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Composting of Municipal Solid Waste Using Earthworms and Ligno-Cellulolytic Microbial Consortia for Reclamation of the Degraded Sodic Soils and Harnessing Their Productivity Potential

Yash Pal Singh *, Sanjay Arora *, Vinay K. Mishra and Arjun Singh

Regional Research Station, ICAR-Central Soil Salinity Research Institute, Lucknow 226002, India
* Correspondence: ypsingh.agro@gmail.com (Y.P.S.); sanjay.arora@icar.gov.in (S.A.); Tel.: +91-730-956-3010 (Y.P.S.)

Abstract: The management of municipal solid waste (MSW) and the reclamation of degraded sodic soils are two serious environmental and socio-economic problems experienced by the developing nations. To overcome these problems, a technology has been developed for the composting of MSW using earthworm and ligno-cellulolytic microbial consortia and its utilization for the sustainable reclamation of degraded sodic soils, as well as for harnessing their productivity potential. To standardize on-farm composting under aerobic conditions, the field experiment consisted of seven treatment combinations, replicated thrice with municipal solid waste (MSW) sole and in combination with agricultural wastes (AW) treated with earthworms (*Eisenia foetida*) and consortia of lingo-cellulolytic microbes such as *Aspergillus* spp., *Trichoderma* spp. and *Bacillus* spp. It was conducted at ICAR-CSSRI, Research farm, Shivri, Lucknow, India. The results revealed that the thermophilic phase was achieved at 60 days of composting and thereafter the temperature decreased. Marked changes in pH and EC were found and they changed from acidic to neutral. The reduction in total C, from initial to maturity, varied from 4.45 to 14.14% and the increase in total P and total K from 4.88 to 88.10% and 12.00 to 35.71%, respectively. The nutrient-rich quality compost based on the lowest C: N ratio, highest nutrient contents, microbial population (bacteria and fungi) and enzymatic activities was obtained from a mix of MSW and AW, enriched with earthworms and consortia of lingo-cellulolytic microbes. The efficacy of this enriched compost was evaluated for the reclamation of sodic soils and their potential for sustaining productivity of the rice-wheat cropping system was harnessed through combined application with a reduced dose of gypsum. The results indicated that the application of on-farm compost @10 t ha^{-1} in conjunction with a reduced quantity of gypsum (25% GR) significantly ($p < 0.05$) improved the physico-chemical and microbial soil properties, and enhanced productivity of the rice-wheat cropping system over the use of only gypsum. This study proved that on-farm compost of MSW and its utilization for the reclamation of degraded sodic soils can be an alternate solution for useful disposal and management of MSW, thereby improving the health and productivity of sodic soils.

Keywords: agriculture wastes; bio-physical changes; crop yield; municipal solid waste; on-farm composting; soil amelioration; sodic soil

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1. Introduction

Municipal solid waste (MSW) is a byproduct of industrial, mining, municipal, agricultural and other processes, and it poses disposal and management challenges globally. As per the available data, about 1300 million Mg of the MSW is annually generated globally and it is estimated to increase to about 2200 million Mg per year by 2025 [1]. A substantial increase in per capita waste generation rates, from 1.2 to 1.42 kg^{-1} day^{-1}, will also be registered in the upcoming fifteen years [1]. According to the reports of the central pollution control board (CPCB) 2012, India produces about 12.74 million Mg of MSW per day [2]. With the increase in populations in cities and the changing lifestyle, more MSW will be generated which will end up in landfills and the aquatic ecosystem, causing gradual deterioration of soil health and climate as well. One of the upcoming eco-friendly solutions for the utilization of MSW waste is to recycle the decomposable organic component into a useful manure and apply it to improve soil health. The composting of MSW can be viewed as the common practice of recycling the organic degradable fraction of the municipal solid wastes. The generated compost can help in alleviating organic matter deficiency in soils vis-à-vis reducing the use of chemical fertilizers in crops. The municipal solid waste compost (MSWC), rich in organic matters with a low concentration of xenobiotic pollutants, is proposed as a low-cost soil recovery option for improving the physical, chemical and microbial properties of soil [3]. Being a rich source of mineralized nutrients, MSWC also contributes toward the improvement in crop productivity [4]. During the biodegradation of MSW, it is ultimately converted to humus rich substances with an increase in mineral content also [5]. The microbes and their concealed enzymes play an imperative role in biological and biochemical changes in the compost during the composting process [6]. The microbial enzymes produced during the composting of MSW proficiently degrade large organic molecules viz. cellulose, hemicellulose, lignin etc., into simple water-soluble compounds [7]. The dynamics of the composting process, including the decomposition of organic matter, its stability and maturity, can be modelled using microbial communities and enzyme activity. This could produce useful data on the compost's quality and rate of biodegradation [8–10].

The salinity affects over 6% of the world's land area (FAO, 2008), which accounts for over 800 million hectares in nearly 100 countries. Sodic/solonetz constitute 581 million hectares [11], out of the total salt affected soils. In India, of the total geographical area (328 million ha), about 2.1% (6.73 million hectares) is salt affected land. Out of this land, 2.8 million ha are sodic and primarily occur in the Indo-Gangetic alluvial plains and the remaining 3.9 million ha are saline soil [12]. Gypsum ($CaSO_4.2H_2O$) is the major chemical ameliorant that is used for reclaiming the sodic soils in India. However, due to low hydraulic conductivity brought on by dispersion, the reclamation of sodic soil with this ameliorant fails to enhance the physical and biological characteristics of sodic soils [13]. Many studies on composting have focused on physio-chemical parameters of the compost to choose the quality of compost [14]. However, microbiological and biochemical parameters are also important indicators for the characterization of the composting process [5,15]. Turning MSW and agricultural wastes to an on-farm compost is an attractive proposition [16], but the farmers lack the techniques and knowledge to make the best use of the composting opportunities. This is because they are not aware of the on-farm composting technology. The present study was, therefore, conducted to standardize an on-farm composting protocol for MSW, along with the agricultural wastes mediated through earthworms and ligno-cellulolytic microbial consortia. The study aims to ascertain the efficacy of enriched compost, with a reduced dose of mineral gypsum, as an inorganic amendment for the amelioration of degraded sodic soils and to harness the productivity potential of degraded sodic soils.

2. Materials and Methods

2.1. Experimental Plan for On-Farm Composting

A three times replicated experiment for on-farm composting of MSW was conducted with seven treatments viz. T_1: 100% MSW; T_2: 100% MSW + microbial consortia; T_3: 50% MSW + 50% agricultural wastes + microbial consortia; T_4: 100% MSW + earthworms; T_5: 50% MSW + 50% agricultural waste + earthworms; T_6: 100% MSW + earthworms (*Eisenia foetida*) + microbial consortia; and T_7: 50% MSW + 50% agricultural waste + earthworms + microbial consortia under aerobic conditions at the Research Farm, Shivri, of ICAR-Central Soil Salinity Research Institute, Regional Research Station, Lucknow (260 47′ N; 800 46′ E), India, during 2014-15. Municipal solid wastes (MSW) were collected from 11 different locations in the Lucknow metro city and were segregated for degradable material, while agricultural wastes (AW) including paddy straw, mustard straw, *Pongamia* and *Casuarina* dry leaves were mixed in the ratio of 1:1 *w/w* and were filled in 360 × 120 × 120 cm HDPE vermi beds. Each bed was filled with a uniform quantity of composting material (Figure 1). Before initiating the composting process, chemical properties of all the composting materials were analyzed (Table 1). Microbial consortia of three efficient ligno-cellulolytic cultures such as *Aspergillus terreus*, *Trichoderma harzianum* and *Bacillus cereus* were used for rapid composting. The consortia were mixed in 10 L of water and 1.0 kg of earthworms (*Eisenia foetida*) were added to the respective treatment beds and watered uniformly (5 L) at 4-day intervals to maintain the moisture in each bed. For proper aeration, at 15-day intervals, the turnings of composting material were performed manually until the maturity of the compost.

Figure 1. Layout of composting experiment.

Table 1. Initial properties of municipal solid waste and agricultural wastes used for on-farm composting.

Properties	Municipal Solid Waste	Agricultural Wastes			
		Pongamia Leaves	Casuarina Leaves	Mustard Straw	Paddy Straw
pH (1:5)	6.97	-	-	-	-
Total Nitrogen (%)	0.52 ± 0.01	2.20 ± 0.11	1.70 ± 0.06	0.56 ± 0.05	0.54 ± 0.04
Total Phosphorus (%)	0.05 ± 0.02	0.15 ± 0.01	0.18 ± 0.02	0.36 ± 0.02	0.17 ± 0.03
Total Potassium (%)	0.28 ± 0.10	0.63 ± 0.12	0.42 ± 0.11	0.64 ± 0.12	0.39 ± 0.14
Total Calcium (%)	0.36 ± 0.12	0.46 ± 0.03	0.51 ± 0.02	0.12 ± 0.02	0.09 ± 0.03
Total Magnesium (%)	0.10 ± 0.02	0.32 ± 0.02	0.30 ± 0.01	0.05 ± 0.01	0.10 ± 0.02
Total Sulphate (%)	0.11 ± 0.01	0.27 ± 0.02	0.42 ± 0.12	0.17 ± 0.02	0.23 ± 0.14
Total Carbon (%)	28.35 ± 0.22	42.06 ± 0.16	53.88 ± 0.52	52.49 ± 0.43	39.65 ± 0.21
C:N ratio	54.51 ± 1.12	19.11 ± 0.52	31.69 ± 0.23	93.73 ± 0.22	73.42 ± 0.32
Bacterial population (Cfu g^{-1})	39 × 10^5	nd	nd	nd	nd
Fungal population (Cfu g^{-1})	18 × 10^5	nd	nd	nd	nd

C: N ratio = carbon: nitrogen ratio; nd = not determined.

2.2. Sampling and Analysis of Composting Material

The samples of MSW and agricultural wastes (mustard stover, paddy straw, *Pongamia* leaves and *Casuarina* leaves) were collected, oven dried at 60 ± 2 °C, ground by a hammer mill, stored in dry airtight containers and analyzed before use for composting (Table 1). The samples were acid digested for analyzing total nitrogen (N) content by the Micro-kjeldahl distillation method and total phosphorus (P) content by the yellow color method by using ammonium molybdate-Meta vandate [17]. The organic carbon content was determined by the chromic acid wet oxidation method [18], and total carbon by the loss on ignition method by placing the sample in muffle furnace at 550 °C. Total Potassium (K), calcium (Ca) and magnesium (Mg) contents were estimated in the diacid digestion extract using the standard protocol. Sulphate content in the diacid extract was estimated by the turbidity method.

2.3. Changes Monitored during Composting

2.3.1. Changes in the Physical Properties

To measure the fluctuations in the temperature, metal probe thermometers of 60 cm [19] were injected up to 30 cm depth at three places in each treatment bed, and the temperature was recorded daily at 11:00AM and reported at an interval of 15 days. For the analysis of moisture content during composting, samples were collected from 30 cm depth from three places in each bed at and at an interval of 15 days. These were mixed together to make a composite sample for gravimetric analysis.

2.3.2. Changes in the Chemical Properties

For the analysis of chemical properties, samples were collected from 30 cm depth at three places in each treatment bed at an interval of 15 days and were mixed together to make a composite sample. The sample was then oven dried (60–70 °C), and ground using a mortar and pestle. The ground samples were then stored in dry, airtight containers for further analytical use. The pH of the sample was determined by taking 5.0 g compost mixed with 25 mL distilled water (1:5 *w*/*v*) and the mixture was stirred for 30 min. The pH and electrical conductivity (EC) were measured in the solution mixture using calibrated digital pH (Systronics µ pH system 661) and conductivity-TDS meter, respectively [20]. Total carbon content in the sample was assessed by the wet oxidation-rapid titration method [18] and the total N content was estimated in acid digestion by the Micro-kjeldahl distillation apparatus. Total P and total K were analyzed using standard methods described in the initial properties of composting material section.

2.3.3. Changes in Microbial Properties

To analyze the quantitative changes in the microbial population during the composting process, bacteria and fungi were enumerated from the compost samples using differential media following the procedure described by Nakasaki et al. 1992 [21]. Nutrient agar (NA) media for bacterial population, Pikovskayàs agar media for phosphate solubilizing microbes and potato dextrose agar (PDA) media for fungal population were used. All microbial counts were estimated on a dry weight basis. A serial dilution technique was employed to estimate the microbial population in the compost samples. The dilution level of 10^{-3} and 10^{-4} of each sample was prepared following the spread plate technique. The average numbers of microorganisms were expressed as colony forming units (CFU) per gram of dry compost. The viable colonies of bacteria and fungi were counted using a digital colony counter after incubation in the BOD incubator [22,23].

2.3.4. Changes in Enzymatic Activities

The 10 g fresh compost sample was collected in a flask containing 50 mL acetate buffer (0.1 M, pH 5.0) and shaken at 150 rpm on a rotatory shaker for 1 h to analyze the enzymatic activities of related enzymes using aqueous compost extracts. The flask content was filtered and then the 10 mL filtrate was centrifuged at 40 °C for 15 min at 5000 rpm. Afterwards, enzymatic activities were measured using supernatant. The α-amylase and xylanase activities were measured as per the procedure described by Shambe and Ejembi (1987) [24].

2.4. Assessing Efficacy of On-Farm Compost for Sodic Soil Reclamation and Crop Productivity

To assess the efficacy of the MSW compost in ameliorating degraded sodic soils and sustaining crop yields, a pot experiment was conducted with three replications imposing the four treatments viz. T_1: Gypsum (G) @ 50% gypsum requirement (GR); T_2: G @ 25% GR + MSW compost (MSWC) @10 Mg ha^{-1}; T_3: G @ 25% GR + industrial processed MSW compost (IPMSWC) @10 Mg ha^{-1}; T_4: G @ 25 % GR + pressmud (PM) @10 Mg ha^{-1} was conducted for three years (2014-15 to 2016-17). To fill the pots, highly sodic soil (pH$_2$ 9.8, EC$_2$ 147 µSm^{-1}, ESP 78, OC 1.3 g kg^{-1}) collected from the research farm Shivri (26° 47′ N; 80° 46′ E) was air dried, ground to pass through a 2 mm sieve, mixed thoroughly for homogeneity and used to analyze physico-chemical properties. A uniform quantity of soil

(8 kg pot^{-1}) was placed in each pot, having a surface area of 0.035 m^2. The Schoonover (1952) method was used to estimate the gypsum requirement (GR) of the sodic soil [25]. Prior to the calculation of the amount of gypsum to be added in the pots as per the treatments, the chemical composition of mineral gypsum was analyzed. The gypsum quantity was calculated on the basis of soil volume and applied in the pots as per treatment, mixed in the soil to the depth of 15 cm and ponded with water for 10 days to displace the Ca-Na reaction product down to the root zone. The industrial processed municipal solid waste compost (IPMSWC) was collected from a nearby municipal solid waste treatment plant and press mud (11%Ca and 0.23% S) was a byproduct of sugar industry from nearby sugar mill. For proper leaching of the salts beyond the root zone, as per the protocol, organic amendments such as MSWC, IPMSWC and PM were applied after completion of the leaching process @10 Mg ha^{-1} and were mixed uniformly in the surface soil (0–15 cm) manually. These amendments were added once only over the study period. The three 30-day-old rice seedlings of salt tolerant variety 'CSR 36′ were transplanted in each pot on July 15 every year. After the harvesting of rice, five seeds of the salt tolerant variety of wheat 'KRL 210′ were sown in each pot on November 23. The recommended doses of chemical fertilizers for rice and wheat were applied uniformly in each treatment through urea, DAP (diammonium phosphate), MOP (muriate of potash) and zinc sulphate monohydrate, following the standard time and methods of application. Other intercultural agronomic operations, such as irrigation and weeding etc., were followed uniformly as per the requirements in all the treatments. All the observations associated with yield contributing characters and crop yield were recorded at maturity. After three years of growing rice-wheat crops, soil samples from 0–15 cm depths were collected from three places in each pot, mixed together to make a composite sample, air dried, ground to pass through a 2 mm sieve and used to analyze soil physico-chemical and microbial properties following the standard procedures.

2.5. Statistical Analysis

The analysis of variance (ANOVA) statistical tool was used to compare the variances across the mean values of each observation from the different samples. For the treatments in which significant differences were observed, individual means were tested using the least significant difference (LSD) test at 5% probability [26]. The pooled yield data generated from the study were analyzed statistically using SPSS software version 21.

3. Results and Discussion

3.1. Physico-Chemical Properties of Composting Material

The analyzed data presented in Table 1 reveal that the MSW was near neutral in reaction, with a pH value of 6.97, total nitrogen content of 0.52%, total carbon content of 28.35%, and C: N ratio of 54.51 ± 1.12. The farm wastes such as *Pongamia* and *Casuarina* leaves, mustard stover and paddy straw had average total N and total carbon contents of 1.25 ± 0.06 and 47.02 ± 0.33%, respectively, with an average C: N ratio of 37.61 ± 0.32 (Table 1). Total P and K in MSW were found to be 0.5 ± 0.02 g kg^{-1} and 2.8 ± 0.10 g kg^{-1}, respectively; whereas, the corresponding values in agricultural wastes were 2.2 ± 0.2 and 5.2 ± 1.2 g kg^{-1}, respectively. The total calcium, magnesium and sulphate contents were found to be 3.6, 1.0 and 1.1 g kg^{-1} in MSW, while being 3.0, 1.9 and 2.7 g kg^{-1} in agricultural wastes.

3.2. Bio-Physical Changes during Composting

3.2.1. Temperature

During composting, there is an increase in temperature as well as carbon dioxide evaluation due to the metabolic actions of microbes and their secreted enzymes [27]. The series of changes that occur during composting are generally characterized in terms of biophysical, chemical, as well as microbial properties [28,29]. Measuring the changes in temperature is one of the important parameters to assess the composting process, and its value determines the speed at which the biological process during composting takes place [30,31]. In our study, changes in temperature under different treatments throughout the composting period ranged between 31.0 and 58.4 °C, being directly governed by the evolution of CO_2 due to microbial activities during composting [32]. Microbes involved in the MSW decomposition process increase the temperature, which is also known as thermophilic phase during composting, and at this stage most of the degradation of recalcitrant organic matter takes place. Statistically, the difference between these treatments was non-significant. This may be attributed to the higher initial activity of microorganisms using organic matter as a substrate from the raw composting materials, and composting environment for microbial and enzymatic activities. The reduction in temperature after 60DOC may be due to declining microbial and enzymatic activities because of the metabolization of most of the organic matter. The same outcome was also recognized during the composting of municipal solid waste by earlier workers [33,34].

3.2.2. Moisture Content

For the metabolic and physiological activities of micro-organisms, moisture content of the composting material is a chief environmental variable as it necessarily provides a medium for the transportation of the dissolved nutrients [35,36]. From the data (Figure 2B), it is evident that the moisture content in all the composting treatments was variable throughout the duration of experimentation. Direct correlations have been established between the microbial population [33] and the physiological activities of micro-organisms [37] on the compost's moisture content. The moisture content during the composting period varied from 19.4% to 67.5%. It was higher at the initial stage of composting and reduced with increasing time. This may be due to the effect of reduced atmospheric temperature and increasing evaporation rate [38]. The highest moisture content (67.5%) was recorded in treatment T_7, whereas the lowest was in T_1 at 15 DOC. However, after 30 days onward, the moisture content between the treatments did not show any stable trend in all the treatments. However, at maturity, the moisture content in all the treatments was reduced significantly over the initial values (Figure 2B).

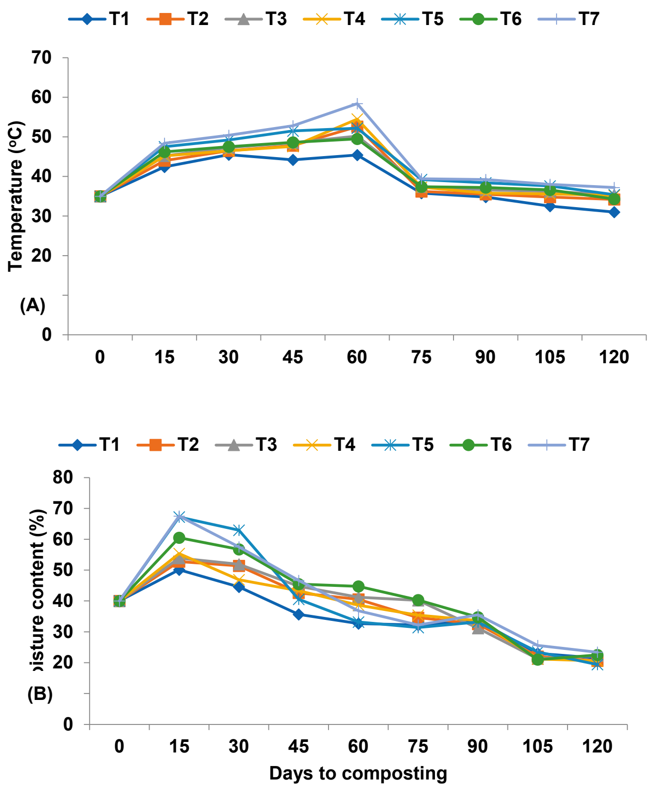

Figure 2. Changes in (**A**) temperature and (**B**) moisture content during composting under different treatments.

3.2.3. Changes in Chemical Properties

Changes in pH values during the composting process are shown in Figure 3A. The initial pH of composting material was 6.97; it increased gradually up to 60DOC and reached the maximum level of 8.52 in treatment T_3. After 60 DOC, the pH started decreasing gradually up to maturity (120DOC) and reduced to the level of 7.32 (Figure 3A). The greatest reduction in pH was observed in treatment T_4, but the differences between the treatments were statistically non-significant. From these data it is evident that the pH at the initial stage was near neutrality, it decreased and thereafter increased with time towards alkalinity, and returned to neutrality at the end of composting (120DAC). The reason behind the increasing pH after 15DOC was the evolution of free ammonia and dropping again due to formation of humus, along with its pH buffering capacity at the completion of the composting process [39–41]. The pH range that is best for composting is 6.0 to 8.0 because microorganisms flourish and are most active in this range. In comparison with recommended standard pH values, ours were found to be higher than the normal range. The possible reason being that during the degradation process, a decrease in pH can be associated with the production of CO_2 from organic acid and loss of nitrogen [36,42].

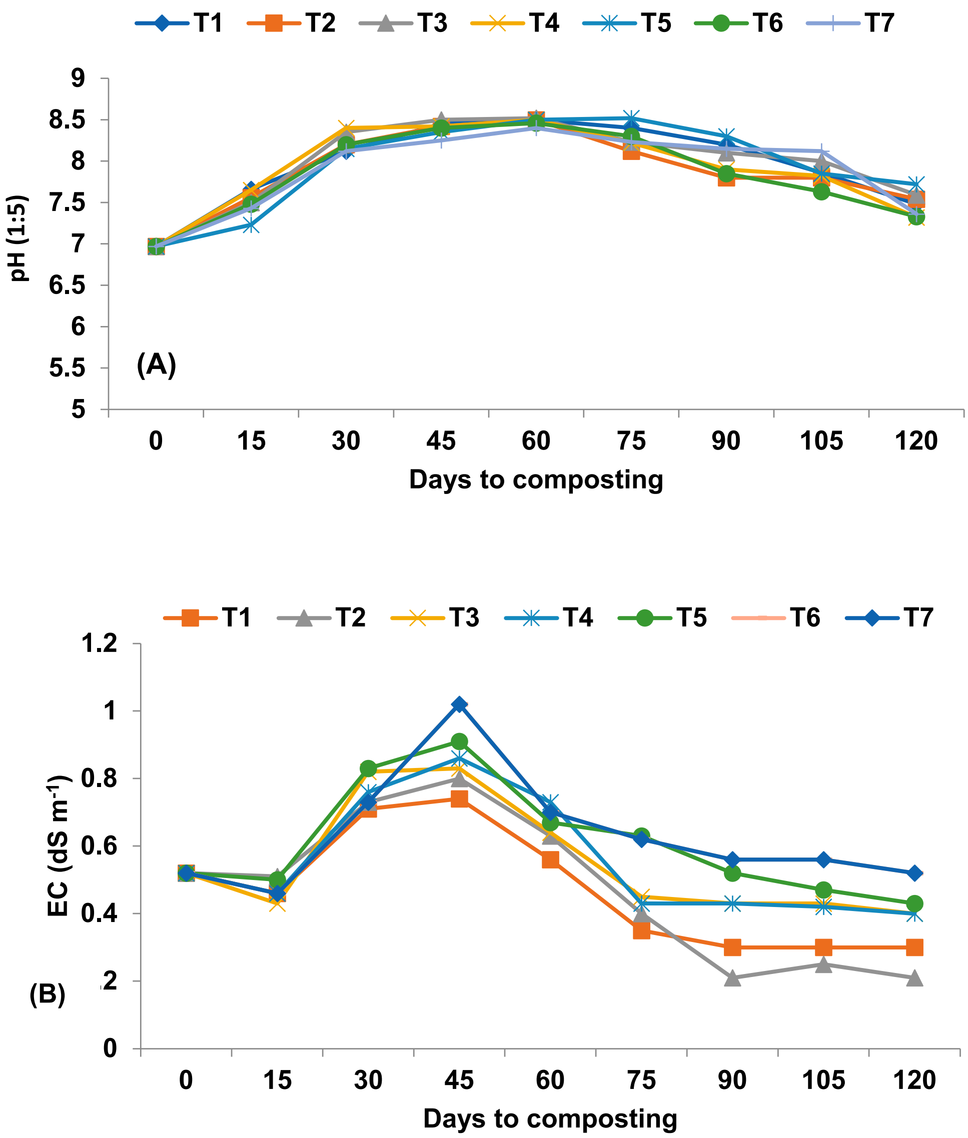

Figure 3. Changes in (**A**) pH and (**B**) electrical conductivity (EC) during composting under different treatments.

The electrical conductivity (EC) is also one of the important factors to define the quality of compost, as its utilization can alter the chemical state of soils and seed germination with the presence of high salt concentration in compost [43]. There was a decrease in EC during the initial stage of composting and then it started increasing gradually up to 45 DOC and again showed a decreasing trend up to the final stage of composting (120DOC) (Figure 3B). During composting, the decline in EC may be the result of increased stability of the bridging bonds of ions and organic matter [37].

3.2.4. Changes in Nutrient Contents

The results obtained showed that the total carbon content at the initial stage ranges from 11.35% to 14.60%. The maximum total carbon content at 15DOC was found in treatment T_7; whereas, it was lowest in T_4, and it decreased gradually to maturity or on completion of composting. The maximum total carbon content was recorded (13.69%) in treatment T_5 and minimum (11.14%) in T_1. The breakdown and the conversion of complex organic compounds releases simpler water-soluble compounds with the evolution of CO_2; the released degraded organic matter is assimilated by microorganisms as well [44–46]. At the beginning, the highest total N was found in treatment T_3 (0.50%) and T_5 (0.50%), followed by the treatments T_2, T_4, T_6, T_7 and T_1 with 0.47, 0.46, 0.43, 0.42 and 0.40 per cent, respectively. At compost maturity (120DOC), the highest and lowest total N (0.79%) contents were estimated in treatment T_7 and the lowest (0.43%) in T_1. The increase in nitrogen content during composting is attributed to the action of nitrogen mineralizing enzymes, nitrogen transformation processes and a decrease in the loss of NH_3 [47]. The highest total P (0.33%) at the initial stage of composting was recorded in the treatment T_2, followed by T_5, T_7, T_3, T_4, T_6 and T_1, with the levels of 0.31, 0.31, 0.26, 0.26, 0.25 and 0.21%, respectively, at the start of composting. An increasing trend was seen in all the treatments, with the values ranging between 0.39 and 0.41%. Potassium is an essential nutrient for plants, and it gets immobilized in the presence of un-decomposed organic matter. The present study revealed that at the initial stage of composting, the highest K content (0.61%) was recorded with treatment T_7, followed by T_5, T_6, T_4, T_2, T_3 and T_1. It increased gradually with time and the highest total K content at maturity was recorded in treatment T_5 (0.76%) and the lowest (0.56%) in T_2 (Table 2). During decomposition of the organic matter, especially sugars, a lot of organic acids and CO_2 are released in the environment. Since potassium tends to get adsorbed in the soil matrix, the solubilizing action of the acids formed during the composting liberates the bound K and increases the ionic potassium in the compost [31,37,48,49]. Calcium is a vital nutrient and is required by organisms and plant cells to maintain their structure. The major sources of calcium in composting material are vegetables, food, animal wastes, organic wastes, etc. The calcium content between the treatments after 15 days of composting (15DOC) ranged from 100 to 190 ppm and at maturity (120DOC), there was a two times increase in its levels (210 to 270 ppm) (Table 2). An increase in calcium content at maturity of composting over the initial values has also been reported [37]. Sodium and Mg contents also increased in matured compost compared to initial levels in all composting treatments (Table 2). The release of adsorbed ions on the decomposition of organic materials and also the contribution from the native content in the raw waste on degradation have been known mechanisms.

The carbon to nitrogen (C:N) ratio is an important determinant of the state of mineralization for evaluating the nutritive value of the compost and whether it has been stabilized scrupulously [50–52]. With the decreasing total carbon (C) with increasing time elapsed vis-à-vis increasing total nitrogen (N) content, total phosphorus (P) content and total potassium (K) content during decomposition of MSW, and the C:N, C:P and C:K ratios also decreased (Figure 4). The C: N ratio in our study was higher (32:1) at the initial stage of composting in all the treatments and it decreased gradually with time. This is because mineralized N becomes part of the overall N pool of the matrix, whereas some part of the C is utilized by microbes and also released as CO_2 in the disintegration of organic matter. These data show that the lowest C:N ratio of 22.35:1 at 15DOC was recorded in the treatment T_2

and it remained the lowest up to 45 DOC (Figure 4A). It decreased subsequently as the C content of the composting material declined and N content increased with time. The indirect role of nitrogen fixing bacteria is also highlighted in the decreasing C:N ratio due to more available nitrogen content from added organic matter [9,53]. It is also reported by several workers that the C:N ratio below 20 is acceptable for the maturity of composting material and is reliable for use in crops. These data show that the C:P and C:K ratios also narrowed with time (Figure 4B,C). The highest decrease in these parameters was observed in treatments where the combined use of MSW and AW was treated with either earthworm or decomposing microbes.

Table 2. Changes in nutrient contents during on-farm composting.

Treatments	Stages	Total N (%)	Total P (%)	Total K (%)	Na (ppm)	Ca (ppm)	Mg (ppm)
T_1	Initial	0.41	0.21	0.49	12.14	130	63.5
	120DOC *	0.43	0.41	0.56	26.46	250	134.0
T_2	Initial	0.47	0.33	0.50	14.66	190	55.5
	120DOC	0.51	0.40	0.56	27.98	270	68.0
T_3	Initial	0.50	0.26	0.50	17.12	140	36.1
	120DOC	0.58	0.40	0.58	23.83	250	56.0
T_4	Initial	0.46	0.26	0.53	14.38	100	35.2
	120DOC	0.51	0.41	0.65	30.22	210	65.0
T_5	Initial	0.50	0.31	0.56	12.54	100	45.0
	120DOC	0.56	0.40	0.76	35.77	230	70.0
T_6	Initial	0.43	0.25	0.54	21.04	140	40.0
	120DOC	0.65	0.40	0.67	28.15	240	54.0
T_7	Initial	0.42	0.31	0.61	26.07	150	32.5
	120DOC	0.79	0.39	0.74	30.29	260	58.2

* Maturity; T_1: 100% MSW; T_2: 100% MSW + microbes; T_3: 50% MSW + 50% agricultural wastes + microbes; T_4: 100% MSW + earth worms; T_5: 50% MSW + 50% agricultural waste + earth worms; T_6: 100% MSW +earth worms + microbes; T_7: 50% MSW + 50% agricultural waste + earth worms + microbes; DOC: days of composting.

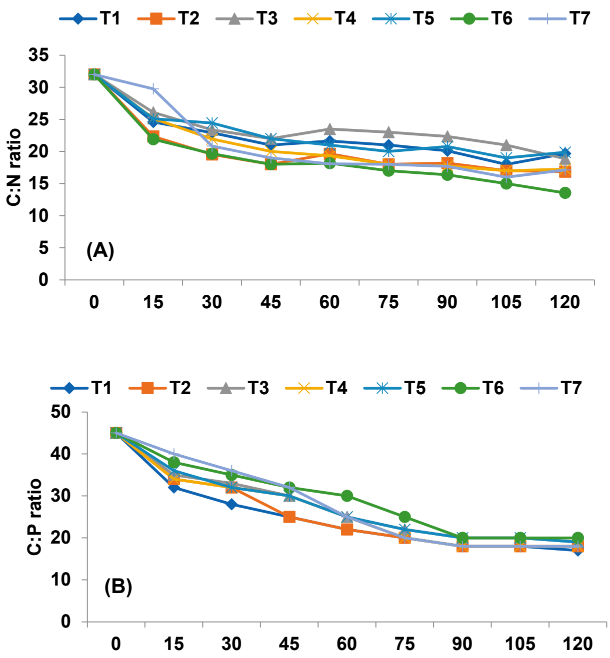

Figure 4. *Cont.*

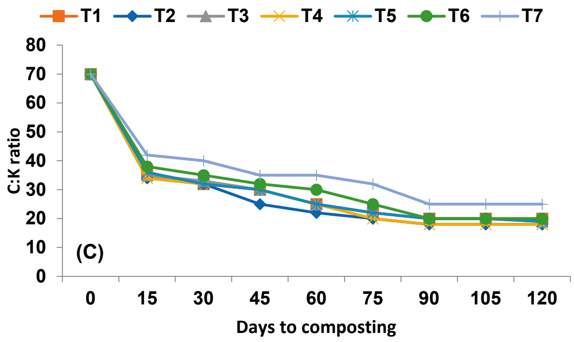

Figure 4. Changes in (**A**) C:N (**B**) C:P and (**C**) C:K ratios during the composting under different treatments.

3.2.5. Changes in Microbial Properties

The primary biological agents responsible for the breakdown of municipal solid waste are microorganisms [54]. The metabolic action of the microbes on organic matter results in the production of CO_2, water, energy and other organics as byproducts [32]. Shifts in microbial loads were observed during the initial and final stages of on-farm MSW compost (Table 3). A decreasing trend of the bacterial and fungal loads from initial stage (15 DOC) to maturity (120DOC) in all the treatments was observed [55]. The decreasing trend in microbial population with composting age has also been reported [32]. The highest bacterial and fungal populations at initial and maturity stages were recorded in treatment T_7 where MSW and AW were mixed together and enriched with earthworm and ligno-cellulolytic microbial consortia. Whereas, the lowest bacterial (26×10^5) and fungal (18×10^5) populations at maturity were recorded in treatments T_1 and T_6, respectively (Table 3). The earthworm gut harbors potential microbial groups which mediate rapid biodegradation of recalcitrant organic matter [56]. The use of composting inoculant also enhances the rate of decomposition of agro-residues; the efficient microorganism consortia consisting of lingo-cellulolytic microorganisms, lactic acid bacteria and a phototrophic-bacteria has been used for ex situ decomposition of paddy straw [57].

Table 3. Changes in microbial properties during on-farm composting.

Treatments	Initial		at Maturity	
	Bacterial Population ($\times 10^5$ Cfu g^{-1})	Fungal Population ($\times 10^5$ Cfu g^{-1})	Bacterial Population ($\times 10^5$ Cfu g^{-1})	Fungal Population ($\times 10^5$ Cfu g^{-1})
T_1	48	45	26	33
T_2	54	60	44	26
T_3	79	60	56	36
T_4	73	42	60	28
T_5	69	52	54	23
T_6	79	41	68	18
T_7	98	79	75	48

T_1: 100% MSW; T_2: 100% MSW + microbes; T_3: 50% MSW + 50% agricultural wastes + microbes; T_4: 100% MSW + earth worms; T_5: 50% MSW + 50% agricultural waste + earth worms; T_6: 100% MSW +earth worms + microbes; T_7: 50% MSW + 50% agricultural waste + earth worms + microbes.

3.2.6. Changes in Enzymatic Activities

Monitoring the changes in enzymatic activities during composting provides useful information on the dynamics of C and N for understanding the transformations taking place during composting [5]. The enzymes produced through the metabolization of insoluble particles of the organic matter through microbes controlled the degradation rates of different substrates which were the main intermediaries of the degradation process [58]. In our study, two important enzymes α-amylase and Xylanase, which are responsible for hydrolysis of starch and hemicellulose, respectively, were monitored. The results obtained in our study revealed that the enzymatic activities were higher under treatment T_7 followed by T_6, where MSW and AW were mixed in equal quantities and enriched with earthworm and earthworm + ligno-cellulolytic microbial consortia (Figure 5). This could be attributed to the dual action of earthworm and microbial consortia on the degradation of organic matter [57,59]. In our study, the maximum α-amylase activity (2.8 μmol mL^{-1} min^{-1}) at 15DOC was recorded with treatment T_7 and it decreased significantly at 120DOC. The higher enzymatic activity at the initial stage may be due to high starch content in the degradable composting material. The highest enzymatic activities at the initial stage and the lowest at the maturity of composting have been reported [60]. The xylanase activities in all the treatments at the initial stage range from 0.6–0.8 μmol mL^{-1} min^{-1} and they decreased to the level of 0.4 μmol mL^{-1} min^{-1} at maturity. The maximum reduction in this parameter was recorded in treatments T_6 and T_7 (Figure 5).

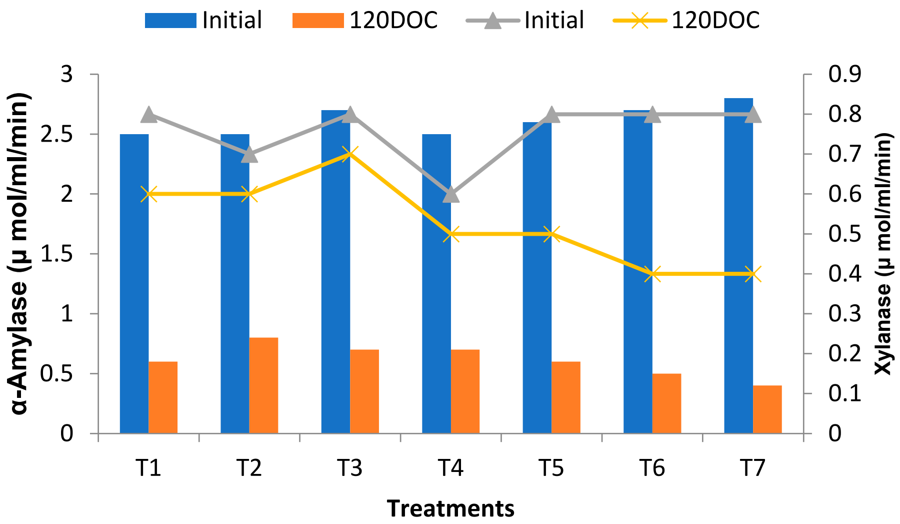

Figure 5. Changes in enzymatic activity during composting under different treatments.

3.3. *Qualiy of On-Farm Compost*

After 120DOC and analysis of physico-chemical and microbial properties, the best quality on-farm compost was obtained from treatment T_7 and the same was compared with industrial processed MSW compost (IPMSWC) produced in the same city. The C:N ratio of on-farm compost was narrower as compared to IPMSW compost (Table 4). The on-farm MSW compost was also found to be richer in nutrient contents such as total N, P, K and carbon, as compared to industrial processed MSW compost. The bacterial and fungal populations in on-farm compost were 104 and 75% higher than the IPMSW. Our results are in conformity with the findings of earlier researchers [61].

Table 4. Comparative evaluation of quality parameters of on-farm and industrial processed municipal solid waste composts.

Quality Parameters	On-Farm Compost	Industrial Processed Compost
Bulk density (g cm^{-3})	0.89	0.78
pH (1:5)	7.36	7.48
EC (1:5) (dS m^{-1})	0.66	0.68
Total N (%)	0.79	0.43
Total P (%)	0.39	0.41
Total K (%)	0.74	0.57
Total C (%)	13.54	11.14
C:N ratio	17.13	25.89
Bacterial population (Cfu g^{-1})	98×10^5	48×10^5
Fungal population (Cfu g^{-1})	79×10^5	45×10^5

C: N ratio = carbon: nitrogen ratio.

3.4. Utilization of On-Farm Compost for Amelioration of Sodic Soils

After three years of cropping under a rice-wheat cropping system, a significant ($p < 0.05$) reduction in soil bulk density was observed. The highest reduction (11.87%) in bulk density was recorded in treatment T_2 (Gypsum @ 25% GR + OFMSWC @10 Mg ha^{-1}) followed by T_3 (Gypsum @ 25%GR + IPMSWC @10 Mg ha^{-1}) (8.13%), T_4 (Gypsum @ 25% GR + PM @10 Mg ha^{-1}) (8.10%) and the lowest was in T_1 (Gypsum @ 50% GR). In comparison to applying only inorganic amendments, it has been found that the addition of organic amendments considerably lowered soil bulk density [62,63]. A similar trend was observed in infiltration rate and soil porosity. A significant increase in infiltration rate was observed with all the treatments. The increase in infiltration rate was significantly higher ($p < 0.05$) in treatment T_2 (719.5%) as compared to treatments T_1, T_3 and T_4. Similarly, a significant increase in porosity was recorded in treatment T_2 (62.07%) followed by T_3 (53.84%), T_4 (49.05%) and T_1 (23.34%) over the initial value. The organic amendment improvement acts as an accelerant for increasing soil microbial activities, and improvement in plant biomass and soil physical parameters are also improved by an increase in macropores [64]. An increase in the infiltration rate and porosity of sodic soils as a result of the addition of organic amendments, which improved pore geometry and transmission pores, has been observed [65]. After three years of the study, a significant reduction in soil pH was observed over the initial value in all the imposed treatments. This reduction in pH was significantly higher ($p < 0.05$) in treatment T_2 (9.79%) as compared to rest of the treatments. This may be due to the release of H^+ through the production of organic acids during decomposition of organic amendments [66,67]. The application of OFMSWC caused a significant reduction in soil EC over the initial values. Although the difference between the treatments for EC was statistically non-significant, the maximum reduction in EC was observed in treatment T_2 (Table 5). These data also reveal that the maximum decrease in exchangeable sodium percentage (ESP) (64.10%) was recorded in treatment T_2 and the lowest in T_1 where only inorganic amendment was used. Moreover, ESP was decreased by 61.5, 58.97 and 53.84% with the application of gypsum (T_1), gypsum + IPMSWC (T_3) and gypsum + PM (T_4). This is attributed to the gradual rise in soil organic carbon content, and thereby organic acids in soil, which lower the redox potential and promote the substitution of Na^+ with Ca^{++} in sodic soil [68–73].

The application of OFMSWC along with the reduced dose of gypsum (25% GR) resulted in a significant improvement in soil organic carbon (SOC) content of the sodic soil (Table 5). The maximum increase in organic carbon over the initial value was observed in treatment T_2 (161.53%) and the minimum (100%) in T_4. Improvement in soil physical properties and rhizospheric environment under amended conditions leads to more root biomass, thereby improving the SOC content of the soil [74]. A similar trend was also observed in available N, P and K contents in soil. The highest improvements in available N, P and K status over the initial value were recorded in treatment T_2 which were 132.63, 97.60 and 40.0% higher over the initial N, P and K status in the soil. The composted materials act as reservoirs of mineralized N and organic acids which solubilize the insoluble or sparingly soluble compounds and thus augment the availability of N, P, and K in soil [58,75]. A significant reduction in Na^+, K^+, CO^{3-} and HCO^{3-} contents was recorded in the treatment where OFMSWC was combined with reduced dose of gypsum (T_2), over the IPMSWC (T_3) and PM (T_4). Moreover, the K^+ content with application of IPMSWC increased over the initial and control treatments. This is because of the reduction in adverse soil properties associated, in sodic soils, with the addition of organic matter from OFMSWC in conjunction with gypsum [76]. The maximum bacterial (11×10^7 cfu g^{-1}) and fungal (9.0×10^5 cfu g^{-1}) loads after three years of sodic soil amelioration and cultivation of the rice-wheat cropping system were enumerated in treatment T_2, whereas, the minimum were with control (T_1). This is on account of improved soil microbial activity resulting from the substantial availability of substrate with the combined application of organic and inorganic amendments, compared to only application of inorganic amendments [77,78].

Table 5. Effect of different treatments on physico-chemical and microbial properties of sodic soil after three years of study.

Treatments	Initial	T_1	T_2	T_3	T_4	$LSD_{0.05}$
Bulk density ($g\ cm^{-3}$)	1.60	1.57 (−1.87)	1.41 (−11.87)	1.48 (−8.10)	1.48 (−8.10)	0.03
Infiltration rate ($mm\ day^{-1}$)	2.1	11.15 (+431)	17.21 (+719.5)	15.65 (+645.2)	15.42 (+634.3)	1.32
Porosity (%)	42.4	52.30 (+23.34)	68.72 (+62.07)	65.23 (+53.84)	63.204 (+49.05)	3.12
pH_2	9.8	9.15 (−6.63)	8.84 (−9.79)	8.99 (−8.26)	9.29 (−5.20)	0.26
EC_2 ($\mu S\ m^{-1}$)	147.0	46.00 (−68.70)	45.00 (−69.38)	56.00 (−61.90)	52.00 (−64.62)	ns
Exchangeable Sodium percentage (ESP)	78	32.00 (−58.97)	28.00 (−64.10)	30 (−61.5)	36.00 (−53.84)	2.31
Soil Organic C ($g\ kg^{-1}$)	1.30	3.10 (+138.46)	3.40 (+161.53)	3.00 (+130.76)	2.60 (+100.00)	0.30
Available N ($mg\ kg^{-1}$)	30.7	65.33 (+112.80)	71.42 (+132.63)	67.24 (+119.02)	67.19 (+118.85)	3.12
Available P ($mg\ kg^{-1}$)	8.3	11.2 (+34.93)	16.4 (+61.44)	14.3 (+72.28)	13.5 (+62.65)	0.83
Available K ($mg\ kg^{-1}$)	173.0	201.4 (+16.41)	242.2 (+40.0)	181.53 (+4.93)	183.2 (+5.89)	6.32
Na^+ (ppm)	342.0	283.75 (−17.03)	229.81 (−32.80)	288.66 (−15.60)	279.56 (−18.25)	23.20
K^+ (ppm)	3.1	3.14 (+1.29)	2.44 (−21.29)	4.37 (+40.96)	2.45 (−20.96)	ns
CO_3^- ($me\ L^{-1}$)	6.0	2.33 (−61.20)	2.33 (−61.20)	0.00 (−100.00)	2.66 (−55.66)	0.24
HCO_3^- ($me\ L^{-1}$)	22.0	1.50 (−93.18)	1.50 (−93.18)	1.33 (−93.95)	1.66 (−92.45)	1.12
Bacterial population ($Cfu\ g^{-1}$)	1.3×10^6	5×10^7	11×10^7	8×10^7	7×10^7	-
Fungal population ($Cfu\ g^{-1}$)	0.2×10^5	4×10^5	8×10^5	9×10^5	3×10^5	-

T_1: Gypsum (G) @ 50% gypsum requirement (GR); T_2: G @ 25% GR + on-farm MSW compost (OFMSWC) @10 Mg ha^{-1}; T_3: G @ 25% GR + industrial processed MSW compost (IPMSWC) @10 Mg ha^{-1}; T_4: G @ 25 % GR + pressmud (PM) @10 Mg ha^{-1}.

3.5. Efficacy of On-Farm Composts on Crop Yield

A significantly higher grain yield of rice (4.71 Mg ha^{-1}) was recorded under treatment T_2 over the other treatments viz. T_1, T_3 and T_4. Application of OFMSWC (T_2) enhanced rice grain yield by 7.53%, 20.46% and 2.83% over control (T_1), IPMSWC (T_3) and PM (T_4) (Figure 6). Similarly, the wheat grain yield with OFMSWC (2.62 Mg ha^{-1}) was 12.9%, 83.21%, and 31.65% higher over T_1, T_3, and T_4, respectively. The enhancement in rice and wheat yield with the combined use of OFMSWC and inorganic amendments is because of an improvement in soil fertility status and build-up of soil C and N content. A significant relationship between the grain yield and soil organic carbon content has been earlier reported [79]. The addition of OFMSWC also induces humus content and available N, P and K, improving the fertility status of soil, resulting in significant increase in grain yield [80,81]. On the basis of the ameliorative potential of MSW compost, on-farm MSW compost could be promoted as an alternate source of organic amendment to reclaim sodic soils and sustain crop productivity.

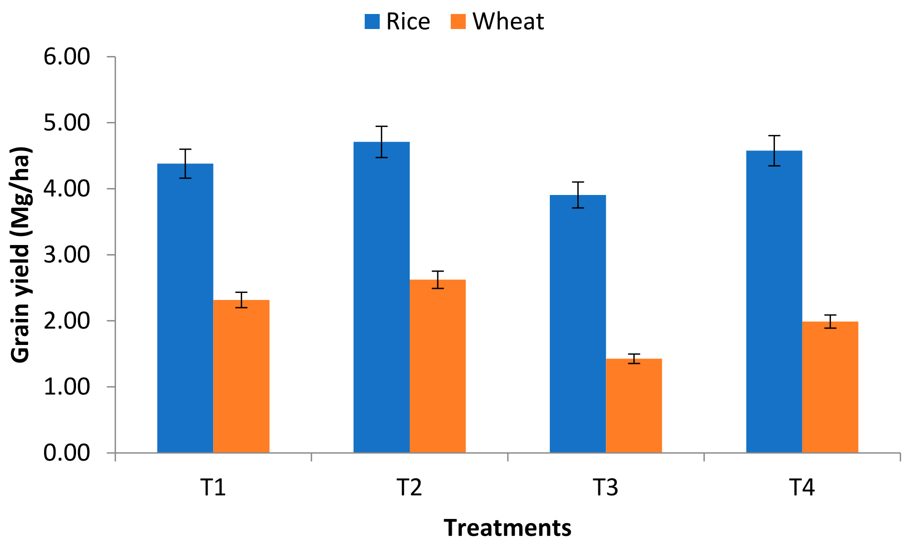

Figure 6. Effect of on-farm composts on grain yield of rice and wheat.

4. Conclusions

It can be concluded from the study that on-farm composting with the combined use of municipal solid wastes and agricultural wastes, in 1:1 *w/w* ratio enriched with earth worms (*Eisenia foetida*) and ligno-cellulolytic microbial consortia, provided a favorable environment for microorganisms and their enzymatic activities, aiding in higher degradation of organic matter. Changes in the microbial population and enzymatic activities enhance decomposing efficiency in terms of narrowing C:N, C:P and C:K ratios. Thus, on-farm composting of MSW and agricultural wastes could be a suitable technology to produce nutrient-rich quality compost. The application of on-farm MSW compost along with the reduced dose of gypsum in sodic soil improved the soil physico-chemical and biological properties by increasing infiltration rate, soil porosity, soil organic carbon, available essential plant nutrients and microbial populations. The sodic soils also registered decreased bulk density, soil pH, EC, ESP, CO_3 and HCO_3. Hence, the addition of on-farm MSW compost ameliorated sodic soils and improved soil health as well as crop productivity. Adoption of this approach may provide a pragmatic solution for the utilization of MSW and agricultural wastes for the sustainable reclamation of sodic soils.

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