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Comparative Performance of Integrated Nutrient Management between Composted Agricultural Wastes, Chemical Fertilizers, and Biofertilizers in Improving Soil Quantitative and Qualitative Properties and Crop Yields under Arid Conditions

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Abstract: The primary goal of integrated nutrient management (INM) strategies is to substitute a portion of chemical fertilizers with a more sustainable and environmentally safe organic compost in order to mitigate soil degradation, improve crop production, and protect the environment. Therefore, the present study was conducted to assess the impacts of different INM practices, namely full-dose NPK (T1), compost of cow manure at 5 t ha^{-1} (T2), compost of poultry manure at 5 t ha^{-1} (T3), compost of mixed sheep and camel manure at 5 t ha^{-1} (T4), 50% NPK combined with the mixture of the three types of composts at the rate of 5 t ha^{-1} (T5) or 10 t ha^{-1} (T6), and mixture of the three types of composts at the rate of 10 t ha^{-1} (T7), 15 t ha^{-1} (T8), or 20 t ha^{-1} (T9) with or without biofertilizers for each treatment on several physiochemical and biological proprieties of soil and final grain yield of field crops after 2 years of field-scale experiments. The results showed that all INM practices generally significantly ($p < 0.05$) improved the initial values of all tested soil physiochemical and biological proprieties, whereas improvement was more prominent for the plots treated with T5–T9, compared with those treated with T1–T4. Seed inoculation with biofertilizers also significantly ($p < 0.05$) increased different soil proprieties by 2.8–12.0%, compared to that of the non-inoculation treatment. Principal component analysis revealed that most soil chemical properties were closely associated with T5–T6 treatments, while most soil physical and biological properties appeared to be more related to T7–T9 treatments. Our results indicated that recycling agricultural wastes into new productive composts and integrating it into appropriate INM practices as shown in T5–T9 treatments may induce favorable changes in soil properties and improve crop production under arid conditions even in the short term.

Keywords: field experiment; microbial biomass; organic composts; recycling agricultural wastes; soil physicochemical properties; sustainability

1. Introduction

Soil is the primary reservoir for different essential nutrients for adequate plant growth and sustainable crop production. Nutrient balance in the soil, that is, the difference between the input and output of nutrients in the soil, is an indicator of soil fertility and can also determine the nutrient use efficiency in different crop production systems [1,2]. There are complex factors affecting nutrient balance in soil, especially the nutrients that are removed from it. In arid conditions, frequent soil tillage, removal of crop residues, and extensive use of synthetic fertilizers, along with high temperature and scarce rainfall, are the most dominant factors that usually result in progressive deterioration in soil fertility and quality by rapidly decreasing soil organic matter (SOM) [3–5]. A significant SOM decline causes a considerable deterioration of a range of chemical, physical, and biological soil characteristics. For instance, a decreasing SOM tends to decrease several important soil properties, such as water-holding capacity, water infiltration rate, macro-porosity, soil aggregate stability and structure, nutrient balance, and activity and abundance of soil microbial biomass [6,7]. Finally, these poor characteristics of soil may have a significantly negative influence on plant growth and final crop yield. Therefore, improving and maintaining SOM by recycling different organic wastes is an important strategy to sustain soil fertility and crop production systems in arid conditions [8].

A sufficient amount of organic wastes with various sources and types is available in both high- and low-income countries. For instance, the production of agricultural wastes such as wheat straw, rice straw, rice husk, sugarcane bagasse, and corncob reached approximately 2.0 billion tons per year worldwide and this amount is annually increased at an average rate of 5–10%. Additionally, it is estimated that about 1.7 billion tons of municipal solid waste is produced yearly [9]. In Egypt, as an example for arid and semiarid land, the amount of organic wastes (agricultural and animal wastes) reached approximately 33.3 million tons per year, with 18% and 30% of agricultural wastes used as fertilizer and animal food, respectively [10]. Since over 70% of livestock is concentrated in low-income countries, the waste of different animals, commonly known as farmyard manure (FYM), is the most significant source of organic wastes in these countries [11]. Animal manure always consists of decomposed animal urine and droppings and different agricultural residues that come from animal fodder or beddings. The FYM is characterized by a low carbon to nitrogen ratio (C/N ratio), which decomposes fast and readily releases plant available nutrients [12,13]. Additionally, co-composting low C/N-ratio materials (e.g., organic manure) with high C/N-ratio materials (e.g., crop residuals) provides sufficient nitrogen to speed the decomposition of the crop residuals [14]. Therefore, the well-decomposed FYM is generally rich in different essential nutrients, particularly nitrogen (N), phosphorus (P), and potassium (K). Furthermore, Liu and Chen [11] reported that if one-half of organic P in confined animal wastes is subject to recycling, animal manure is responsible for returns of approximately 2.5 million metric tons of organic P per year to croplands. Zhang et al. [15] also reported that the estimated total nitrogen produced from animal manure increased from 21.4 million metric tons per year in 1860 to 131.0 million metric tons per year in 2014. The concentrations of N, P_2O_5, and K_2O in well-decomposed FYM can reach 0.55%, 0.28%, and 0.52%, respectively [16]. Regarding agricultural wastes, especially crop residuals, Zhang et al. [17] reported that the total NPK assimilated in crop residues is equivalent to approximately 30%, 30%, and 200% of the amount of each nutrient contained in the available chemical fertilizers, respectively. For that reason, many farmers in low-income countries have been widely using different sources of organic composts with minimum synthetic fertilizer application in order to maintain soil fertility and sustainable crop production, especially as the cost of these sources of plant nutrients can be 18% lower compared with that of synthetic fertilizers [18–20].

The integrated use of organic composts along with chemical fertilizer has been well-recognized as a vital agricultural practice to gain more benefits or at least comparable results with that of solely applying chemical fertilizers. For example, Francioli et al. [21] reported that the integrated use of FYM at a rate of 20 t ha^{-1} along with 50% of the recommended dose of NPK significantly increased SOM, total nitrogen content (TNC), and soil microbial biomass carbon (MBC), compared with applying the full recommended dose of NPK; whereas the final crop yield for both treatment was on a par. Li et al. [22] also recorded that the application of NPK + cattle manure increased SOC content, TNC, avalible P content (AP), and available K content (AK) by 52.3%, 36.4%, 48.6%, and 27.6%, as compared with unfertilized control, and by 15.8%, 17.2%, 16.5%, and 7.7%, as compared with solely applying hig rate of NPK, respectively. Ning et al. [23] found that the integrated use of 20% of organic manure along with 60% of the recommended dose of chemical fertilizer or 40% of organic manure along with 40% of the recommended dose of chemical fertilizer significantly increased soil organic matter, soil catalase activity, and urease activity, but reduced soil-available P and K, and soil acid phosphatase activity, compared with applying 100% of the recommended dose of chemical fertilizer. In a short-term field experiment, Lazcano et al. [24] reported that the partial replacement of chemical fertilizer by manure had a significant positive impact on microbial activity, and maintained nutrient supply and crop yield at similar levels with chemical fertilizer. Agegnehu et al. [25] also reported that when the effects of the full recommended NP dose (60/20 kg NP ha^{-1}) were compared with that of the integrated use of half the recommended rate of organic manure (3.25 ton ha^{-1}) and half the recommended NP dose (30/10 kg NP ha^{-1}) on grain yield of wheat, the former treatment increased grain yield by 151.0% and 85.0%, whereas the latter increased grain yield by 129.0% and 68.0%, as compared with the control (without fertilizer) and farmers' standard (23/10 kg NP ha^{-1}) treatments, respectively. Importantly, the integrated use of organic compost and chemical fertilizers not only improves different soil properties and crop productivity, but also significantly minimizes the use of chemical fertilizer, which subsequently conserves energy, minimizing the risk of pollution, improving fertilizer use efficiency, reducing the cost for farmers especially in low-income countries, and ensuring ecosystem sustainability against the degradation of soil and water resources [18,19]. Tayebeh et al. [26] reported that about 30% of the required N fertilizer can be replaced by organic fertilizers, because organic fertilizer application improved N use efficiency, compared with the sole application of chemical fertilizers. Chatterjee et al. [27] also reported that the integrated use of chemical and organic (green manure) fertilizers can save 50–75% of the required N fertilizers in rice as well as increasing the availability of several other plant nutrients through its positive effects on various soil properties.

In general, the comparison between using organic composts and chemical fertilizers revealed that applying organic composts either alone or in combination with chemical fertilizers has become an effective approach towards nutrient management [28]. Given the importance of revitalizing and restoring soil fertility and quality by the combination of organic composts that slowly releases nutrients and supplies them to plants for a long time, and chemical fertilizers that rapidly provide nutrients for plants, this will maximize the agronomic value of organic composts and encourage recycling agricultural wastes into new valuable products for agricultural enhancement in arid regions with poor soil quality [5,29].

However, the key benefits of organic composts, especially short-term ones, largely depend on several complex factors, including the source of organic composts and its application rate [18], the physical, biological, and chemical properties of organic composts and soil [30], local climate conditions and agronomic practices [20], and crop types [31,32]. For instance, Das et al. [18] reported that with the same application rate, composted cattle manure was more effective than swine manure in improving different soil properties, such as MBC, SOM, TOC, TNC, soil enzyme activity, and available P, C, and N. Compared with different organic manures, poultry manure has more beneficial effects on soil properties and final crop yields than other animal manure, because the nitrate level in poultry manure is nearly 10 times greater than all other animal manure, including that of cattle, horse and swine [33]. Alvarez et al. [31] observed yield reduction in potato in the first season after dairy manure application, whereas Thomsen et al. [32] reported an increase in the grain yield of wheat in the first season following the soil application of cattle manure. Lastly, the yield benefits of organic manure were evident in the soils with low organic matter and in arid climates. These conditions are characteristic of many farms in arid regions where organic manures are more likely to be used as a substitute for chemical fertilizers [20]. Several studies have documented the beneficial effects of organic composts application in improving several soil physical and chemical properties under arid and semiarid conditions [34].

Because the balance of soil microbial communities is mostly sensitive to the long-term application of chemical fertilizers [28], the integrated use of organic manure and chemical fertilizers along with biofertilizers is also a promising approach in preserving soil microbial communities and activities, which will ultimately show positive impacts on different soil physicochemical properties and crop production [22,26,35]. Importantly, using effective microorganisms or biofertilizers holds great promise not only to improve soil biological fertility by promoting the proliferation of beneficial bacteria, but also by suppressing soil-borne pathogens, especially as several of these pathogens co-exist in soil [36]. Because the diversity, health, equilibrium, and function of soil microbial communities, which are primarily useful indicators of soil health and the capacity of soil to function as a living system, are notably influenced by different soil physicochemical properties, such as pH, TNC, SOC, and available K—and these soil properties are notably influenced by the combined application of organic manure and chemical fertilizers;—integrated nutrient management (INM) strategies, such as the combination of three sources of nutrients (organic compost, chemical fertilizers, and biofertilizers), are important strategies to enhance soil fertility, nutrient use efficiency, and the sustainability of agricultural production systems.

Given the potential socioeconomic, ecological, and agronomic benefits of the integrated use of organic manure, chemical fertilizers, and biofertilizers, it is important for researchers to continue seeking ways to establish quantitative benchmarks for INM strategies for developing countries in arid regions. Importantly, the crop production in these countries is very susceptible to risks that exist as a result of many factors, including decreased soil self-sufficient nutrients, poor soil physiochemical properties, depletion of natural resources, climate change, irresponsible practices by farmers, and social habits that are difficult to predict or control. Within this context, the primary objective of this study was to compare the effects of various INM practices on soil physical, chemical, and biological properties, which consist of applying the full dose of NPK, different types of organic composts produced from decaying agricultural wastes, and a mixture of different organic composts either alone or in combination with 50% of chemical fertilizers. The improvement in the grain yield of different crops as a function of the positive impacts of INM practices on different soil properties was also investigated.

2. Materials and Methods

2.1. Site and Soil Descriptions

A field study was carried out for two consecutive years in 2014/2015 and 2015/2016 at the research station of the College of Food and Agriculture Sciences, King Saud University, Riyadh, Saudi Arabia (24°25′ N, 46°34′ E, and altitude 600 m). The field had an arid climate with high temperature and dry summer seasons. The minimum and maximum temperature ranged from 6.5 to 19.0 °C and 20.3 to 34.7 °C during the winter growing season (from December to May), and from 21.2 to 29.3 °C and 35.3 to 43.6 °C during the summer growing season (from June to October), respectively. The average total monthly precipitation ranged from 0.25 mm in May to 10.67 mm in December, with a total annual precipitation of 32.0 mm.

No organic substances had been applied to the field during the last 15 years of cultivation history prior to the study, and the application of chemical fertilizers is a common practice during this period. Before the start of experiment (winter season of 2014), twenty soil samples from the soil layer approximately 0–30 cm deep were collected from different places of the experimental site and mixed together, and four representative samples were taken to determine the baseline soil physicochemical properties. The soil texture at the experimental site was classified as sandy loam (57.92% sand, 27.26% silt, and 14.88% clay) and had the following properties: organic matter 0.46%, electrical conductivity (EC) 3.88 dS m^{-1}, pH (soil paste 1:5) 7.86, and calcium carbonate ($CaCo_3$) 29.42%. The levels of available N, P_2O_5, K_2O, Fe, Mn, Zn, and Cu were 35.4, 14.8, 243.5, 3.27, 2.44, 6.07, and 0.70 ppm, respectively. The capillary, total porosity, hydraulic conductivity, and water holding capacity were 25.3%, 40.29%, 3.25%, and 30.25%, respectively.

2.2. Cultural Practices

The cropping system was wheat-mung bean, wheat-maize, barley-sorghum or faba bean–maize rotations. The crops during the study period included maize during the summer season and faba bean during the winter season. In the first winter season, soil preparation was done by plowing the field to a depth of 30–35 cm several times, leveling it, and dividing it into plots. The borders of each plot were manually made as per the experimental sketch for each crop (Figure S1). In the following seasons, conservation tillage was applied to the top 20 cm of soil when organic manure was incorporated into the soil. The seeds of maize and faba bean were planted in five 4-m-long rows spaced 60 cm apart (12.0 m^2 total area for each crop). The seeds of maize and faba bean were sown at a seeding rate of 35 and 24 kg ha^{-1}, respectively. The field was irrigated using a low-pressure surface irrigation system that had one water-emitting tube per plot. The sub-main hose for each plot was equipped with a manual control valve to control the amount of water delivered to each plot.

2.3. Experimental Design and Treatments

A randomized complete block split-plot design with four replicates was used for each crop and each season. The different INM treatments and biofertilizer were randomly assigned to the main plot and subplots, respectively. The INM treatments resulted from the sole application of chemical NPK fertilizers, and different types and rates of organic compost or a combination of both fertilizers. The first treatment was the recommended NPK dose for each crop and was considered as the control treatment (T1). Treatments two to four were the sole application of three different types of prepared organic compost, that is, organic compost based on cow manure activator (T2), poultry litter activator (T3), and mixture of sheep and camel activator (T4) at the rate of 5 t ha^{-1} for each organic compost. Treatments five and six were 50% of the recommended NPK dose in combination with a mixture of the three types of organic compost at the rate of 5 t ha^{-1} (T5) or 10 t ha^{-1} (T6). Treatments seven to nine were the application of a mixture of the three types of organic compost at the rate of 10 t ha^{-1} (T7), 15 t ha^{-1}(T8), or 20 t ha^{-1} (T9).

The recommended NPK dose for legume crop (faba bean) was 100 kg N ha^{-1}, 150 kg P_2O_5 ha^{-1}, and 60 kg K_2O ha^{-1}, whereas for cereal crop (maize) it was 150 kg N ha^{-1}, 90 kg P_2O_5 ha^{-1}, and 60 kg K_2O ha^{-1}. The NPK dose was recommended according to the Saudi Arabian Ministry of Environment, Water and Agriculture. The chemical NPK fertilizers were applied in the form of ammonium nitrate (33.5% N), calcium superphosphate (15.5% P_2O_5), and potassium chloride (60% K_2O). The entire amount of phosphorus was applied before sowing and after mixing the organic composts with soil by spreading it on the soil surface, whereas the nitrogen and potassium fertilizers were applied 20 and 35 days after sowing in three and two equal doses, respectively, with 15-day intervals between doses.

The different organic composts were applied 2–3 weeks before sowing each crop by spreading it evenly on the surface of the soil in each plot and thoroughly mixing it with the top 20 cm of the soil using a rotary cultivator. The different INM and biofertilizer treatments were distributed randomly in the main plots and subplots, respectively, in the first winter season of the experiment, but after that, they were applied to the same plots every season and year.

The two biofertilizer treatments (with "+" and without "−") were randomly nested within each main plot of the nine INM treatments as a split-plot. The seeds of each crop, which were treated with biofertilizer (+), were coated with nitrogen-fixing bacteria (*Azotobacter*) and phosphate-dissolving bacteria (*Pseudomonas* sp.). Two grams of an adhesive agent (Arabic gum) were dissolved in liquid bacterial suspension at a dose of 100 mL ha^{-1} (approximately 0.05 mL g^{-1} of seeds and a guarantee of 2 × 108 CFU mL^{-1}) for each bacterial inoculant strain, stirred, and allowed to stand for 1 h to create a homogeneous suspension. Then, the bacterial suspensions and seeds of each crop were mixed together in plastic bags and shaken manually until the seeds were uniformly coated. The seeds were inoculated one hour before planting. The seeds of each crop were planted approximately 2.5 cm below the soil surface in all plots.

2.4. Preparing the Three Types of Organic Compost

The three types of organic compost used in this study were prepared by co-composting different agricultural wastes with 10% of one of the three types of organic manure (cow, poultry, and mixed sheep and camel manures) as activators for 120 days. The main chemical composition of the three organic manure activators is shown in Table 1.

Table 1. Chemical composition of the three types of organic manures used as activators in preparing the different organic composts, the raw waste materials used in preparing different organic composts, and the three types of organic composts at the end of the composting period (120 days).

Parameters	Cow Manure	Poultry Manure	Mixture of Sheep and Camel Manures
pH	7.97	7.81	7.35
Electrical conductivity (EC), (dS m^{-1})	5.95	7.36	7.19
Organic matter (%)	29.20	50.10	36.40
Organic carbon (%)	16.94	29.06	21.11
Total N (%)	2.05	7.97	1.35
Total P (%)	0.32	1.06	0.63
Total K (%)	0.62	1.56	0.84
C/N ratio	8.26	3.65	15.64
	Palm leaves	**Wheat straw**	**Household wastes**
pH	8.19	8.27	8.32
EC (dS m^{-1})	0.93	1.23	0.86
Organic matter (%)	89.9	94.19	81.45
Organic carbon (%)	52.14	54.63	47.24
Total N (%)	0.61	0.56	0.81
Total P (%)	0.08	0.22	0.19
Total K (%)	0.17	0.19	0.11
C/N ratio	85.48	97.55	58.32
	Organic compost based on cow activator	**Organic compost based on poultry litter activator**	**Organic compost based on mixture of sheep and camel activator**
pH	7.27	7.11	7.32
EC (dS m^{-1})	3.79	3.52	3.91
Organic matter (%)	42.98	41.65	46.96
Organic carbon (%)	26.90	24.16	27.24
Total N (%)	1.39	1.54	1.46
Total P (%)	0.568	0.695	0.708
Total K (%)	0.472	0.535	0.518
Moisture (%)	25.50	20.20	22.83
C/N ratio	48.91	37.17	28.08
Amount of NPK (kg ha^{-1}) and organic matter (ton ha^{-1})applied through sole application of three different types of organic compost at rate of 10 ton ha^{-1}			
	Organic compost based on cow activator	**Organic compost based on poultry litter activator**	**Organic compost based on mixture of sheep and camel activator**
Total N (kg ha^{-1})	103.7	122.9	112.7
Total P (kg ha^{-1})	42.3	55.5	54.6
Total K (kg ha^{-1})	35.2	42.7	40.0
Organic matter (ton ha^{-1})	2.0	2.13	2.11

The agricultural waste that was scattered around the experimental site (palm leaves and wheat straw), along with household waste, was collected, mechanically crushed to small particles, and mixed together. The main chemical composition of the raw waste materials used in preparing the organic composts are presented in Table 1. Thereafter, these crushed materials were divided into three heaps that were equal in size, and each heap was mixed with 10% of one of the three types of selected organic manures and 2% calcium carbonate (to maintain a more favorable pH conditions for growth of bacteria in composting heaps), and then inoculated with a mixture of 1×10^8 CFU/g bacteria of *Streptomyces aurefaciens*, *Trichoderma viridie*, *T. harzianum*, *Bacillus subtilis*, *B. licheniformis* (1 l ton^{-1}) to speed up the decomposition process and enrich compost quality [37]. The final heap size was $5 \times 10 \times 1.50$ m. During the composting period, each heap was mechanically turned upside down and watered every 15 days to maintain the aerobic and composting process in optimum conditions. After 120 days of composting, representative samples from each heap were taken to determine the different chemical compositions of the three different types of organic compost, as shown in Table 1.

2.5. Soil Physical and Chemical Properties

Several physical and chemical properties of soil were recorded following the completion of the two-year study to assess the impacts of different INM treatments on soil health and fertility, which is the primary goal of the present study. Soil samples (a total of 72 soil samples from eighteen treatments with four replications) were taken from the treatment groups at a depth of 30 cm. Each soil sample was randomly collected from four points in each plot and mixed thoroughly to get one composite sample for each plot. Then, each composite sample was passed through a 2-mm sieve and air-dried for 24 h before analysis.

Soil pH and EC were determined by suspending soil in distilled water at a ratio of 1:2 (*w/v*) as previously described by Jones [38] using a portable calibrated conductivity multi-parameter instrument (Hanna HI 9033).

Soil organic carbon (SOC) was determined using the method previously described by Walkley [39] and modified by Nelson and Sommers [40]. The procedure involved wet combustion of the organic matter with a mixture of potassium dichromate ($K_2Cr_2O_7$) and sulfuric acid (H_2SO_4) (1:2) for 30 min, followed by titration of unconsumed potassium dichromate with standardized ferrous sulfate or ferrous ammonium sulfate.

SOM was determined by measuring the organic carbon content in the soil samples using the loss-on-ignition procedure [41]. In this procedure, approximately 10 g of air-dried soil was placed in a porcelain crucible, oven-dried at 105 °C overnight, cooled, and weighed (W1). Next, the samples were combusted in a muffle furnace at different temperatures (300, 360, 400, 500 and 550 °C) for 2 h, cooled, and weighed again (W2). The weight before (W1) and after (W2) heating was applied to the following equation to calculate SOM percentage in the sample:

$$\text{SOM}\ (\%) = \frac{\text{W2} - \text{W1}}{\text{W1}} \times 100 \tag{1}$$

Different soil nutrients following the completion of the study (total N and available N, P, and K expressed in kg ha^{-1}) were determined using standard laboratory methods of soil and plant analysis [42]. Total N (TN) was determined using the Kjeldahl digestion method. The TN in soil and organic compost was determined by H_2SO_4 digestion in the presence of selenium (Se), potassium sulfate (K_2SO_4), and copper sulfate ($CuSO_4$) as catalyst. Soil samples were analyzed for available N using the alkaline potassium permanganate ($KMNO_4$) method in a micro-Kjeldhal apparatus [43], available P by 0.5 M sodium bicarbonate ($NaHCO_3$) at pH 8.5 [44], and available K by 1 M ammonium acetate ($NH_4CH_3CO_2$) at pH 7.0 [45]. The molybdenum blue method was used to determine P, followed by analysis using a double-beam spectrophotometer, whereas K was analyzed using flame photometry.

In addition to the aforementioned chemical properties, other soil physical parameters (water-holding capacity, infiltration rate, total porosity, and hydraulic conductivity) were also analyzed. Soil water-holding capacity (WHC) was measured from the core samples using the following formula

$$\text{WHC} = \frac{\text{weight of water in soil (g)}}{\text{weight of oven dry soil (g)}} \times 100 \tag{2}$$

The infiltration rate (IR, m s^{-1}) was evaluated using the double-ring infiltrometer technique and calculated using Philip's infiltration equation [46]

$$\text{IR} = \frac{1}{2}\text{St}^{-1/2} + \text{A} \tag{3}$$

where S is the sorptivity of the soil (m $s^{-1/2}$), t is time (s), and A is the soil water transmissivity (m s^{-1}).

When soil is saturated, all air in the soil is displaced by water. Thus, the volume of water is an indication of the total porosity of the soil (i.e., the volume of pores).

The different porosity parameters (total porosity, non-capillary porosity, and capillary porosity) were determined in an undisturbed water-saturated core, assuming no air is trapped in the pores, using the following equations

$$\text{Total porsity } (\%) = \frac{\text{Weight of soil at saturation} - \text{oven dry weight of soil}}{\text{Volum of soil}} \times 100 \quad (4)$$

$$\text{Non} - \text{capillary porsity } (\%) = \frac{\text{weight of soil at saturation} - \text{weight of soil after 50 cm tension}}{\text{volum of soil}} \times 100 \quad (5)$$

$$\text{Capillary porosity } (\%) = \text{Total porosity} - \text{Non capillary porosity} \quad (6)$$

In addition to the aforementioned chemical and physical properties, soil microbial biomass carbon (MBC), nitrogen (MBN), and phosphorous (MBP) in the soil samples surrounding the root zone of plant rhizospheres were also analyzed at the time of harvesting. Soil MBC and MBN were estimated through the chloroform fumigation extraction method previously described by Vance et al. [47]. Briefly, fresh soil samples were weighed into 500-ml glass Schott bottles and fumigated for 24 hours at 25 °C with alcohol-free chloroform ($CHCl_3$). The un-fumigated soil samples were extracted under the same conditions at the time fumigation commenced. The fumigated and un-fumigated soil samples were extracted with 0.5 M K_2SO_4 by shaking for 30 min at a soil: solution ratio of 1:4. Thereafter, it was filtered through a Whatman no. 42 filter paper and the filtrates were analyzed for organic C using an automated TOC analyzer (500 model; Shimadzu, Japan). MBC is the difference between organic carbon derived from fumigated samples and organic carbon derived from un-fumigated samples divided by the standard correction factor that is equal to 0.45 [48]. MBP was estimated using the modified method previously described by [49], in which the soil : solution ratio changed from 1:2 to 1:4 and omitted pre-incubation. MBP is the difference between extractable P in the fumigated soil over that in the un-fumigated soil divided by the standard correction factor that is equal to 0.4 [49].

2.6. Measurement of Grain Yield

Grain yield was measured by manually harvesting two complete central rows for maize and faba bean (4.8 m^2 total area for each crop) from each subplot. Total grain yield per ha was adjusted to 14.5% moisture. Grain moisture was determined from a 250-g sample taken from each subplot.

2.7. Statistical Analyses

The data obtained for different soil properties and final grain yield of each crop were subjected to statistical analysis of variance (ANOVA) that is appropriate for a randomized complete block split-plot design, with the different INM treatments as the main factor and biofertilizers as the split factor. All data were checked for normality and homogeneity before being subjected to ANOVA using the Shapiro–Wilk test and Bartlett's test, respectively. A Fisher's protected least significant difference test at 0.05 probability level was used to further elucidate the significant differences between the mean values of the treatments. The associations between all soil properties and grain yield were evaluated using Pearson's correlation coefficient (*r*) matrix. Principal component analysis (PCA) was performed to classify a large number of variables into major components, as well as to investigate the influences of different INM treatments on different soil properties and final grain yield. PCA was conducted based on the correlation matrix to correct the differences in the metrics among measured variables. Statistical analysis, correlations, and PCA were performed using the MS office XLSTAT statistical package software (ver. 2019.1, Excel Add-ins soft SARL, New York, NY, USA).

3. Results and Discussion

The results of this study showed that the various INM treatments played an important role in regulating several soil physical, chemical, and biological properties where poor soil management strategies, extensive use of synthetic fertilizers, frequent soil tillage, removal of crop residues, and intensive cultivation systems are the most dominant factors that lead to deteriorated soil fertility and crop production under arid conditions. The impact of different types and rates of organic compost application either solely or in combination with chemical fertilizers on soil fertility (in terms of soil pH, EC, SOM, SOC, availability of N, P, K, and S, different water relations of soil, and microbial biomass communities) and crop yield performance were presented and discussed in the following sections.

3.1. Impacts of INM Treatments on Soil Chemical Properties

Soil pH is the only soil characteristic that can singly elucidate an overall picture of the medium for plant growth, including available nutrient supply trend, fate of added nutrients, soil salinity, sodicity and aeration, and health and equilibrium of soil microbial communities [21,22,50]. The data presented in Table 2 indicated that a significant decrease in soil pH was observed with the different INM treatments compared with the initial soil pH value (pH, 7.86), although the numerical values of pH for all treatments are within the normal soil pH range of calcareous soils. It also revealed that treatment with different types of organic composts either alone or in combination with 50% of the recommended NPK dose slightly decreased pH (7.21–7.29 for such treatments), compared with those treated with the full recommended NPK dose (pH 7.34) (Table 2). The slight decrease in soil pH through INM application may be due to the pH of the three organic composts is still alkality; their pH ranged from 7.11 to 7.32 (Table 1). The decreased soil pH for soil treated with organic composts may be attributed to H^+ ions, as well as other organic and inorganic acidic compounds that are released into the soil atmosphere during the continuous decomposition processes of organic composts in the soil, dissolution of CO_2 released from organic composts in water and converted into carbonic acid (H_2CO_3), the biological oxidation of elemental sulfur, and/or mixing soil with low-pH substrates (the pH of the three organic compost ranged from 7.11 to 7.32 (Table 1)), where the initial pH value of soil was 7.86 [51,52].

The results of EC reveal a significant change among INM treatments, compared with the initial value of soil EC. The results in Table 2 show that the organic compost treatments resulted in significantly decreased soil EC, which was more obvious in the groups treated with a mixture of the three types of organic composts at rates of 15 (T8) and 20 (T9) ton ha^{-1} (the EC decreased by 1.36 and 1.39 dS m^{-1} for T8 and T9, respectively, compared with the initial soil EC value). The decrease in soil EC for the groups that were individually treated with different types of organic composts (T2, T3, and T4) or in combination with 50% of the recommended NPK dose (T5 and T6) ranged from 1.26 to 1.31 dS m^{-1}, compared with the initial soil EC value (Table 2). The decreased soil EC as a result of organic compost treatment may be attributed to the changes in soil physical properties, such as increased total porosity and hydraulic conductivity, especially for calcareous soil, which ultimately stimulates the mobility of Na^+ ions to leach into deep layers of the soil [53]. Within this context, previous studies also reported that applying different organic manures to calcareous soil resulted in decreased soil EC and increased solubility of Na^+, Cl^-, and HCO_3^- [54–56].

Table 2. Effects of different integrated nutrient management (INM) with (+) and without (−) seed inoculation (seed Inc.) on soil chemical properties (mean, n = 4) after 2 years of field-scale experiments.

INM	Seed Inc.	pH	EC	Organic Matter (%)	Organic Carbon (%)	Total N (%)	Available Nutrients (kg ha^{-1})			
							N	P_2O_5	K_2O	S
Initial values		**7.86 a**	**3.88 a**	**0.46 f**	**0.34 d**	**0.12 d**	105.26 f	22.21d	115.62 e	5.32 d
T1 (Full recommended NPK)	-	7.38	2.74	0.58	0.41	0.14	141.30	31.87	116.95	9.93
	+	7.29	2.68	0.67	0.57	0.17	172.35	40.54	132.05	7.74
	Mean	7.34 b	2.71 b	0.63 ef	0.49 cd	0.16cd	156.83 e	36.21 c	124.50 d	8.84 c
T2 (compost of cow manure at 5 t ha^{-1})	-	7.34	2.60	0.68	0.54	0.15	160.50	35.60	120.80	8.15
	+	7.20	2.54	0.74	0.64	0.17	166.60	37.07	125.80	8.58
	Mean	7.27cd	2.57cd	0.71 ef	0.59bcd	0.16cd	163.55e	36.34c	123.30d	8.37c
T3 (compost of poultry manure at 5 t ha^{-1})	-	7.32	2.58	0.98	0.78	0.22	225.95	46.54	169.65	14.41
	+	7.25	2.65	1.08	0.79	0.24	228.64	49.14	169.65	14.87
	Mean	7.29c	2.62bc	1.03cd	0.79abc	0.23ab	227.30cd	47.84b	169.65c	14.64a
T4 (compost of mixture of sheep and camel at 5 t ha^{-1})	-	7.30	2.55	0.87	0.75	0.20	220.00	46.46	189.95	13.62
	+	7.24	2.63	0.95	0.76	0.22	222.85	48.55	172.20	13.95
	Mean	7.27cd	2.59cd	0.91de	0.76abc	0.21bc	221.43d	47.51b	181.08bc	13.79b
T5 (50% NPK + 5 t ha^{-1} mixture of three types of compost)	-	7.28	2.54	1.16	0.80	0.24	236.55	50.28	176.22	14.45
	+	7.22	2.66	1.22	0.86	0.26	244.59	58.99	195.64	14.65
	Mean	7.25de	2.60e	1.19bcd	0.83ab	0.25ab	240.57b	54.64ab	185.93b	14.55a
T6 (50% NPK+10 t ha^{-1} mixture of three types of compost)	-	7.24	2.62	1.18	0.88	0.27	248.22	56.72	189.97	14.85
	+	7.20	2.56	1.28	0.95	0.27	256.60	60.44	198.97	14.99
	Mean	7.22fg	2.59cd	1.23bc	0.92a	0.27a	252.41a	58.58a	194.47a	14.92a
T7 (mixture of three types of compost at 10 t ha^{-1})	-	7.25	2.55	1.34	0.88	0.26	228.75	52.28	188.91	14.80
	+	7.22	2.67	1.45	0.96	0.26	235.45	62.54	199.82	14.95
	Mean	7.24ef	2.61bc	1.40ab	0.92a	0.26ab	232.10bc	57.41a	194.37a	14.88a
T8 (mixture of three types of compost at 15 t ha^{-1})	-	7.22	2.54	1.52	0.88	0.25	231.22	53.33	190.27	14.90
	+	7.20	2.50	1.64	0.92	0.27	236.31	63.22	199.68	14.96
	Mean	7.21g	2.52cd	1.58a	0.90a	0.26ab	233.77bc	58.28a	194.98a	14.93a
T9 (mixture of three types of compost at 20 t ha^{-1})	-	7.27	2.52	1.55	0.84	0.26	231.57	53.67	191.22	14.90
	+	7.20	2.46	1.72	0.90	0.27	237.82	64.44	199.95	14.92
	Mean	7.24ef	2.49d	1.64a	0.87ab	0.27a	234.70bc	59.06a	195.59a	14.91a
Mean of seed inoculation	-	7.29a	2.58a	1.10b	0.75b	0.22a	213.78b	47.42b	170.44b	13.33a
	+	7.22b	2.59a	1.19a	0.82a	0.24a	222.36a	53.88a	177.08a	13.29a
LSD INM×seed inc.		0.04	0.11	0.50	0.07	0.08	4.52	5.21	7.22	0.14

Values followed by the same letter in the same column are not significantly different at $p \leq 0.05$ according Fisher's protected least significant difference test.

Managing SOM remains a sound basis for maintaining soil conditions in a suitable status for enhancing crop growth and productivity, as it is one of the best indicators or proxies for soil fertility and quality. Furthermore, it can be used as a predictable indicator for soil production, especially when a baseline number can be obtained for the soil being studied before starting the planting process, and when soil can be observed over a period of time or after harvest. In other words, SOM is responsible for the provision of the all functions of the soil at present and in the future [57–60]. Therefore, developing agricultural cultivation and nutrient management strategies is needed to enhance or maintain SOM under different cropping production systems. Applying different soil enhancers, such as organic composts, plant residues, agricultural wastes, and chemical fertilizers is considered an effective way to enhance SOM and carbon concentration under different soil types and cropping systems [61,62]. In the present study, SOM content was gradually increased by increasing the application rates of the mixture of three types of organic composts, with respect to the initial values of 67.1%, 70.9%, and 72.0% for T7 (10 t ha^{-1}), T8, (15 t ha^{-1}), and T9 (20 t ha^{-1}), respectively (Table 2). Importantly, the treatment groups received a combination of 50% of the recommended NPK dose and organic composts (T5 and T6) showed more SOM in comparison with the treatment groups that received sole application of organic compost (T2, T3, and T4) or the full recommended NPK dose (T1), and the percentage of increase in SOM compared with the initial value was 62.6%, 61.3%, 49.5%, 55.3%, 35.2%, and 27.0% for T6, T5, T4, T3, T2, and T1, respectively (Table 2). These results indicate that the application rate and type of organic composts play important roles in enhancing SOM. Additionally, applying a mixture of different organic compost alone or combining it with chemical fertilizers is a more appropriate INM practice for improving and maintaining SOM content, which safeguards long-term soil productivity, than applying chemical fertilizers alone even at the full recommended doses. Previous research concluded that the combined application of organic manure and chemical fertilizers or the high application rate of organic manure alone induced noticeable quantitative and qualitative changes in several soil properties, particularly SOM content [18,21,22]. Furthermore, McConnell et al. [63] also found that applying organic manure at a varied rate ranging from 18 to 146 t ha^{-1} produced a 6.0% to 163.0% increase in SOM.

The declining SOC contents in various soil types was found to be associated with intensive cropping and application of chemical fertilizers, which increase the loss of carbon in the soil [64]. However, good farming practices, such as balanced fertilization by solely applying organic manure or combining it with chemical fertilizers can maintain higher C concentration, directly increasing SOC stock. For instance, Tejada et al. [65] showed that applying organic compost (composted sewage sludge) increased SOC by 100% in approximately 1 year. Antil and Singh [66] also reported that applying organic manure alone or in combination with chemical fertilizers (NP) for 10 years resulted in a significant increase in SOC, whereas the value of SOC for soil continuously treated with NP fertilizers did not differ from its initial value. Bouajila and Sanaa [67] also showed that the application of 120 t ha^{-1} of organic manure and household waste compost increased SOC by 36.7% and 60.3%, respectively, compared with the control treatment (without any application). Additionally, according to Blanchet et al. [68], with the application of organic manure, SOC significantly increased by 6.2%, compared with the application of chemical fertilizer alone. In the present study, 2 years after the last organic compost application, the application of the organic compost in a combination with 50% of recommended NPK dose (T5 and T6) or application of the mixture of the three types of organic compost alone (T7, T8, and T9) resulted in 41.0–46.7% higher SOC, compared with T1 treatment. In addition, application of the organic compost alone (T2, T3, and T4) increased SOC by 16.9%, 38.0%, and 35.5% relative to T1 treatment, and by 42.4%, 57.0%, and 55.3% relative to the initial value, respectively (Table 2). These results indicate that INM strategies, such as the integration of organic and inorganic fertilizers, is a good strategy for maintaining soil fertility and sustainability, and preserving the SOC is one of the factors associated with this sustainable system. Furthermore, the type of organic compost added to the soil, and not the amount, is the determining factor for building-up of SOC, which may be due to the variations among organic manures in terms of chemical composition and release patterns into the soil, as well as in the losses of organic carbon during decomposition. Similarly, Antil and Singh [66] also reported that the type of organic manure affects SOC build-up, and in their study, the highest SOC value was obtained by applying FYM, followed by pressmud, and then poultry manure. Roy and Kashem [69] also reported that the plots treated with chicken manure, cow dung, and a mixture of equal amounts of both caused an increase in soil carbon by 16.8%, 14.4%, and 12.9%, respectively, compared with the initial value. Islam et al. [70] observed that the SOC was influenced by different types of organic manure, and the maximum and minimum SOC values were obtained by applying dairy compost and drainage compost, respectively. However, Barzegar et al. [71] pointed out that increasing the compost application rate did not always augment SOC and nutrient contents in soil. Flavel and Murphy [72] also reported that the limited increase in SOC and nutrients after applying compost at high rates may be attributed to the rapid mineralization of labile SOM.

As shown in Table 2, the total soil nitrogen (TN) and availability of N, P, K, and S were also significantly influenced by different INM strategies. A significant increase in TN and availability of different soil nutrients was observed when the mixture of the three types of organic composts was applied alone at different application rates (T7, T8, and T9) or in conjunction with 50% of recommended NPK dose (T5 and T6), relative to the sole application of full-dose NPK (T1). The increase level of TN and availability of N, P, K, and S for T5–T9, over T1, ranged from 36.0–40.7%, 32.4–37.9%, 33.7–38.7%, 33.0–35.9%, and 39.2–40.8%, respectively (Table 2). TN and the availability of different soil nutrients for the group treated with 5t ha^{-1} organic compost based on cow manure (T2) did not show any statistically significant difference from T1; however, the application of organic compost based on poultry litter (T3) and a mixture of sheep and camel manure (T4) at the rate of 5t ha^{-1} increased TN by 30.4% and 23.8%, N by 31.0% and 29.2%, P by 24.3% and 23.8%, K by 26.6% and 31.2%, and S by 39.6% and 35.9%, respectively, over T1 (Table 2). These findings indicate that consortia of organic composts and chemical fertilizers or consortia of different types of organic composts could be a better INM strategy for maintaining soil fertility. In addition, the increase in soil nutrient levels may rely on the type of organic compost added to the soil. The importance of organic compost in enhancing the availability of different soil nutrients may be attributed to several reasons, including the fact that organic compost usually stimulates soil microbial activities and their biomass, thereby enhancing the release of organic nutrients, such as nitrogen and phosphorus, in the soil [18,64]; organic compost acts as a nutrient source, wherein the different inherited ions of organic composts are released into the soil during decomposition and after application in the soil [73]; organic compost can increase cation exchange capacity, which is a very important indicator for retaining nutrients and making them available to plants [25,65]; organic compost releases ions to the soil at a slow and consistent rate, which prevents ions from leaching into ground water [74]; organic compost produces organic acids that have a positive effect in reducing the pH of calcareous soil, which help in releasing phosphorus by the solubilizing action of native soil phosphorus [75,76]; the humic and fulvic acid that are released from organic compost can improve the status of nutrients in the soil by chelating them with phenol and carboxylic groups [77].

3.2. Impacts of INM Treatments on Soil Physical Properties

Capillary and non-capillary porosity can be calculated by replacing volume of air in the dry soil at field capacity state with water. The soil that has the highest value of field capacity it also has the highest value of porosity percentage. The results of capillary and total porosity showed significant differences among INM treatments, ranging from 33.21% to 40.75% for capillary and 47.15% to 64.60% for total porosity (Table 3). The highest values of either soil capillary percentage or total porosity percentage were observed in T7, T8, and T9, followed by T6. These treatments (T6, T7, T8, and T9) had 3.7%, 7.4%, 8.1%, and 9.3% higher soil capillary percentage, and 6.0%, 9.4%, 10.2%, and 14.6% higher total porosity percentage, respectively, than that observed in T1, which consisted of sole application of full-dose NPK. The values of either soil capillary percentage or total porosity percentage for T2, T3, T4, and T5, which received a low rate of organic compost alone (T2, T3, and T4) or in combination with

50% NPK (T5) were lower than those of T1 (Table 3). These results indicate that the application of high rates of organic compost resulted in a higher increase in soil porosity percentage (either in soil capillary percentage or total porosity percentage) than at low rates. This may be attributed to that the high rates of organic compost application resulted in high SOM increases. The high SOM generally increased the aggregate stability and total porosity, reduced bulk density, and changed the pore-size distribution of the soil. In the same respect, several previous studies have reported a significant positive correlation between SOM and total porosity percentage [51,78–82]. The Pearson's correlation in the present study reaffirmed this finding and it was found that the SOM exhibited a positive and high correlation with capillary percentage (r = 0.80) and total porosity percentage (r = 0.83) (Figure 1).

Table 3. Effects of different integrated nutrient management (INM) with (+) and without (−) seed inoculation (seed Inc.) on soil physical properties (mean, n = 4) after 2 years of field-scale experiments: capillary (cap), total porosity (TP), hydraulic conductivity (HC), water holding capacity (WHC), and infiltration rate (IR).

INM	Seed Inc.	Cap (%)	TP (%)	HC ($ms^{-1} \times 10^{-6}$)	WHC (%)	IR ($ms^{-1} \times 10^{-6}$)
Initial values		25.30f	40.29g	3.25g	30.25h	1.98i
T1 (Full recommended NPK)	-	37.55	56.00	4.22	44.50	2.19
	+	36.32	54.32	4.11	46.31	2.20
	Mean	36.94bc	55.16c	4.17c	45.41f	2.20gh
T2 (compost of cow manure at 5 t ha^{-1})	-	32.20	45.38	3.49	40.11	2.00
	+	34.22	48.92	3.70	41.50	2.11
	Mean	33.21e	47.15f	3.60f	40.81g	2.06hi
T3 (compost of poultry litter manure at 5 t ha^{-1})	-	34.20	49.74	3.92	45.05	2.11
	+	37.52	52.60	4.12	46.21	2.44
	Mean	35.86cd	51.17de	4.02de	45.63ef	2.28fg
T4 (compost of mixture of sheep and camel manure at 5 t ha^{-1})	-	33.24	47.68	3.88	43.44	2.34
	+	35.50	50.44	4.00	49.50	2.41
	Mean	34.37de	49.06ef	3.94e	46.47ef	2.38f
T5 (50% NPK + 5 t ha^{-1} mixture of three types of compost)	-	35.22	51.74	4.12	46.05	2.41
	+	35.64	55.70	4.17	48.64	3.15
	Mean	35.43cde	53.72cd	4.15cd	47.35de	2.78e
T6 (50% NPK + 10 t ha^{-1} mixture of three types of compost)	-	38.42	58.23	4.14	48.12	3.16
	+	38.27	59.08	4.31	49.25	3.54
	Mean	38.35ab	58.66b	4.23c	48.69cd	3.35d
T7 (mixture of three types of compost at 10 t ha^{-1})	-	39.61	59.75	4.39	49.26	3.33
	+	40.00	61.95	4.66	50.28	3.85
	Mean	39.81a	60.85b	4.53b	49.77bc	3.59c
T8 (mixture of three types of compost at 15 t ha^{-1})	-	39.80	61.11	4.56	49.38	3.76
	+	40.61	61.75	4.75	52.34	3.95
	Mean	40.21a	61.43b	4.66b	50.86b	3.86b
T9 (mixture of three types of compost at 20 t ha^{-1})	-	39.84	63.34	5.19	52.15	3.95
	+	41.65	65.86	5.44	54.67	4.08
	Mean	40.75a	64.60a	5.32a	53.41a	4.02a
Mean of seed inoculation	-	36.68b	54.77b	4.21b	46.45b	2.81b
	+	37.75a	56.74a	4.36a	48.74a	3.08a
LSD INM×seed inc.		0.98	2.44	0.49	1.42	0.12

Values followed by the same letter in the same column are not significantly different at $p \leq 0.05$ according Fisher's protected least significant difference test.

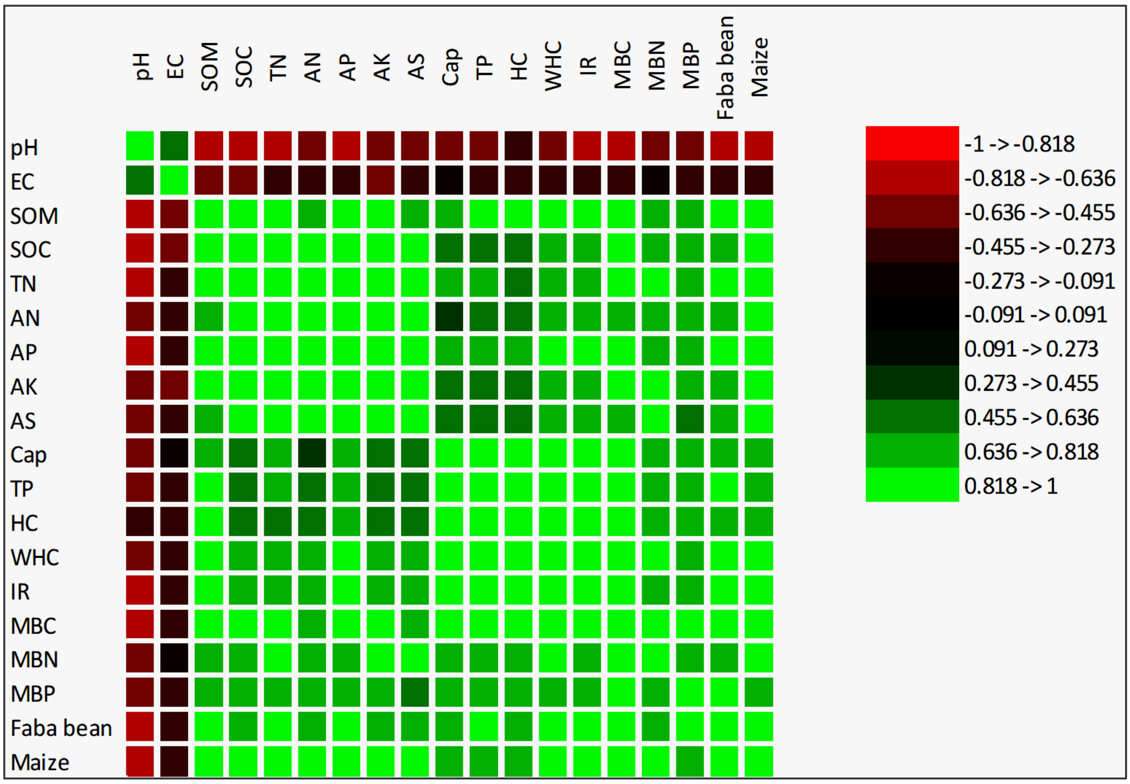

Figure 1. Correlation matrix between soil chemical (pH, EC, soil organic matter (SOM), soil organic carbon (SOC) total nitrogen (TN), available of N (AN), P (AP), K (AK), and S (AS), soil physical (capillary (Cap), total porosity (TP), hydraulic conductivity (HC), water holding capacity (WHC), and infiltration rate (IR)) soil biological (soil microbial biomass carbon (MBC), nitrogen (MBN), and phosphorous (MBP)) properties, and grain yield of faba bean and maize.

Another important soil physical property is hydraulic properties, such as hydraulic conductivity, WHC, and infiltration rate. Generally, the value of the three soil physical properties was highest in T9 (mixture of the three types of organic compost at a rate of 20 t ha^{-1}) and lowest in T2 (application of 5 t ha^{-1} organic compost based on cow manure activator alone). Additionally, the values of the three soil physical properties gradually increased with the increase in the application rate of a mixture of the three types of organic composts. Soil hydraulic conductivity, WHC, and infiltration rate were 21.6%, 15.0%, and 45.3% higher in T9 (20 t ha^{-1}); 10.5%, 10.7%, and 43.0% higher in T8 (15 t ha^{-1}); and 7.9%, 8.8%, and 38.7% higher in T7 (10 t ha^{-1}), respectively, compared with T1 (Table 3). Importantly, when organic compost was applied in conjunction with 50% of the recommended NPK dose (T5 or T6), it resulted in significant improvements in the soil hydraulic properties, especially infiltration rate, over T1. The increased infiltration rate over the value of T1 was 20.9% and 34.3% for T5 and T6, respectively (Table 3). These results indicate that the different soil hydraulic properties generally improved by enhancing the SOM content. This was because the SOM content is considered a major binding agent that enhances the formation and stabilization of soil aggregates [83]. Enhancing the stability of soil aggregation is widely considered as a major contributing factor that has a positive significant effect on a range of soil physical properties and functions, especially those related to soil hydraulic properties, such as hydraulic conductivity, water infiltration rate, and WHC [6,64,84]. Moreover, the SOM lowered soil compaction and soil bulk density, which results in an improved total soil porosity and permeability, and because of that, there was a close relationship between SOM and soil hydraulic properties [51]. In this respect, several studies have reported that there was a direct relationship between different soil hydraulic properties and the amount of organic compost applied [64,80,84]. In the present study, the treatments that resulted in an improved SOM, such as observed in T7, T8, and T9, they also exhibited an improved in porosity percentage and hydraulic properties (Table 3).

Therefore, a positive and significant correlation was observed between the soil's hydraulic properties and SOM (r = 0.80–0.94, Figure 1).

In the present study, applying organic compost along with 50% of the recommended NPK dose (T5 or T6) also improved the soil WHC and water infiltration rate, compared with the application of 100% NPK alone (Table 2). Brar et al. [84] also reported that, with the addition of FYM to 100% NPK, cumulative infiltration rate increased significantly by 9.5%, compared with 100% NPK application only. Bhattacharyya et al. [85] further reported that FYM, in conjunction with NPK, increased the infiltration rate by 39.4%, compared with NPK alone. However, Haynes and Naidu [86] reported that the continuous application of chemical fertilizers reduced aggregate formation and stability by dispersing soil colloids and secondary particles, which subsequently reduced the soil's hydraulic properties. Therefore, our results indicate that any treatment enhanced the SOM content, and also resulted in improved several soil physical properties, which has been found in soil treated with a mixture of the three types of organic composts alone (T7, T8, and T9) or in conjunction with 50% NPK (T5 and T6).

3.3. Impacts of INM Treatments on the Soil Biological Properties

The influence of different organic composts individually or combined at different rates with or without chemical fertilizers on soil MBC, MBN, and MBP are presented in Table 4. The increased MBC, MBN, and MBP levels for different treatments of fertilizers (T1–T9) over the initial value of soil ranged from 20.0% to 47.5%, 32.2% to 65.2%, and from 33.3% to 56.4%, respectively, whereas the maximum improvement in these three soil microbial indicators was recorded in the soil treated with a mixture of three types of organic compost alone (T7, T8, and T9) or in conjunction with 50% NPK (T5 and T6). Regarding the type of organic compost, the organic compost based on poultry manure activator (T3) and mixed sheep and camel manure activator (T4) increased the three soil microbial indicators better than the organic compost based on cow manure activator (T2). Additionally, the former two types of organic compost were also better than treatment with the full recommended NPK dose (T1), whereas the latter organic compost (T2) showed the lowest values for the three parameters among all the treatment groups (Table 4). These results indicate that the incorporation of organic composts, either alone or in conjunction with chemical fertilizers, triggered a manifold increase in the diversity and activity of soil microbial biomass. In this context, Brown and Cotton [78] reported that the incorporation of composted organic manure increased soil microbial activity by about 2.2 times, compared with that of the control treatment, because the decomposed organic manure provides a sufficient energy source in terms of C and N for different soil microbial biomass, leading toward the improved proliferation of heavy soil microbial populations [18,50,87]. Ginting et al. [88] also reported that the incorporation of composted organic manure increased MBC and MBN levels by 20–40% and 42–74%, respectively, compared with that of chemical N fertilizer application. Taken together, these indicate that the incorporation of organic compost with or without NPK fertilizer augmented soil health by enhancing the microbial communities, which is implicated in the decomposition of complex organic matter and soil carbon, nitrogen, and phosphorus transformations.

Table 4. Effects of different integrated nutrient management (INM) with (+) and without (−) seed inoculation (seed Inc.) on soil microbial indicators (mean, n = 4) after 2 years of field-scale experiments.

INM	Seed Inc.	Microbial Biomass C (mg kg^{-1} soil)	Microbial Biomass N (mg kg^{-1} soil)	Microbial Biomass P (mg kg^{-1} soil)
Initial values		**189.25 h**	**16.59 g**	**5.56 g**
T1 (Full recommended NPK)	-	266.78	38.66	9.12
	+	291.08	37.58	9.51
	Mean	278.93f	38.12e	9.32ef

Table 4. *Cont.*

INM	Seed Inc.	Microbial Biomass C (mg kg^{-1} soil)	Microbial Biomass N (mg kg^{-1} soil)	Microbial Biomass P (mg kg^{-1} soil)
T2 (compost of cow manure at 5 t ha^{-1})	-	218.62	22.55	8.68
	+	254.26	26.36	7.99
	Mean	236.44g	24.46f	8.34f
T3 (compost of poultry litter manure at 5 t ha^{-1})	-	287.00	37.19	9.04
	+	312.40	44.20	9.85
	Mean	299.70e	40.70d	9.45def
T4 (compost of mixture of sheep and camel manure at 5 t ha^{-1})	-	283.74	40.10	9.50
	+	300.21	42.16	9.60
	Mean	291.98e	41.13d	9.55def
T5 (50% NPK + 5 t ha^{-1} mixture of three types of compost)	-	309.06	44.19	10.22
	+	336.40	47.28	12.18
	Mean	322.73d	45.74ab	11.20bc
T6 (50% NPK + 10 t ha^{-1} mixture of three types of compost)	-	317.02	45.69	11.47
	+	358.77	47.89	12.45
	Mean	337.90c	46.79a	11.96ab
T7 (mixture of three types of compost at 10 t ha^{-1})	-	342.54	43.29	10.43
	+	343.20	44.16	11.14
	Mean	342.87bc	43.73c	10.79bcd
T8 (mixture of three types of compost at 15 t ha^{-1})	-	343.15	44.22	10.25
	+	344.32	45.43	9.92
	Mean	343.74b	44.83bc	10.09cde
T9 (mixture of three types of compost at 20 t ha^{-1})	-	348.16	46.12	11.66
	+	373.02	49.14	13.82
	Mean	360.59a	47.63a	12.74a
Mean of seed inoculation	-	301.79b	40.22b	10.04a
	+	323.74a	42.69a	10.72a
LSD INM×seed inc.		8.24	1.12	1.57

Values followed by the same letter in the same column are not significantly different at $p \leq 0.05$ according Fisher's protected least significant difference test.

3.4. Impacts of Biofertilizer Treatments on Different Soil Properties

Biofertilizers are known to play an important role in sustaining soil fertility and condition, as well as crop production by mobilizing the available nutrients with their biological activities [5,22,89]. Additionally, Li et al. [50] and Ansari and Mahmood [90] reported that an integration of organic compost and biofertilizers is a widely recognized INM strategy to improve several soil physical, chemical, and biological proprieties. The microorganisms that are added to the soil by seed encapsulation have notable advantages for improving soil health and fertility through the promotion of biological nitrogen fixation, solubilization of insoluble phosphates, decomposition of organic matter, suppression of soil-borne pathogens, regulation of soil biological properties, and strengthening of the microbial community structure, as well as preservation of the soil microbiota balance in a continuous crop cultivation cycle [5,22]. The results of this study revealed that seed inoculation with biofertilizers significantly improved all the different tested soil properties, more than non-inoculation treatments. Regardless of the different fertilizer treatments, seed inoculation increased different soil proprieties by 2.8–12.0%, compared to that of the non-inoculation treatment (Tables 2–4). Seed inoculation showed a slight decrease in soil pH, compared with the non-inoculation treatment (Table 2). Importantly, the maximum improvement in different soil proprieties was recorded in soil that received a mixture of the three types of organic composts at different application rates (T7, T8, and T9) along with seed inoculation with biofertilizers.

The soil treated with the mixture of the three types of organic composts in conjunction with 50% NPK (T5 and T6) along with seed inoculation with biofertilizers also gained considerable improvement, but their levels were ranked after T7, T8, and T9 (Tables 2–4). These results indicate that INM practices through consortia of organic composts and chemical fertilizers in the presence of biofertilizers exhibited considerable improvement in several soil chemical, physical, and biological properties. A similar trend was also observed in previous studies [5,50,90–92].

3.5. Impacts of INM Treatments on Grain Yield of Different Crops

Several studies reported that the integration of chemical and organic fertilizers always resulted in a remarkable increase in crop yield or at least achieved comparable productivity to that of the sole application of the full recommended dose of chemical fertilizers [5,22,25,29,50]. This is because chemical fertilizers rapidly enhance crop growth in a short period by rapidly providing nutrients for plants, but lack balanced crop growth for long periods. On another note, organic fertilizers provide a good balance of nutrient supply for plant and soil in the long run and in the critical yield-forming period due to the slow release of nutrients and decreased nutrients loss from organic materials [5,25,29]. Together, they obtain the best results for plant growth and final crop yields. The results of the present study reveal that the integration of 50% of the recommended NPK dose for each crop and the mixture of the three organic composts (T5 and T6) or the integration of different types of organic composts at high application rates (T7, T8, and T9) resulted in a substantially increased final grain yield for the cereal crop (maize) and the leguminous crop (faba bean) over those treatments that received the full recommended NPK dose only (T1) or with one type of organic compost at low application rates (T2, T3, and T4) (Figure 2). For instance, the increase in grain yield of maize and faba bean for T5–T9 over T1 ranged from 11.1% to 15.6% and 27.2% to 32.2%, respectively (Figure 2). Due to the multiple positive effects of integrated organic and chemical fertilizers on physical, chemical, and biological soil properties as shown in Tables 2–4, such integrated treatments contribute to the stabilization of and increase in final crop yields. Such treatments have the potential to improve different soil water relations, and replenish SOM and essential micronutrients, which ultimately lead to ameliorated soil health and offering higher crop yields [90,93]. The Pearson's correlation coefficient matrix between the grain yield of the two crops and different soil properties reaffirmed this finding, and it was found that the grain yield of two crops showed highly positive significant correlations with the different tested soil properties (r = 0.68–0.94), with the exception of soil pH that showed negative significant correlations with the grain yield of the different crops (r ranged from −0.64 to −0.70) (Figure 1). These results indicate that any fertilizer treatment may have positive effects on different soil properties, leading to ameliorated soil health and offering higher crop yields. Therefore, integrating organic and chemical fertilizers or integrating different types of organic composts with a high application rate can be a good option for improving crop production, especially in arid regions with poor soil quality.

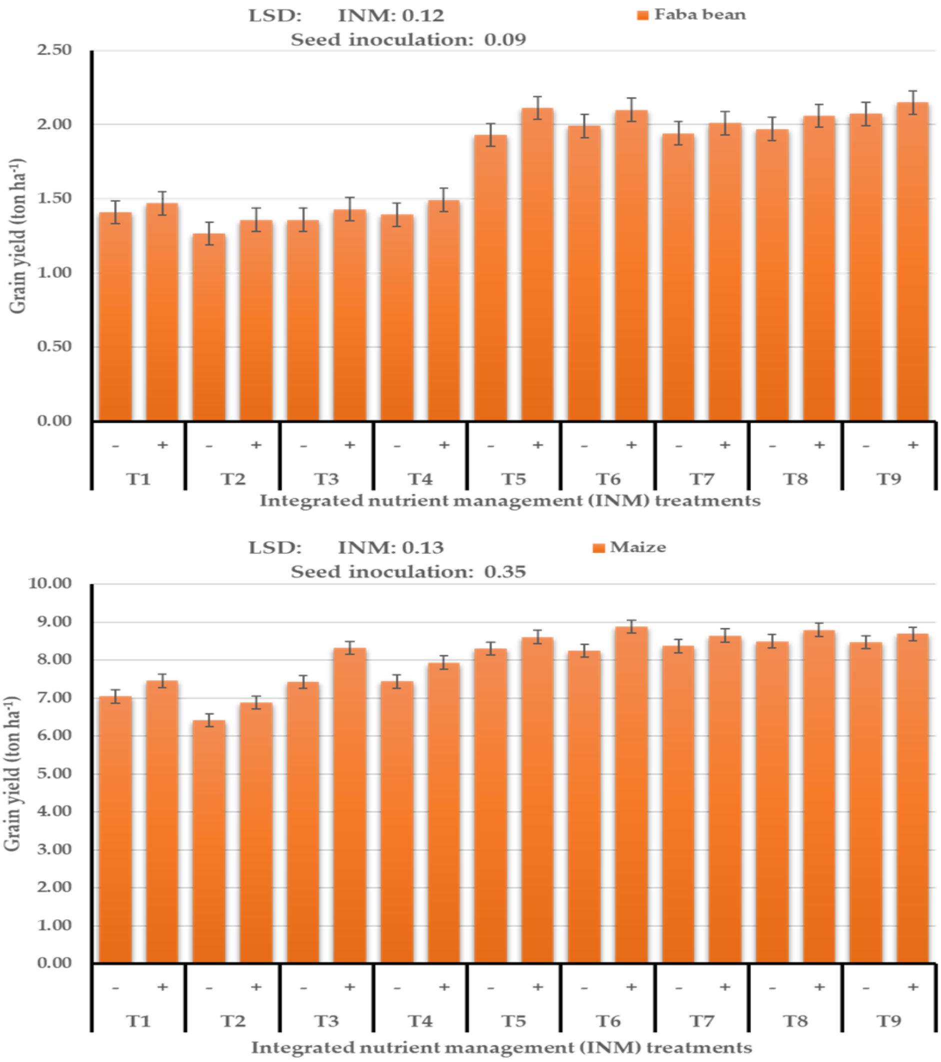

Figure 2. Effects of different integrated nutrient management (INM) on final grain yield of faba bean and maize. Vertical bars indicate standered error ($n = 8$). T1, T2, T3, T4, T5, T6, T7, T8, and T9 indicate the treatments of full recommended NPK, compost of cow manure at 5 t ha^{-1}, compost of poultry litter manure at 5 t ha^{-1}, compost of mixture of sheep and camel manure at 5 t ha^{-1}, 50% NPK + 5 t ha^{-1} mixture of three types of compost, 50% NPK + 10 t ha^{-1} mixture of three types of compost, mixture of three types of compost at 10 t ha^{-1}, mixture of three types of compost at 15 t ha^{-1}, and mixture of three types of compost at 20 t ha^{-1}, respectively. (+) and (−) indicate with and without seed inoculation, respectively.

3.6. Comprehensive Evaluation of the Relationship between INM Strategies and Soil Properties by Principal Component Analysis (PCA)

PCA was conducted for all the tested soil properties, INM strategies, and grain yield of both crops simultaneously (Figure 3). PCA distributed the different soil properties and INM treatments in several groups, with the first principle (PC1) and second principle (PC2) components explained 75.6% and 8.8% of the total variability between all parameters included in the PCA, respectively. Interestingly, SOC; TN; available N (AN), P_2O_5 (AP), K_2O (AK), and S (AS); MBN; and grain yield of maize were closely related to T5 and T6, wherein the both were treated with the integration of 50% of the recommended NPK dose and the mixture of the three organic composts, and leaned toward the positive region of PC1 and negative region of PC2, whereas SOM, different soil hydraulic properties (capillary, total porosity, hydraulic conductivity, WHC, and infiltration rate), MBC, MBP, and grain yield of faba bean were closely related to T7, T8, and T9, wherein all were treated with a mixture of different types of organic composts at high application rates, and situated along the positive region of PC1 and PC2. Along the negative regions of PC1 and positive region of PC2, T1 (full recommended NPK dose) and T2 (organic compost based on cow manure activator at 5 t ha^{-1}) appeared associated with soil pH and EC (Figure 3). These findings indicate that the scattering of different soil properties was largely associated with INM strategies. For instance, the different soil hydraulic properties and SOM were closely associated with soil receiving high application rates of the mixture of different organic composts alone (T7, T8, and T9), whereas the availability of different nutrients and SOC were more related to the soil receiving a combination of organic and inorganic fertilizers (T5 and T6). Several studies have reported that the different soil physical properties, especially those related to soil hydraulic properties, can be improved by incorporating sufficient amounts of organic manure, which help to reduce bulk density and surface crusting, and increase aggregate stability, porosity, and microbial activity [81,94,95]. Ozlu and Kumar [64] reported that soil receiving high application rates of organic manure increased the level of water-stable aggregates by 11% and 13%, compared with those receiving medium and high levels of chemical fertilizer, respectively. These findings may be due to the humic acid that is released from organic compost, which plays an integral role in improving soil physical properties by forming an adhesive film around soil particles, thereby promoting soil aggregation [96].

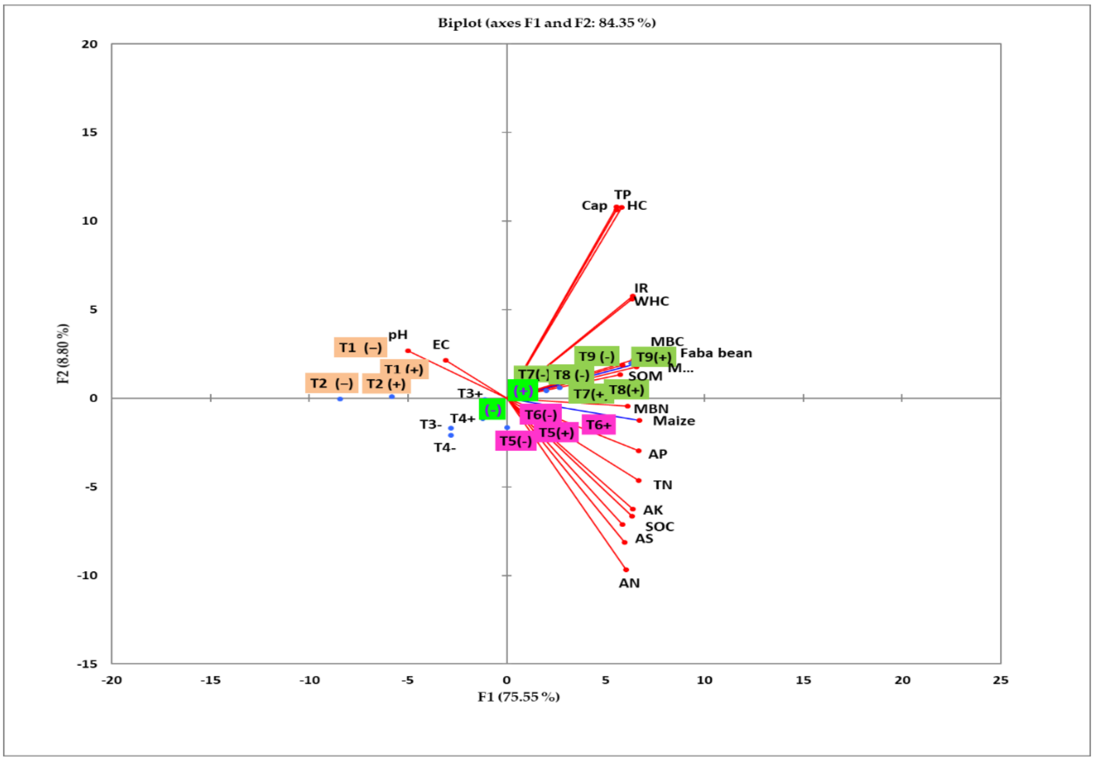

Figure 3. Biplot of the principle component analysis for the first two principle components of effects of different integrated nutrient management (INM) with (+) and without (−) seed inoculation on soil chemical (pH, EC, soil organic matter (SOM), soil organic carbon (SOC) total nitrogen (TN), available of N (AN), P (AP), K (AK), and S (AS), soil physical (capillary (Cap), total porosity (TP), hydraulic conductivity (HC), water-holding capacity (WHC), and infiltration rate (IR)) soil biological (soil microbial biomass carbon (MBC), nitrogen (MBN), and phosphorous (MBP)) properties, and grain yield of faba bean and maize. T1, T2, T3, T4, T5, T6, T7, T8, and T9 indicate the treatments of full recommended NPK, compost of cow manure at 5 t ha^{-1}, compost of poultry litter manure at 5 t ha^{-1}, compost of mixture of sheep and camel manure at 5 t ha^{-1}, 50% NPK + 5 t ha^{-1} mixture of three types of compost, 50% NPK + 10 t ha^{-1} mixture of three types of compost, mixture of three types of compost at 10 t ha^{-1}, mixture of three types of compost at 15 t ha^{-1}, and mixture of three types of compost at 20 t ha^{-1}, respectively.

The application of organic compost alone or in combination with 50% of the recommended NPK dose is also a promising INM strategy to preserve the soil microbial communities and activities, because the activity and abundance of soil microbial communities is very sensitive to high NPK application rates [28,35]. The PCA in this study reaffirmed this finding and found that the different soil microbial biomass (MBC, MBN, and MBP) were largely associated with T5 and T6 (MBN), and T7, T8, and T9 (MBC and MBP) (Figure 3). Furthermore, because the soil microbial communities and activities are indirectly influenced by different soil physicochemical properties on the one hand, and these soil properties are notably influenced by INM practices on the other hand, a highly positive correlation was also found between the different soil physicochemical properties and soil MBC, MBN, and MBP; that is, the Pearson's correlation coefficients (r) ranged from 0.62 to 0.90 (Figure 1). In this study, all treatments that received a mixture of different types of organic composts alone or in combination with the half-dose of NPK improved the selected soil physicochemical properties than the sole application of one type of organic compost and the full recommended NPK dose. These findings further explain why the soil microbial biomass (MBC, MBN, and MBP), as well as the selected soil physicochemical properties, are closely related to T5–T9.

The PCA also showed that soil pH and EC were grouped apart from the other soil chemical properties and were situated with T1 (full dose of NPK) and T2 (organic compost based on cow manure activator) along the negative regions of both principle components (Figure 3), indicating that the chemical fertilizer and the type of organic compost play an important role in controlling soil pH and EC. Additionally, since too much of both parameters can bring about negative effects on other important soil physicochemical properties and final grain yield, it may be a practicable measure to establish the proper range of both parameters through INM strategies. Many previous studies have demonstrated that chemical fertilizer application (NPK fertilizer) was more efficient in decreasing soil pH, compared with organic compost [64,97,98]. The efficiency of chemical fertilizers for decreasing soil pH can be explained by the fact that the N that was applied is converted to NH_4^+ first before being absorbed by the plants, then the plants release the H^+ ions into soil, which thereby decreases soil pH [99], whereas the ability of organic compost to decrease soil pH may be attributed to the formation of organic acids during the continuous decomposition of organic compost after being incorporated into soil. However, the efficiency of organic composts for decreasing soil pH depends on the type of organic manure. Similarly, Antil and Singh [66] reported that the reduction in soil pH was more pronounced with FYM application than those with pressmud and poultry manures. All of these explanations can further elucidate why soil pH is closely related to T1 and T2.

4. Conclusions

The successive two-year results of the field experiments provided valuable data for an agronomical evaluation of various INM practices for arid conditions based on different aspects of soil fertility and quality, as well as crop productivity. The results confirmed the agricultural value of incorporating organic compost in INM practices in improving several soil physiochemical and biological properties, and final crop yields. The results demonstrated that the integrated use of a mixture of different organic composts at high application rates (10–20 t ha^{-1}) either alone (T7–T9) or in combination with half of the recommended NPK and half the application rates of a mixture of different organic composts (T5–T6), are advisable INM practices that had considerable beneficial effects on soil fertility and crop yields. The increased soil fertility values for these treatments ranged from 21.7% to 72.0% and from 1.4% to 61.6%, compared with their initial value and with soil receiving the full recommended NPK dose (T1), respectively. The increase in crop yield for these treatments ranged from 11.1% to 32.2%, compared with T1. Additionally, the results of seed inoculation with biofertilizers revealed that, in general, seed inoculation improved all the different tested soil properties more than non-inoculation treatments. In conclusion, the incorporation of organic compost in INM practices can help not only in substituting chemical fertilizers totally or partially, but also in encouraging farmers to recycle different agricultural waste into a more sustainable, cost-beneficial, and environmentally friendly alternative product by composting.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4395/10/10/1503/s1, Figure S1: Layout of four replications of an experimental design that includes 9 integrated nutrient management (INM) treatments and two biofertilizers treatments (with (+) and without (−) seed inoculation), showing locations of INM and biofertilizers treatments. The all treatments were applied in the same place in two seasons (winter for faba bean and summer for maize) and in two years.

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