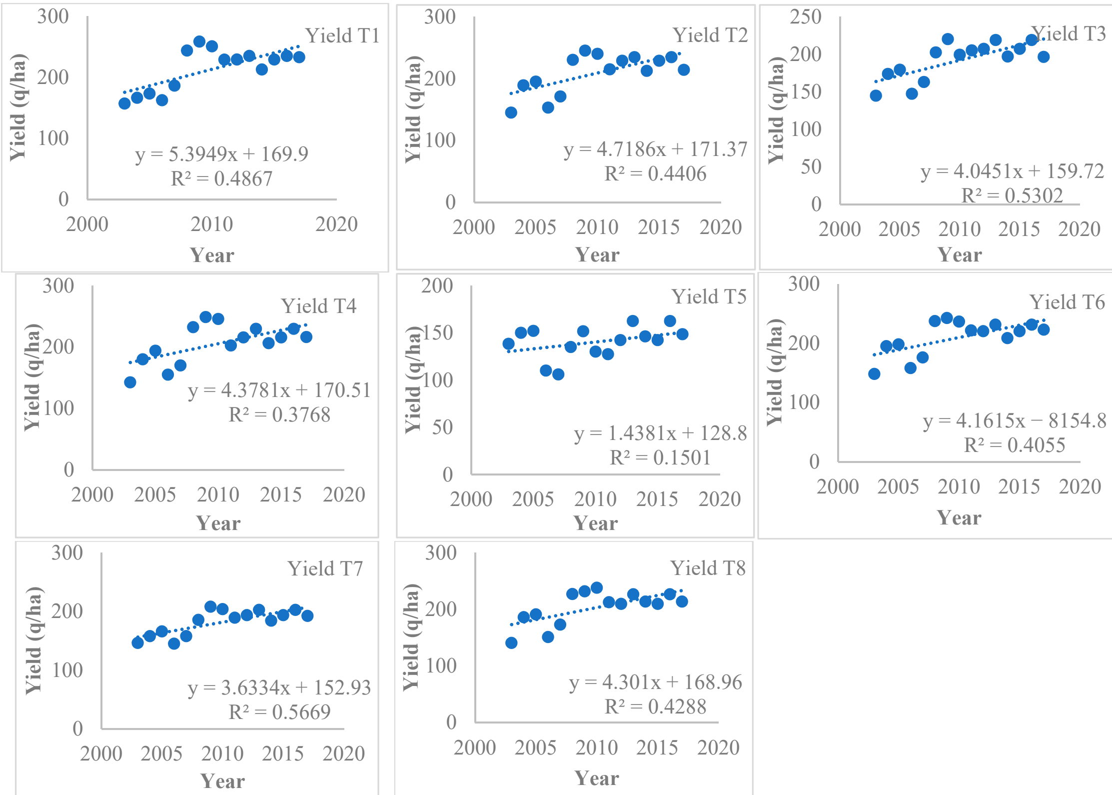

Figure 3. Grain-yield trends of onions in maize–potato–onion LTEs. Note: Horizontal line represents *X*-axis (Time), and vertical lines represent *Y*-axis (Yield).

The data also indicate that in the maize–potato–onion system, potato and onion (vegetables) yields showed more favourable trends than maize yields (Figure 4). The maize grain production showed positive trends, but some fluctuations may have been caused by seasonal changes in temperature and humidity [44]. Additionally, the crop's productivity in an organically managed field was lower in the first year than in the following years because soil fertility levels rise with time when organic materials are introduced to the organic management system [45]. Potato and onion yields significantly improved compared to maize crops, indicating that vegetables are more responsive to organic sources of nutrition than cereals (Figure 4). According to Patil er al. [46], applying vermicompost at 4 t ha^{-1} and FYM at 25 t ha^{-1} considerably increased the production of potato (*Solanum tuberosum* L.) tubers.

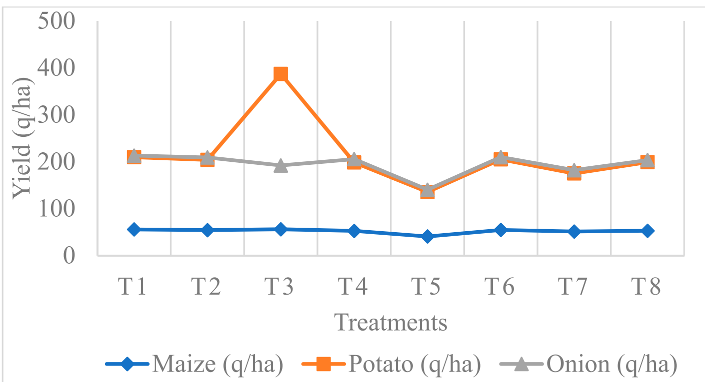

Figure 4. Grain yield of maize, potatoes, and onions (Average 15 years).

3.3. Nutrient Uptake in the Maize–Potato–Onion Cropping System

The maximum N uptake (93.60 kg/ha) of maize grain was recorded in T6, followed by organic farming treatments (T2) (85.30 kg/ha) and T4 (84.89 kg/ha), wherein N was applied through organic sources, with 1/3 of the N coming from each of FYM, vermicompost, and nonedible cake, followed by T7 (80.92 kg/ha). In all the pure organic farming treatments, the value of the N uptake varied between 71.59 and 93.60 kg/ha. A similar response regarding biological yield and N, P, K, and Zn uptake to organic sources was found by Meena et al. [47]. The value of the N uptake in maize stalks in organic manure treatments varied from 71.59 to 85.30 kg/ha compared to the 80.92 kg N/ha in chemical fertilizer treatment alone (Table 6). The study by Prasad et al. [48] discovered that the maize crops absorbed more NPK when organic and inorganic fertilizers were combined compared to a treatment in which a complete dose of NPK was delivered as urea, a single superphosphate, and muriate of potash. The N uptake in potato tubers varied from 64.11 to 97.73 kg/ha. The potatoes responded favourably to the organic manure treatment and yield levels were comparatively better than those obtained in maize crops, alleviating the considerable variation in N uptake (Table 7). According to Mourao et al. [49], potatoes of cv. Raja produced just 46.6% of the conventional yield, whereas organically cultivated potatoes of cv. Virgo produced 66%. Compared to the respective nitrogen uptakes of 21.1 percent and 27.8 percent with mineral fertilizer, the nitrogen uptake of the organic crop (tubers and leaves) was 37.0 kg/ha for Raja and 50.5 kg/ha for Virgo.

Table 6. Nutrient uptake (kg/ha) of grains and straws of maize in the maize–potato–onion cropping system.

Treatments	Grain			Straw		
	N	P	K	N	P	K
T1	81.8 ^{a}	16.4 ^{d}	19.7 ^{b}	82.3 ^{ab}	18.1 ^{cd}	145 ^{b}
T2	85.3 ^{bc}	20.2 ^{b}	20.2 ^{ab}	74.7 ^{c}	15.5 ^{d}	129 ^{d}
T3	78.8 ^{d}	22.7 ^{a}	20.5 ^{ab}	82.6 ^{ab}	18.1 ^{cd}	138 ^{bc}
T4	84. 9 ^{bc}	17.9 ^{cd}	21.9 ^{a}	70.5 ^{c}	21.7 ^{bc}	136 ^{cd}
T5	71.6 ^{e}	18.0 ^{c}	19.5 ^{b}	80.1 ^{b}	19.9 ^{c}	123 ^{d}
T6	93.6 ^{a}	16.2 ^{d}	21.9 ^{a}	82.3 ^{ab}	30.6 ^{a}	159 ^{a}
T7	80.9 ^{cd}	17.0 ^{cd}	17.6 ^{c}	76.2 ^{bc}	24.5 ^{b}	142 ^{bc}
T8	88.7 ^{ab}	19.2 ^{bc}	19.6 ^{b}	86.6 ^{a}	16.8 ^{d}	124
CD (p = 0.05)	5.6	1.4	1.8	4.3	3.0	8.4
SE (±)	1.867	0.467	0.60	1.433	1.00	2.80

Note: Letters means within columns followed by the same letter are not significantly different (LSD at p = 0.05).

Table 7. Nutrient uptake (kg/ha) of tubers and straws of potatoes in the maize–potato–onion cropping system.

Treatments	Tuber			Straw		
	N	P	K	N	P	K
T1	87.4 ^{ab}	5.46 ^{a}	87.4 ^{ab}	7.61 ^{a}	2.44 ^{ab}	6.85 ^{ab}
T2	86.1 ^{ab}	5.96 ^{a}	92.7 ^{a}	9.84 ^{a}	2.27 ^{ab}	6.05 ^{b}
T3	87.6 ^{ab}	6.44 ^{a}	96.6 ^{a}	8.44 ^{a}	1.83 ^{b}	7.03 ^{ab}
T4	92.6 ^{a}	7.17 ^{a}	95.2 ^{a}	6.65 ^{a}	2.14 ^{ab}	7.76 ^{a}
T5	64.1 ^{c}	5.13 ^{a}	65.0 ^{c}	4.98 ^{a}	1.66 ^{b}	3.80 ^{c}
T6	97.7 ^{a}	6.02 ^{a}	95.0 ^{a}	8.32 ^{a}	2.34 ^{ab}	6.43 ^{b}
T7	77.9 ^{b}	6.68 ^{a}	80.1 ^{b}	7.42 ^{a}	1.55 ^{b}	5.57 ^{b}
T8	87.6 ^{ab}	4.98 ^{a}	86.6 ^{ab}	8.01 ^{a}	2.35	5.88 ^{b}
CD (p = 0.05)	12.14	NS	12.47	NS	0.63	1.25

Note: NS—non-significant; Letters means within columns followed by the same letter are not significantly different (LSD at p = 0.05).

On the contrary, the N uptake in onions varied between 67.53 and 91.61 kg/ha (Table 8). The onion in the maize–potato–onion cropping sequence gave almost the same yield level as that observed in chemical fertilizer treatment, which reduced the extent of N uptake variations. The N uptake in onion stalks varied from 18.88 to 26.16 kg/ha. It was about 75.98 percent less than the uptake observed in onion bulbs (Table 8).

Table 8. Nutrient uptake (kg/ha) of bulbs and straws of onions in the maize–potato–onion cropping system.

Treatments	Bulb			Straw		
	N	**P**	**K**	**N**	**P**	**K**
T1	84.1 ^{ab}	22.9 ^{a}	75.2 ^{bc}	20.2 ^{a}	5.51 ^{a}	36.3 ^{b}
T2	84.8 ^{ab}	24.6 ^{a}	81.1 ^{b}	20.9 ^{a}	4.70 ^{a}	34.6 ^{bc}
T3	81.7 ^{ab}	27.8 ^{a}	81.1 ^{b}	23.5 ^{a}	4.94 ^{a}	37.5 ^{ab}
T4	91.6 ^{a}	23.5 ^{a}	86.6 ^{b}	24.0 ^{a}	5.63 ^{a}	39.9 ^{ab}
T5	67.5 ^{b}	21.9 ^{a}	64.9 ^{c}	26.2 ^{a}	6.10 ^{a}	41.4 ^{a}
T6	81.3 ^{ab}	36.3 ^{a}	94.5 ^{ab}	23.3 ^{a}	6.17 ^{a}	38.7 ^{ab}
T7	78.5 ^{b}	24.9 ^{a}	75.2 ^{bc}	21.25 ^{a}	6.17 ^{a}	37.9 ^{ab}
T8	84.0 ^{ab}	23.4 ^{a}	76.0 ^{bc}	18.9 ^{a}	4.72 ^{a}	31.6 ^{c}
CD (p = 0.05)	11.72	NS	11.39	NS	NS	4.28

Note: NS—non-significant; Letters means within columns followed by the same letter are not significantly different (LSD at p = 0.05).

The maximum P uptake in maize (22.70 kg/ha) was accrued in the organic farming treatment (T3), receiving N through a combination of FYM, vermicompost, and nonedible cake, followed by T2 (20.16 kg/ha) and the T4 (17.91 kg/ha). In organic manure treatments, the values range between 16.19 and 22.70 kg/ha. The trend of P uptake in maize stalks was almost the same as that of maize grain but with a different magnitude (Table 6). The P uptake in potatoes ranged between 4.98 and 7.17 kg/ha. The low values may be due to less dry matter, and the moisture content varied from 80 to 82 percent. A similar trend of P uptake in potato stalks was observed and ranged from 1.55 to 2.44 kg/ha (Table 7). On the other hand, the P uptake in onion bulbs varied from 22.94 to 36.29 kg/ha, whereas in onion stalks, the values fell from 4.72 to 6.17 kg/ha. In onions, the moisture content was found to be 90 percent, and the dry-matter yield of onions was 8–9 percent more than that of potatoes (Table 8).

The K uptake in maize stalks was approximately five times more than the K uptake in maize grains. However, the K uptake in maize stalks varied from 124.5 to 159.18 kg/ha (Table 6). On the contrary, the K uptake in potatoes was almost at par with N uptake (Table 7). The K uptake in onion bulb varied from 64.90 to 86.65 kg/ha, whereas the corresponding value in onion stalks varied from 31.58 to 41.42 kg/ha. The data indicated that the K uptake of the onion bulbs was much lower than that of potato tubers (Table 8). Similar results were reported by Sullivan et al. [50]. Much-increased N, P, and K uptakes were discovered when organic and inorganic fertilizers were applied together rather than separately [51]. In addition to the additional nutrients provided by FYM and NPK fertilizers, the crops responded to the combined application of both fertilizers is the enhanced availability of N, P, and K in the soil reservoir. This was ascribed to the consistent availability of N, P, and K throughout the growing season. Similarly, Prajapat et al. [52] reported that the maximum total uptakes of N and P by soybeans increased significantly when 25% of the recommended inorganic fertilizer was combined with 50% of the recommended FYM and biofertilizers, as opposed to using just inorganic fertilizer and FYM.

3.4. Quality Parameters

Applying a 50% recommended dose of fertilizers in combination with the application of 50% N through FYM resulted in higher protein, oil, and starch contents in maize grain. Among organic treatments, the one receiving 50% N through farmyard manure

+ biofertilizer + rock phosphate + PSB showed a lower grain protein content than other treatments. However, applying organic manures with inorganic fertilizers supply nutrients in synchrony with crop growth, resulting in higher nitrogen content and more protein. A higher protein content in maize with integrated treatment was reported due to better nitrogen availability [53]. Likewise, the highest starch content in integrated treatment was due to more photosynthate production and translocation in plants and better nutrient availability [54]. In the case of oil content, among organic treatments, T6 showed a higher oil content when compared to other treatments (Table 9).

Table 9. Quality characters of potatoes and onions in the maize–potato–onion cropping system.

Treatments	Protein (%)	Oil (%)	Starch (%)	TSS (%)	Acidity (%)	Ascorbic Acid mg/100 g	Moisture (%)	Total Solids (%)	TSS (%)	Acidity (%)	Ascorbic Acid mg/100 g	Moisture (%)	Total Solids (%)
	Maize			Potato					Onion				
T1	11.2	4.4	68.4	5.2	0.26	3.8	75.6	24.4	11.4	7.8	3.4	13.2	86.8
T2	11.0	4.1	68.2	5.8	0.28	4.2	75.4	24.6	11.6	8.0	3.8	13.0	86.6
T3	10.8	4.0	67.9	5.6	0.30	4.2	75.2	24.8	11.6	7.8	3.8	12.8	86.8
T4	10.9	4.1	67.9	5.4	0.26	4.4	75.0	25.0	11.8	8.0	3.6	13.0	86.6
T5	9.6	3.8	66.3	5.2	0.22	3.8	74.8	25.2	10.8	7.4	3.4	12.8	87.0
T6	11.1	4.3	68.2	5.6	0.28	4.4	75.0	25.0	11.6	7.8	3.8	13.0	86.6
T7	10.7	3.9	67.8	4.8	0.24	3.8	77.0	23.0	11.0	7.2	3.2	11.8	87.2
T8	10.6	4.0	68.3	5.4	0.26	4.2	75.2	24.8	11.8	7.8	3.8	12.8	87.2

According to the quality study of potatoes and onions in Table 9, organic farming treatments produced the highest acidity, ascorbic acid, and total soluble sugars. The intercropping method, which had a modest advantage over the chemical farming method, was close behind. In all organic farming treatments, the total solids were 24.6% to 25.0% compared to chemical farming treatment (23.0%). Similarly, total solids, ascorbic acid, and reducing sugars in onion were higher in all organic farming treatments than in chemical farming treatments (Table 9). Compared to chemical farming (11.4%), all organic farming treatments had total solids contents that ranged from 11.2 to 11.8%. Similarly, the total solids, ascorbic acid, and reducing sugars were higher in all organically cultivated onion treatments compared to a chemically produced onion.

3.5. Soil Physical Properties

Applying 100% NPK showed maximum bulk density (1.57 g cm^{-3}) and soil resistance at all soil depths. In contrast, minimum bulk density was observed under 1/3 N FYM + 1/3 N vermicompost + 1/3 N (castor cake) (1.50) due to more pore space and a decrease in soil compaction (Tables 10 and 11). Bulk density and soil resistance under organic treatment were lower than integrated and chemical treatments. According to Thakur et al. and Selvi et al. [55,56], organic manures reduced bulk density and soil resistance during long-term tests. The reduction was attributed to higher organic carbon levels, more pore space, and improved soil aggregation. Contrarily, chemical treatment reduced soil's ability to hold water compared to integrated and organic farming methods. The maximum water holding capacity was reported under T2 + agronomic practices from weed control (21.12% and 13.26%) at 0.3 and 3 bar, which was nonsignificant to other treatments (Table 10). However, at 15 bar highest value (10.23%) was recorded with 50% recommended NPK + 50% N as FYM. The water-holding capacity of the soil was more in organic plots because organic manure improves soil structure and micropore space, which is helpful for more water retention [57].

Table 10. Soil physical properties under maize–potato–onion cropping system.

Treatments	Bulk Density (g/cm^{-3})	Water Holding Capacity (%)			Water-Stable Aggregate (g/50 g Soil)				
		0.3 Bar	3.0 Bar	15 Bar	2 mm	1–2 mm	1–0.5 mm	0.5–0.25 mm	0.1 mm
T1	1.55 ^{a}	18.5 ^{a}	12.3 ^{a}	10.2 ^{a}	13.5 ^{a}	4.17 ^{a}	8.34 ^{a}	20 ^{a}	3.90 ^{e}
T2	1.50 ^{a}	20.0 ^{a}	11.9 ^{a}	9.91 ^{a}	8.79 ^{b}	3.26 ^{b}	6.80 ^{a}	19.4 ^{a}	6.82 ^{b}
T3	1.50 ^{a}	18.8 ^{a}	11.4 ^{a}	8.99 ^{a}	8.92 ^{b}	3.58 ^{ab}	7.20 ^{a}	19.5 ^{a}	7.55 ^{a}
T4	1.52 ^{a}	21.1 ^{a}	13.3 ^{a}	9.85 ^{a}	8.80 ^{b}	3.14 ^{b}	6.30 ^{a}	18.9 ^{a}	7.68 ^{a}
T5	1.54 ^{a}	16.0 ^{a}	10.7 ^{a}	7.35 ^{a}	9.05 ^{b}	3.63 ^{ab}	7.31 ^{a}	19. 7 ^{a}	5.03 ^{d}
T6	1.52 ^{a}	19.0 ^{a}	11.3 ^{a}	9.42 ^{a}	12.8 ^{a}	3.78 ^{ab}	7.08 ^{a}	19.2 ^{a}	5.63 ^{c}
T7	1.57 ^{a}	15.5 ^{a}	9.72 ^{a}	6.74 ^{a}	8.55 ^{b}	2.88 ^{b}	5.90 ^{a}	17.7 ^{a}	6.91 ^{b}
CD (0.05)	NS	NS	NS	NS	1.90	0.64	NS	NS	0.58

Note: NS—non-significant; Letters means within columns followed by the same letter are not significantly different (LSD at $p = 0.05$).

Table 11. Soil resistance and infiltration rate (cm hr^{-1}) under a high-value-based cropping system.

Treatments	Soil Resistance (k/Pascal)					Time Interval (min)							
	5 cm	10 cm	15 cm	20 cm	25 cm	1	5	10	20	40	80	140	180
T1	291 ^{a}	571 ^{a}	1010 ^{a}	1421 ^{a}	1852 ^{a}	62	19	11.3	5.1	3.3	2.1	1.3	1.0
T2	273 ^{a}	558 ^{a}	1002 ^{a}	1411 ^{a}	1843 ^{a}	68	21	11.8	5.4	3.6	2.2	1.3	1.2
T3	280 ^{a}	554 ^{a}	996 ^{a}	1408 ^{a}	1832 ^{a}	71	23	13.2	5.8	4.4	2.3	1.4	1.3
T4	271 ^{a}	549 ^{a}	988 ^{a}	1408 ^{a}	1829 ^{a}	68	22	12.6	5.4	3.7	2.1	1.3	1.1
T5	284 ^{a}	567 ^{a}	993 ^{a}	1413 ^{a}	1836 ^{a}	65	18	11.4	5.1	3.3	2.1	1.2	1.0
T6	291 ^{a}	568 ^{a}	1007 ^{a}	1415 ^{a}	1845 ^{a}	69	23	12.9	5.7	4.4	2.2	1.4	1.2
T7	295 ^{a}	577 ^{a}	1017 ^{a}	1430 ^{a}	1856 ^{a}	60	17	10.4	5.0	3.2	2.0	1.1	1.0
CD (0.05)	NS	NS	NS	NS	NS	-	-	-	-	-	-	-	-

Note: NS—non-significant; Letters means within columns followed by the same letter are not significantly different (LSD at $p = 0.05$).

Application of 50% recommended NPK + 50% N as FYM recorded in highest water stable aggregate (13.53 and 4.17 g/50 g soil) at 2 and 1 mm sieve, which was significantly better than 100% NPK (8.55 and 2.88 g/50 g soil) and organic treatment except for T6 at 2 mm. At 1 mm, it was at par with T2, T3, and T5 treatments (Table 10). Treatment T6 showed the highest water-stable aggregate among organics treatments at 2 and 1 mm sieve. It differed significantly from other organic treatments at 2 mm and par with all organic treatments at 1 mm. Water stable aggregate was nonsignificant at 0.5 and 0.25 mm sieves. However, at 0.1 mm sieve highest aggregate was observed with T2 + agronomic practices from weed control, which was at par with T2 + intercropping (soybean). Similar results were reported by Pareek and Yadav [58]. In addition, the infiltration rate was more in organic treatments. At the all-time interval, the highest infiltration rate was observed under T2 + intercropping (soybean). However, at a time interval (5 and 180 min), similar results were observed with T2 + biofertilizer containing N and P carriers. Integrated treatment showed an approximately similar result with 50% N as FYM + biofertilizer + rock phosphate + PSB (Table 11). A minimum infiltration rate was observed under 100% NPK treatment. Water transmission through the soil profile depends on the antecedent water content, aggregation, and macropore channels [59].

3.6. Soil Fertility Status of Maize–Potato–Onion Cropping Sequence

On completing the fifteen crop cycles, the organic carbon in the soil increased over the initial soil status (0.39 percent) (Table 12). However, during 2003–2004, the value of OC reduced (0.38 percent) over the initial status where 100 percent recommended fertilizers were added along with micronutrients and where no organic source of nutrition was added. However, it gradually increased over the years and the value remained lower than the organic treatments. The level of OC ranged from 0.48 to 0.68 percent in all the treatments during 2017–2018. Organic carbon status in all the treatments lies in the medium range except in T7 treatments, which is classified in the low range where no organic source of nutrients was added (0.49 percent). The maximum OC build-up occurred in T4, where one-third of the nitrogen was replaced with FYM, one-third with vermicompost, and one-third with nonedible cake, without adding herbicides or pesticides. According to Bhatt et al. [60], the application of N + P + K + Zn(F) + FYM resulted in the highest levels of organic carbon (1.20% and 0.80%) in the surface and subsurface soil layers. In contrast, the absence of fertilizer/FYM significantly decreased the organic carbon content (0.72% and 0.58%) in controlling the surface and subsurface soil layers. It was reported that the treatments where 50 percent N was applied using FYM accrued a maximum organic carbon content build-up that ranged from 0.510% to 0.543% [61].

Table 12. Soil fertility status after onion crops in 0–15 cm depth under LTEs.

Treatments	OC (%)			N (kg/ha)			P (kg/ha)			K (kg/ha)		
	2003–2004	2013–2014	2017–2018	2003–2004	2013–2014	2017–2018	2003–2004	2013–2014	2017–2018	2003–2004	2013–2014	2017–2018
T1	0.40	0.52	0.58	180.1	213	216	23.6	24.8	22.6	137	146	138
T2	0.48	0.56	0.68	186.2	229	223	26.7	26.4	24.2	151	160	156
T3	0.46	0.52	0.54	188.2	233	238	26.4	28.2	26.6	147	164	158
T4	0.49	0.54	0.56	188.3	242	266	26.9	31.2	34.8	148	169	162
T5	0.41	0.54	0.64	180.3	230	229	24.8	25.8	26.1	137	170	170
T6	0.48	0.51	0.52	191.3	240	266	28.6	31.6	32.4	150	158	168
T7	0.38	0.46	0.49	172.4	219	213	22.8	28.2	26.5	139	153	147
T8	0.46	0.58	0.48	188.6	246	211	27.7	32.4	22.2	149	165	138
Initial		0.39			179			22.3			136	

Similarly, there were improvements in the N and P status of the soil for almost all the treatments except for the N status of soil in the T7 treatment over its initial value (179.4 kg/ha) (Table 12). However, all the *p* values lie in a higher range than their initial value (22.3 kg/ha). The maximum value of N and P were accrued where biofertilizers were added containing N and P source in combination with T2 treatment. The results clearly revealed that applying organic sources (FYM, vermicompost, nonedible cake and biofertilizers) increased the soil's N and P status in all treatments. However, the K status of the soil falls in the medium category in all the treatments except the initial K status of the soil. The soil fertility status clearly evinced that soil fertility build-up was there, but it was of low magnitude except in P treatments, where an organic source of nutrients was applied. Otherwise, it was discovered that the experimental soil had low levels of OC, N, and K, indicating the need for an integrated nutrient management strategy to maintain soil productivity throughout time. The soil properties, increase in organic carbon, soluble phosphorus, exchangeable potassium, pH, and sustained electrical conductivity (EC) levels are all improved by organic and low-input farming practices after four years [62]. Organic fertilizer sources enhance soil characteristics, organic matter content, and nutrient availability. According to Tetarwal et al. [63], the application of the recommended dose of fertilizers (40–15 kg N-P/ha) + FYM 10 t/ha resulted in a significant accumulation of organic carbon (0.74%), available N (316.0 kg/ha), available P (10.8 kg/ha), and Zn uptake. Likewise, Almaz et al. [64] showed that an integrated application of 50 percent NPK and 50 percent poultry dung boosted maize's nutrient (N, P, and K) uptake over just inorganic fertilizer and poultry manure.

The correlation matrix about important characters, viz., average yield (maize, potato and onion) and soil fertility status after *rabi* 2017–2018 (OC, N, P and K) was determined (Tables S1 and S2). The data thus clearly revealed a strong and positive correlation with crop yields and the amount of N present in the soil but a negative correlation with P and K except in average potato yield and amount of K present in the soil, indicating that with an increase in crop yields of maize, potato and onion, the soil is becoming deficient in P and K and requires the application of phosphorus and potassium fertilizers. The results followed the study of Bhunia et al. [65] and revealed that OC concentration was significantly and positively correlated with N.

So far, the availability of the micronutrients is concerned in high-value-based cropping system of maize–potato–onion, the micro-nutrient contents are decreased (Table S2). However, all the micro-nutrients showed a positive and weak correlation with average yields (maize, potato and onion) except Copper (Cu), which showed a negative correlation with the average yield of onion. In addition, Zinc (Zn) showed a negative correlation with Manganese (Mn), indicating the soils are becoming deficient in Zn over time and require the application of Zn to the soil to keep the threshold level intact.

3.7. Soil Biological Properties

Different fertilizers treatments influenced the microbial population significantly. T2 + biofertilizer containing N and P carriers (T6) resulted in significantly higher bacterial (42.2 × 10^6 CFU g^{-1} soil), fungal (35.9 × 10^3 CFU g^{-1} soil), and actinomycetes count (34.0 × 10^4 CFU g^{-1}) in soil, respectively, as compared to 100% RDF, T4, T5 and integrated treatments. However, it was at par with 1/3 N FYM + 1/3 N vermicompost + 1/3 N castor cake (Table 13). The higher soil microbial population was mainly due to the more available carbon source, which provides energy for soil microbes, and less soil disruption provided a stable habitat for the growth of microbes [66].

Table 13. Effect of high-value-based cropping system on soil biological properties.

Treatments	Microbial Count			Enzymatic Activities			
	Fungi (10^3 CFU/g)	Actinomycetes (10^4 CFU/g)	Bacteria (10^6 CFU/g)	Phosphate (Micro g PNP/g Soil/min)	Dehydrogenase (Micro g TPF/g Soil/min)	Urease (Micro g Urea/g Soil/h)	Labiel Carbon (mg/kg)
T1	28.2 ^{c}	29.7 ^{c}	35.3 ^{c}	48.2 ^{ab}	26.1 ^{a}	230 ^{b}	957 ^{a}
T2	34.3 ^{ab}	33.3 ^{a}	40.2 ^{ab}	49.7 ^{ab}	24.4 ^{a}	242 ^{a}	965 ^{a}
T3	32.8 ^{b}	31.8 ^{b}	38.6 ^{b}	51.9 ^{a}	26.3 ^{a}	225 ^{bc}	986 ^{a}
T4	28.8 ^{c}	31.6 ^{b}	37.4 ^{bc}	49.5 ^{ab}	24.6 ^{a}	225 ^{bc}	984 ^{a}
T5	32.2 ^{b}	32.2 ^{ab}	36.3 ^{bc}	47.5 ^{b}	25.1 ^{a}	224 ^{c}	959 ^{a}
T6	35.9 ^{a}	34.0 ^{a}	42.2 ^{a}	44.8 ^{b}	18.6 ^{b}	246 ^{a}	963 ^{a}
T7	25.2 ^{d}	26.3 ^{d}	30.0 ^{d}	37.1 ^{c}	21.1 ^{b}	228 ^{bc}	928 ^{a}
CD (p = 0.05)	2.4	1.8	2.8	3.8	2.9	5.5	NS

Note: NS—non-significant; Letters means within columns followed by the same letter are not significantly different (LSD at p = 0.05).

Furthermore, phosphatase is an enzyme which is helpful for the conversion of organic phosphorus into inorganic phosphorus. Dehydrogenase is a credible indicator of microbial activity in the soil. The urea fertilizer applied to the soil is hydrolysed by urease. In T2 + intercropping (soybean), phosphatase and dehydrogenase activity were much higher than in 100% RDF. It was comparable to 50% recommended NPK + 50% N as FYM, 1/3 N FYM + 1/3 N vermicompost + 1/3 N castor cake, and T2 + agronomic approaches from weed control (Table 13). Compared to integrated, 100 percent NPK, and other organic treatments, T2 + biofertilizer comprising N and P carriers had significantly better urease activity (246.5 g urea/g soil/h), except for 1/3 N FYM + 1/3 N vermicompost + 1/3 N (castor cake) treatment. The higher dehydrogenase activity with legume crops was also reported in [67,68]. Labile carbon is a portion of the total carbon in the soil available for use by microorganisms. There was a nonsignificant difference in the status of labile carbon under different fertilizer treatments. However, the highest labile carbon content was found under T2 + intercropping (soybean) (985.7 mg/kg).

3.8. Energy-Use Efficiency

The total energy input of various treatments varies from 29.97 × 10^3 to 54.27 × 10^3 MJ/ha, as presented in Table 14. The highest energy input was recorded in chemical treatment (T7), which receives recommended doses of fertilizers (54.27 × 10^3 MJ/ha), followed by T1, which receives 50% of recommended NPK fertilizers along with 50% N from FYM/crop residues or other sources of nutrition (42.79 × 10^3 MJ/ha), T6 (32.47 × 10^3 MJ/ha) and T5 (31.57 × 10^3 MJ/ha). However, the organic treatments, viz., T2, T3, and T5 require an equal amount of energy measured at 29.97 × 10^3 MJ/ha. The higher energy inputs needed for chemical-based treatment might be due to using energy-richer inputs such as fertilizer in higher quantities. Similarly, the total energy output of different treatments, as computed from the main product and by-product, ranged from 339.0 × 10^3 to 535.52 × 10^3 MJ/ha (Table 14). The highest total energy output was obtained from T3 treatment, where soybeans were grown as an inter-row crop in maize, radishes in potatoes, and coriander in onions (535.52 × 10^3 MJ/ha) followed by T1, which receives an integrated source of nutrition (463.59 × 10^3 MJ/ha), T2 (441.23 × 10^3 MJ/ha), T4 (437.0 × 10^3 MJ/ha) and T6 (434.12 × 10^3 MJ/ha). The chemical-based treatment produced energy measured at 410.20 × 10^3 MJ/ha, less than all the chemical treatments except T5 (339.0 × 10^3 MJ/ha).

Table 14. Energy input–output relationship of high-value-based cropping system.

Treatments	Energy Input (×10^3 MJ/ha)	Energy Output (×10^3 MJ/ha)	Energy-Use Efficiency	Energy Output Efficiency (×10^3 MJ/ha/Day)	Energy Productivity (Kg REY/MJ)
T1	42.8	464	10.8	1.46	4.88
T2	30.0	441	14.7	1.39	6.84
T3	30.0	535	17.9	1.69	11.5
T4	30.0	437	14.6	1.38	6.74
T5	31.6	340	10.8	1.07	3.87
T6	32.5	434	13.4	1.37	6.32
T7	54.3	410	7.56	1.29	2.99
T8	30.0	456	15.2	1.44	6.66

The treatment (T3) in which soybeans were grown as an inter-row crop in maize, radishes in potatoes, and coriander in onions showed the highest energy-use efficiency (17.87) and energy output efficiency (1.69 × 10^3 MJ/ha/day), and this was mainly due to the increased energy output of the system [69]. Moreover, this treatment also revealed the highest energy productivity, valued at 11.51 kg/MEY/MJ, over the other treatments, mainly due to its higher REY. The treatments with significantly high energy-use efficiencies were T3, T2, T4, and T6. Similarly, except for T5, all the organic treatments showed higher energy output efficiencies and energy productivities than the chemical-based treatment (T7).

4. Conclusions

This LTE research investigation has confirmed that organic farming can provide quality food without adversely affecting the soil's health and the environment. Another critical finding realized that applying an organic source of nutrients sustained productivity and improved soil health and production efficiency. This study revealed that organic manure treatments produced higher maize grain, potato, and onion yields, about 9.4%, 19.79%, and 17.07% more than the chemical farming treatment, respectively. The negligible trends in maize were observed in treatments that had average yields ranging from 0.245 q/ha in T7 to 0.610 q/ha in T3, indicating that the yield improved with each incremental dose of fertilizer. In the case of potato and onion crops, all the treatments showed favourable yield trends, except for T5 and T7, wherein the yields did not offer many variations over time; thereby, potato and onion yields appear to be more stable than maize yields. Applying organic manures in combination with inorganic fertilizers (T1) supplies nutrients in synchrony with crop growth, resulting in a higher nitrogen content and more protein in maize. The quality analyses of potatoes and onions revealed that acidity, ascorbic acid, and total soluble sugars were highest in organic farming treatments. There were improvements in the N and P statuses of the soil for almost all the treatments over their initial values, with the exception of the N status of soil in the T7 treatment (179.4 kg/ha). However, all the *p* values lie in a higher range than their initial value (22.3 kg/ha). The maximum values of N and P were accrued where biofertilizers containing N and P sources were added in combination with the T2 treatment. Thus, the results amply elucidate the importance of organic farming—supplementing chemical fertilizers with an organic source of nutrients—towards the restoration of soil health, along with increases in productivity and further improvements in the quality characteristics. For organic production that meets the global market's demands, selecting suitable crops and products on a regional basis is necessary.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15108254/s1, Table S1. Pearson correlation coefficients of soil properties (macro-nutrients) with 15 years average yield in maize-potato-onion high value based cropping system; Table S2. Pearson correlation coefficients of soil properties (micronutrients) with 15 years average yield in maize-potato-onion high value based cropping system.

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