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Synergizing Microbial Enriched Municipal Solid Waste Compost and Mineral Gypsum for Optimizing Rice-Wheat Productivity in Sodic Soils

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Abstract: Municipal solid waste management and poor fertility status of sodic soils are two important issues experienced by all developing nations including India. Disposal of municipal solid waste (MSW) being produced in huge amounts is a challenging task for researchers and policy makers. Reclamation of salt affected soils with chemical amendments is a costly affair for resource-poor farmers. Composting of MSW and its enrichment with microbes is one of the options for its recycling and utilization for the reclamation of salt-affected soils. A field experiment was conducted in sodic soil to study the performance of microbial enriched municipal solid waste compost (EMSWC) alone and in combination with a reduced dose of gypsum on growth, yield, nutrient uptake, and grain quality of rice and wheat. The experiment was conducted for three consecutive years from 2018 to 2019 and 2020 to 2021 at ICAR Central Soil Salinity Research Institute, Research farm, Shivri, Lucknow, India, in sodic soil having pH 9.2, electrical conductivity (EC) 1.14 dSm^{-1}, exchangeable sodium percentage (ESP) 48, and organic carbon 0.30%. There were six treatments consisting of control, recommended dose of gypsum (50% GR), and enriched and un-enriched MSW compost with reduced dose of gypsum (25% GR). Based on the results pertaining to plant growth, yield-attributing characters, and yields, the treatment T_6 (application of microbial enriched MSW compost @ 10 t ha^{-1} in conjunction with gypsum @25% GR) performed the best. Grain yield of rice and wheat (5.45 and 3.92 t ha^{-1}) with treatment T_6 was 29.45% and 110.75% higher over control (T_1) and 29.45% and 110.06% over the recommended dose of gypsum (T_2). Maximum nutrient content and N, P, and K uptake in rice-wheat grain and straw was observed with the treatment T_6 (MSW compost plus gypsum @ 25 GR). However, the highest Na content and Na: K ratio in plant parts were recorded in treatment T_2. The highest positive net return and benefit to cost (B/C) ratio were observed in treatment T_6 followed by T_5 and the lowest in treatment T_1 (control), whereas negative return was calculated in treatment of gypsum alone (T_2). This shows that the cost of sodic soil reclamation with application of gypsum was not recovered until the second year of cultivation. The results of this study showed significant impacts in MSW management for regaining the productivity potential of sodic soils.

Keywords: enriched MSW compost; mineral gypsum; municipal solid waste; growth and yield; nutrient uptake; grain quality; rice and wheat; sodic soil

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1. Introduction

Salt-induced soil degradation is a global concern because it frequently results in the dramatic decline of agricultural production in arid and semi-arid regions [1]. It is estimated that about one billion ha of the world's soil is affected by some degree of salinization and sodification problems [2] and it is projected that by the end of 2050 more than 50% of arable land will be salt affected. On one side, cultivated land around the world is expected to decrease due to increasing salinity and sodicity and on the other side, the population is increasing. By 2050, the world population will reach 9.1 billion, more than 34% of the present population. To meet the food requirement of increasing population, about 70% more food production will be required. Thus, there is a need to develop cost-effective technology for harnessing production potential of salt-affected soils.

In salt-affected soils, plant growth and nutrient availability is subdued due to low osmotic potential of soil solution, toxicity, and imbalance of ions [3]. In such soils, the salt load also reduces soil microbial activities as well as microbial biomass [4,5]. Of the 329 million ha geographical area of India, 6.73 million ha is salt-affected soil [6] having excess amounts of soluble salts, which gravely affect crop growth and yield. Out of the total salt-affected soils, 2.8 million ha is sodic land suffering from low hydraulic conductivity caused by dispersion. Part of this sodic land has been reclaimed with a chemical amelioration approach using gypsum ($CaSO_4 \cdot 2H_2O$) with 50% of the gypsum requirement of the soil. However, this approach fails to improve the physical and biological properties of sodic soils [7]. Application of organic amendments, such as farm yard manure (FYM) and pressmud (by product from sugar mills) in combination with reduced dose of mineral gypsum, i.e., 25% GR + 10 t ha^{-1} FYM/pressmud/municipal solid waste (MSW) compost was found equally effective in improving soil physical, chemical, and biological properties without any significant loss in grain yield, besides its role as a fertilizer but, their availability in such a large quantity is a major concern [8–12].

As per the global estimates, the municipal solid waste (MSW) is generated in a quantity of about 1.3 billion tons per year and is becoming a grave problem for dumping. It is expected that by the year 2025, MSW may reach about 2.2 billion tons per year [13]. About 12.74 million tons of MSW per day is produced in India [14] and the Government of India has initiated integrated municipal solid waste-management projects and established MSW treatment plants in almost every metropolitan city for producing compost from the MSW. Several strategies have been applied for efficient utilization of MSW compost but very few studies have been conducted to find its efficacy for sustainable reclamation of salt-affected soils. From the studies, it has been observed that the municipal solid waste (MSW) compost application helps in improving the soil, physical, bio-chemical, and microbiological properties of sodic soil because of high organic matter content and low concentration of inorganic and organic pollutants present in the compost, thereby providing low-cost soil recovery solution [9,15]. Furthermore, MSW compost is found to be a good source of nutrients that help in improving fertility of soil and may thereby contribute in restoring the productivity of salt-affected soils [9–12,16]. Halophilic plant growth-promoting microbes are known to have potential in bio-remediation of salt-affected soils by alleviating salt stress and enhancing availability of nutrients for plant growth and yield [17–19]. To enhance the efficacy of compost further, the present study was undertaken with the hypothesis that the enrichment of the municipal solid waste compost with halophilic plant growth promoting microbes can fasten the bio-reclamation process vis-à-vis enhancing productivity of rice-wheat cropping systems in sodic soils.

2. Materials and Methods

2.1. Enrichment of MSW Compost

Marketable municipal solid waste compost for this study was obtained from a company that has established an MSW treatment plant. This company is producing and marketing MSW compost from the solid waste collected from Lucknow city, India. This compost was enriched with halophilic plant growth-promoting microbial consortium consisting of *Azotobacter*, Phosphobacteria, and zinc-solubilizing bacterial strains to upgrade the nutritive value of this industrial compost. Both enriched and un-enriched composts were analyzed for physico-chemical and microbial properties. The chemical composition of the enriched and un-enriched compost material is presented in Table 1.

Table 1. Bio-chemical composition of enriched and un-enriched MSW composts.

Parameters	Concentration	
	Un-Enriched MSW Compost ± SD	Enriched MSW Compost ± SD
Bulk density (Mg m^{-3})	0.78 ± 0.01	0.89 ± 0.01
Moisture (%)	9.23 ± 0.21	11.12 ± 0.16
pH_w (1:5)	7.60 ± 0.24	7.86± 0.32
EC_w (dS m^{-1})	0.64 ± 0.26	1.22 ± 0.24
CEC [cmol (p$^+$) kg^{-1} compost]	186 ± 8.0	183 ± 11.0
Total C (%)	25.47 ± 0.32	20.38 ± 0.26
Total N (%)	0.64 ± 0.06	0.79 ± 0.04
C:N ratio	39.80 ± 0.40	25.79 ± 0.35
Total P (%)	0.41 ± 0.04	0.71 ± 0.04
Total K (%)	0.57 ± 0.02	0.84 ± 0.04
Total Ca (mg kg^{-1})	340.00 ± 26.2	406.00 ± 21.3
Total Mg (mg kg^{-1})	195.00 ± 26.5	228.00 ± 23.5
Total Zn (mg kg^{-1})	1620.00 ± 45.6	2115.00 ± 51.2
Bacterial population (cfu g^{-1} × 10^5)	48 ± 4.0	75 ± 6.0
Fungal population (cfu g^{-1} × 10^5)	45 ± 5.0	79 ± 4.0
Phosphate solubilizing microbes (cfu g^{-1} × 10^5)	9.0 ± 3.0	53 ± 5.0
Total Ni (mg kg^{-1})	49.12 ± 2.3	42.6 ± 4.1
Total Pb (mg kg^{-1})	29.30 ± 4.0	24.3 ± 5.0
Total Cd (mg kg^{-1})	7.30 ± 0.23	5.12 ± 0.11
Total Cr (mg kg^{-1})	45.50 ± 1.2	40.23 ± 1.3

2.2. Site Characterization

2.2.1. Climatic Features

The study site has a semi-arid, subtropical, and monsoonal climate receiving an average annual rainfall of 817 mm. Maximum rainfall received between standard weeks 23 and 40 (June–October) in 2014 amounts to 394 mm, which accounts for 91% of the total annual rainfall. The remaining 9% rainfall is received during 41–19 standard weeks (November–May). The mean annual evaporation is 1580 mm and the evaporation rate varies with increasing air temperature, and atmospheric water demands steadily increase from weeks 1–22 (January–June). In the rainy season, generally between weeks 23–40 (June–October), the evaporation rate gradually decreases following rains. Thereafter, up to 52 weeks (December), there is a gradual decrease in evaporation due to low temperature. The water surplus is generally during the period from weeks 23 to 40 (June–October). There is a water deficit period between weeks 1–22 and 41–52 because of low rainfall and higher evaporation rates. On an average, the mean maximum temperature of 39 °C is noted in the month of May and the mean minimum temperatures of 7.1 °C in the month of January, indicating a seasonal climate. During the study period, the mean annual temperature was recorded as 24.6 °C (Figure 1).

2.2.2. Soil Characteristics

Initial soil samples were collected from 0–15 cm soil depth before initiation of the experiment. The soil samples were air-dried and ground in a mortar and pestle to pass through a 2.0 mm sieve. Soil physical properties including sand, silt, and clay content were determined using the International Pipette Method [20], bulk density was determined through intact cores [21] extracted with a core sampler of 10 cm in diameter and 15 cm length, and the infiltration rate was measured using double concentric infiltrometer cylinders with 60 cm outer and 30 cm inner diameters. The porosity was calculated from the bulk density (BD) and particle density (PD) as $(1 - bD/pD) \times 100$ [22]. The cation exchange capacity of soil was determined by ammonium acetate–sodium acetate substitution method [22]. The soil pH and EC were determined in 1:2 soil:water suspension through digital pH and conductivity meters, respectively. The calculation for exchangeable sodium percentage

(ESP) was performed as exchangeable sodium concentration (cmol·kg^{-1})/cation exchange capacity (cmol·kg^{-1}) × 100. Soil organic carbon content was determined by the rapid titration method [23]. Available N content was determined by steam distillation of soil with $KMnO_4$ and NaOH [24], while available P content by the Olsen sodium bicarbonate extraction method [25] and available K content by the sodium acetate extraction [26]. The concentrations of Na^+ and K^+ in the soil saturation extract were measured by Flame Photometer, and the concentrations of cations viz. Ca^{2+} and Mg^{2+} in the soil extract were estimated by the Versenate titration method [27] using EDTA. Anions, carbonate (CO_3^-), and bi-carbonate (HCO_3^-) contents in the soil extract were determined by titration with 0.01 N H_2SO_4 using phenolphthalein and methyl orange indicators. Gypsum ($CaSO_4{\cdot}2H_2O$) requirement (GR) of the soil from the experimental field was determined through a modified Schoonover (1952) method [28]. Bacterial and fungal population in fresh soil samples were enumerated using the standard serial dilution plate-count method on nutrient agar, potato dextrose agar, and actinomycetes-specific media [29] (Dubey and Maheshwari 2002). The physico-chemical and biological properties of the initial soil from experimental field are presented in Table 2.

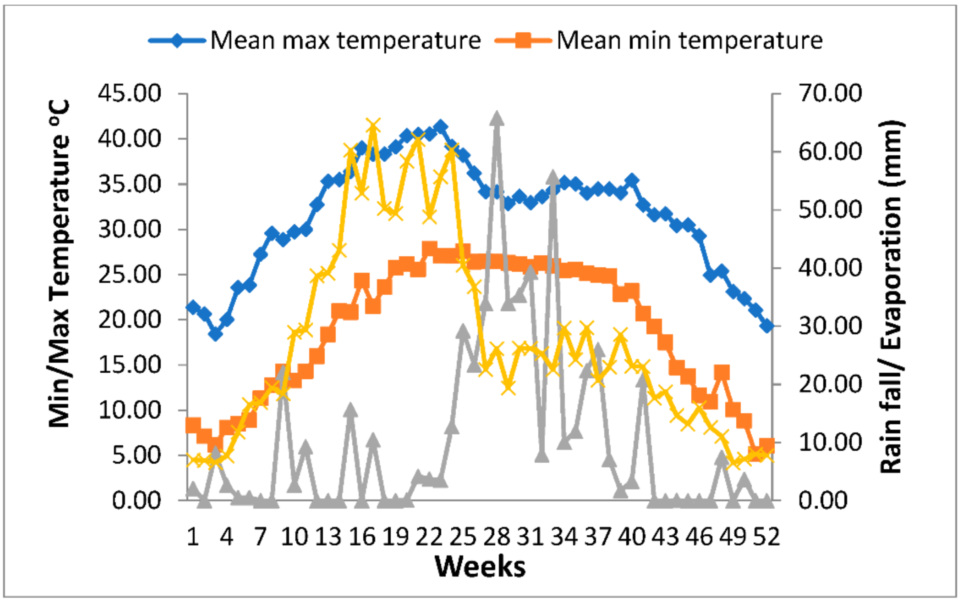

Figure 1. Climatic features of the experimental site.

Table 2. Initial soil (0–15 cm) properties of the experimental field soil.

Soil Properties	Values	Soil Properties	Values
Sand (%)	65.55	Available P (kg ha^{-1})	16.5
Silt (%)	18.5	Available K (kg ha^{-1})	238
Clay (%)	16	Ca (mel^{-1})	2.2
Textural class	Loam	Mg (mel^{-1})	2.4
Bulk density (Mg m^{-3})	1.57	Na (mel^{-1})	60.34
Porosity (%)	46.4	K (mel^{-1})	2.29
Infiltration rate (mm day^{-1})	2.1	CO_3 (mel^{-1})	3.1
pH_2	9.2	HCO_3 (mel^{-1})	1.8
EC_2 (dSm^{-1})	1.14	Cl (mel^{-1})	4.8
ESP	48	GR (t ha^{-1})	10
OC (%)	0.3	Bacterial count (Cfu g^{-1})	1.3×10^6
Available N (kg ha^{-1})	142.5	Fungal count (Cfu g^{-1})	0.2×10^5

2.2.3. Irrigation Water Quality

The irrigation water quality was examined employing the standard methods ascribed by APHA (1998) and Singh et al. (2007) [30,31]. The irrigation water drawn from a tubewell that was applied to the experimental crops was having low electrolyte concentration and EC ranging between 0.57 and 0.68 dSm^{-1} and moderately alkaline in reaction. Among cations, Na^+ dominated over Ca^{2+} and Mg^+ followed by K^+. To assess the irrigation water quality, bicarbonates plus carbonates dominated over chloride, while sulphates were absent in irrigation water with residual alkalinity to the extent of 1.3 to 1.5 $meql^{-1}$, which categorize it as safe for irrigation (Table 3).

Table 3. Quality of irrigation water applied to the crop.

Quality Parameters	Tube Well No. 1	Tube Well No. 2
EC (dSm^{-1})	0.68	0.57
pH	7.56	8.08
CO_3 (mel^{-1})	1.20	1.20
HCO_3 (mel^{-1})	4.00	3.20
Cl^- (mel^{-1})	2.10	1.50
SO_4 (mel^{-1})	0.00	0.00
Ca^{2+} Mg (mel^{-1})	3.70	3.10
Na^+ (mel^{-1})	4.10	3.70
K^+ (mel^{-1})	0.12	0.12
RSC	1.50	1.30
SAR	3.00	2.90

RSC: residual sodium carbonate, SAR: sodium adsorption ratio.

2.2.4. Experimental Design and Treatment Details

Before calculating the amount of gypsum to be applied as per treatment, the mineral gypsum used was analyzed for its chemical composition. The gypsum ($CaSO_4{\cdot}2H_2O$) had 18.3% Ca and 16.1% SO_4. The calculated quantity of gypsum in different treatment plots was broadcasted in the month of June and mixed with power tiller in the surface soil up to 10–12 cm depth (Figure 2). Heavy irrigation and ponding of about 10 cm water for at least 8–10 days was carried out to displace the reaction product of Ca–Na exchange down to the root zone. After appropriate leaching of salts, organic amendments such as un-enriched MSW compost and enriched MSW compost were applied at 10 t ha^{-1} as per the treatment and mixed in the surface soil up to 15 cm depth (Figure 2).

The field experiment comprised of six treatments, viz. T_1-Control (No amendments), T_2-Gypsum @50% GR, T_3-Un-enriched MSW compost at 10 t ha^{-1}, T_4-Enriched MSW compost at 10 t ha^{-1}, T_5-Gypsum @25%, GR + un-enriched MSW compost at 10 t ha^{-1}, T_6-Gypsum @25%, GR + Enriched MSW compost at 10 t ha^{-1} and was conducted during 2018–19 to 2020–21 and replicated four times in a Randomized block design (RBD) having plot area of 90 m^2.

The seedlings of the salt-tolerant variety of rice 'CSR 36′ grown in normal soil was transplanted at 30 days after sowing in 20 × 15 cm row-to-row and plant-to-plant spacing in the month of July and harvested in November. Recommended dose of nutrients (150 kg N: 60 kg P_2O_5: 40 kg K_2O: 25 kg $ZnSO_4$ ha^{-1}) through chemical fertilizers: urea, diammonium phosphate (DAP), muriate of potash (MOP), and zinc sulphate (heptahydrate) were applied uniformly in all the treatments. Basal application of half dose of N and full dose of P, K, and zinc sulphate were applied uniformly in all the treatment plots. The remaining half quantity of N was applied in two equal splits at 30 days after transplanting and at panicle initiation stage. Other agronomic practices were followed as and when required. The grains were harvested from each net plot area and were dried to weigh at 14% moisture content and the yield was expressed in t ha^{-1}. Straw was sun dried from each plot and straw yield was expressed in t ha^{-1}. Plant samples collected from tagged plants were chopped into pieces, dried, and ground into fine powder in a Willy mill and used for chemical analysis.

Total nitrogen content in grain and straw was analyzed in acid digest of sample following the micro-Kjeldhal method [32]. Phosphorus was determined in di-acid digested extract of samples through calorimetric method [22] and K through flame photometric method [22]. The experimental field was irrigated from a bore tube well situated about 100 m away from the experimental field. The quality of irrigation water is given in Table 3.

Figure 2. Layout plan and imposition of treatments in the experimental field.

2.2.5. Statistical Analysis

The data collected from the experiment were statistically analyzed using MSTAT-C version 2.1. The least significant difference (LSD) test at 5% significance level probability was used to test the significance ($p < 0.05$) of treatment effects [33]. The data are presented as average values of four replications ± standard error.

3. Results and Discussion

3.1. Effect of Enriched MSW Compost and Gypsum on Growth and Yield of Rice and Wheat

The data given in Table 4 showed that the maximum plant height of rice (124.40 cm) and wheat (83.55 cm) crops was recorded with treatment T_2 and T_6, respectively; however, there was no significant difference in this character due to application of inorganic amendment alone (T_2) or in combination with organic amendments. Number of productive tillers hill^{-1} is a very important parameter in rice as it is directly related to panicle density and grain yield. Tilling was distinctly influenced by the application of microbial-enriched municipal solid waste compost (EMSWC) along with mineral gypsum. Maximum number of productive tillers hill^{-1} and panicle density were recorded with treatment T_6 where enriched compost was applied along with gypsum, which were significantly higher over T_1, T_3, and T_4 but statistically at par with T_5 and T_6. Application of enriched MSW compost (T_6) in combination with reduced dose of gypsum had a significant effect on panicle/spike density and dry matter content in rice and wheat over the application of inorganic amendment alone (T_2) and control (T_1). Highest panicle length in rice was recorded with treatment T_6 which was significantly higher than treatments T_1, T_3, and T_4 but at par with treatment T_2 and T_5. Highest spikelet fertility was recorded with T_2, which was significantly higher over T_1, T_3, and T_4 but at par with T_5 and T_6. Significantly higher numbers of grains per panicle were recorded in treatment T_6 where microbial-enriched MSW compost was applied in combination with a reduced dose of gypsum but it was at par with T_5. Maximum of 1000 grain weight was recorded in treatment T_2 but it was on par with rest of the treatments. The grain yield of rice increased significantly with the addition of organic amendments over the sole application of inorganic amendment. The yield varied from 4.21 to 5.45 t ha^{-1} over the treatments (Table 5). Like other parameters, treatment T_6 (gypsum @25% GR + Enriched MSW compost at 10 t ha^{-1}) produced the highest grain yield, showing 29.45% and 3.41% yield enhancement over control (T_1) and gypsum @50% GR (T_2) which was at par with treatment T_5 but significantly higher over T_1, T_3, and T_4 (Table 5). Wheat yield-attributing characteristics such as length of spike, grains/spike, and 1000 grain weight in wheat were significantly higher in treatment T_6 over treatments T_1, T_3, and T_4 but almost at par with treatment T_2 and T_5. Maximum grain yield was recorded with treatment T_6 and minimum with control. The grain yield can be attributed by the increase in yield-attributing characteristics. Muhammad et al., 2008 [34] reported that the application of compost increased plant height, tillers $hill^{-1}$ 1000 grain weight, and yield of rice. Grain yield of wheat with treatment T_6 (enriched EMSWC @ 10 t ha^{-} + gypsum @25% GR) was 110.75% and 20.61% higher over the treatments T_1 and T_2 (Table 5). Treatment T_2 having only gypsum @50%GR produced significantly higher grain yield over the treatment T_3 and T_4 where only MSW compost were used. The yield advantage due to enrichment of MSW compost over un-enriched MSW compost with a similar dose of gypsum was 21.36%. The increase in plant growth and yield with synergistic use of organic and inorganic sources of organic amendments may be because the decomposition of organic matter available in MSW compost increases organic acid exudates in soil that mobilizes dissolution of soil calcium and reduces soil pH and ESP and increases soil organic carbon, resulting in increased plant growth [35,36]. Addition of organic matter into soil can bring beneficial effects on crop root growth by improving the physical and chemical environments of the rhizosphere [37]. This may also be due to the enhancement of biological activities in the crop rhizosphere by amino acid and some physiological active substances such as humic acid in the organic amendments [38]. Yield and yield-related attributes significantly affected alkaline soils because of restricted water movement, nutrient translocation, and the toxic effect of sodium in the rhizosphere. Addition of organic matter in the form of EMSWC improved soil physico-chemical and biological properties, resulting in improved crop growth and related yield attributes and yields [37,39]. EMSWC, being an organic source of amendment, helped in leaching of excessive salts to the deeper soil layer and reduced the salt concentration in top soil, which favored plant growth and ultimately increased crop yields [40].

3.2. Effect of Enriched MSW Compost and Gypsum on Nutrient Content in Grain and Straw of Rice and Wheat

The nitrogen content in the rice grain and straw was affected owing to combined use of organic and inorganic amendments. The maximum content of N (1.25%) in rice grain and straw (0.35%) was obtained with treatment T_6 where the reduced dose of gypsum (25% GR) was applied in combination with enriched MSW compost at 10 t ha^{-1} (Figure 3). This may be due to the slow release of organic nitrogen from MSW compost and improvement in soil physico-chemical properties. The phosphorus content in rice grain and straw differed significantly due to different treatments. Maximum P content in rice grain (0.28%) as well as straw (0.11%) was recorded in treatment T_6 followed by T_5 and minimum content (0.13% and 0.05%) with T_1.

Table 4. Combined effect of inorganic amendments and enriched municipal solid waste compost on crop growth of rice and wheat.

Treatments	Rice				Wheat		
	Plant Height (cm)	Productive Tillers hill^{-1}	Panicle Density (m^2)	Dry Matter (g hill^{-1})	Plant Height (cm)	Spike Density (m^2)	Dry Matter (g hill^{-1})
T_1	111.22	9.65	286.0	93.59	69.2	363.41	647.3
T_2	124.40	14.77	387.9	144.55	77.9	388.22	674.6
T_3	123.43	11.65	345.0	123.63	76.12	341.30	623.3
T_4	122.35	12.80	359.1	130.43	76.22	343.90	632.3
T_5	123.40	13.42	381.0	144.55	77.90	391.31	681.4
T_6	123.40	16.47	389.6	148.10	83.55	394.20	688.3
LSD (p = 0.05)	ns	3.12	11.23	6.35	ns	6.23	8.63

LSD = least significant difference. ns= non-significant. T_1—Control (No amendments), T_2—Gypsum @50% G.R., T_3—Un-enriched MSW compost at 10 t ha^{-1}, T_4—Enriched MSW compost at 10 t ha^{-1}, T_5—Gypsum @25% G.R. + un-enriched MSW compost at 10 t ha^{-1}, T_6—Gypsum @25% G.R. + Enriched MSW compost at 10 t ha^{-1}.

Table 5. Effect of organic and inorganic amendments on yield attributes and yields of rice and wheat crops.

Treatments	Rice					Wheat			
	Panicle Length (cm)	Spikelet Fertility (%)	Grains Panicle^{-1}	1000 Grain Weight (g)	Grain Yield (t ha^{-1})	Length of Spike (cm)	Grains Spike^{-1}	1000 Grain Weight (g)	Grain Yield (t ha^{-1})
T_1	21.30	73.2	114.30	22.22	4.21	13.08	30.95	32.0	1.86
T_2	25.37	87.5	132.22	26.62	5.27	18.78	33.70	41.8	3.25
T_3	23.52	76.3	126.02	24.62	4.50	16.85	30.95	38.5	2.43
T_4	23.77	81.2	129.62	23.55	4.70	17.20	32.20	30.4	2.47
T_5	25.37	85.3	138.05	25.37	5.17	18.05	33.50	40.9	3.23
T_6	25.52	85.8	138.30	25.95	5.45	19.55	35.10	43.1	3.92
LSD (p = 0.05)	0.53	5.23	5.32	ns	0.43	0.63	3.12	2.13	0.21

LSD = least significant difference; ns = non-significant. T_1—Control (No amendments), T_2—Gypsum @50% G.R., T_3—Un-enriched MSW compost at 10 t ha^{-1}, T_4—Enriched MSW compost @10 t ha^{-1}, T_5—Gypsum @25% G.R. + un-enriched MSW compost at 10 t ha^{-1}, T_6—Gypsum @25% G.R. + Enriched MSW compost at 10 t ha^{-1}.

There was a significant correlation of total P content in rice grain and straw with the organic P contents of both EMSWC and gypsum. This may be due to the increased solubility of organic P with diminishing soil pH under sodic soils. Uwasawa et al. (1988) and Willet (1989) [41,42] also reported that the contribution of organic matter to P release under salt stress appears to be mainly through organic P mineralization, which increased under stress environment. Organic acids produced by micro-organisms or plant roots results in org-P being solubilized to a greater extent. Potassium content in rice grain was not significantly affected due to different treatments; however, a significant effect among the treatments was observed in the case of rice straw. The highest content of K in the rice grain (0.37%) and straw (2.2%) was observed in case of treatment T_6 and the lowest K content in T_1.

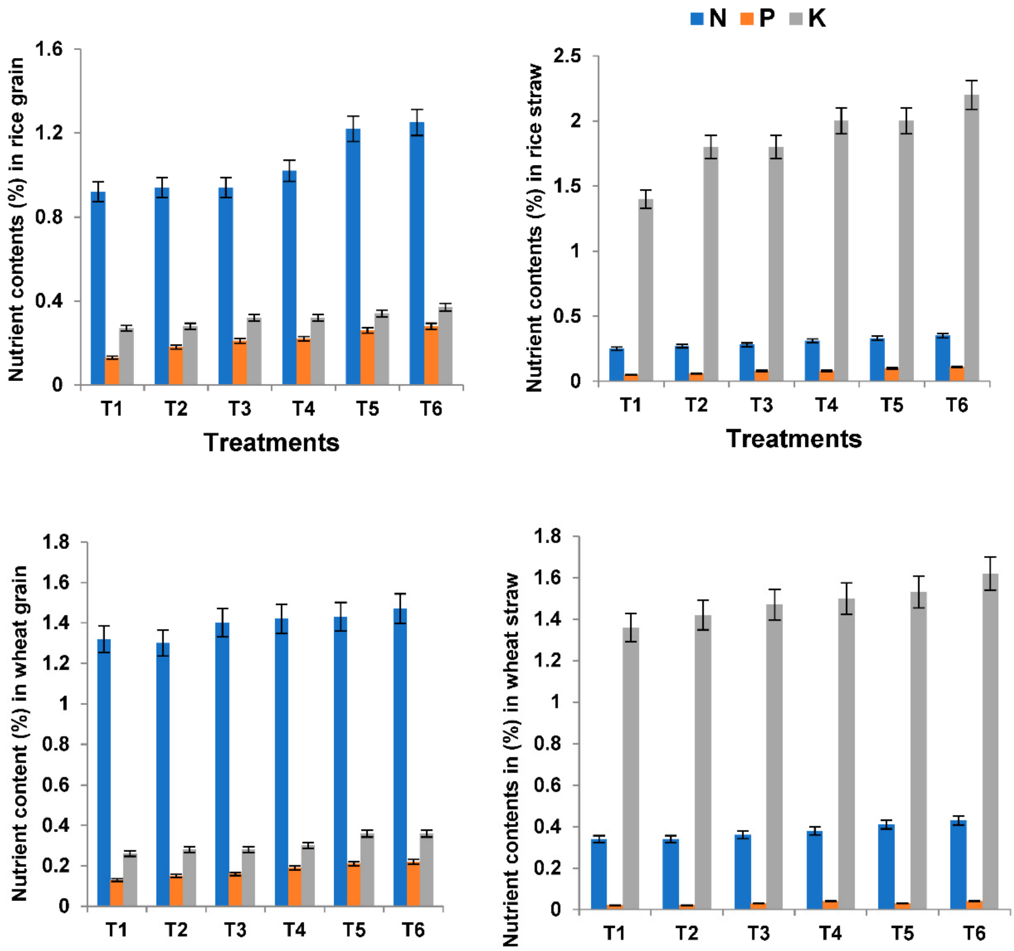

Figure 3. Effect of organic and inorganic amendments on nutrient contents in grain and straw of rice and wheat.

In case of wheat, the nitrogen content in both grain and straw varied significantly ($p < 0.05$) with the application of organic and inorganic amendments. The combined application of organic and inorganic amendments resulted in an increased N content in wheat grain and straw (Figure 3). In wheat grain, maximum N content (1.25%) was recorded in treatment T_6 where a reduced dose of gypsum was applied in combination with enriched MSW compost and minimum with control. A similar trend was recorded in the case of wheat straw. The soil nitrogen level influencing its uptake is a function of several factors [43,44]. The phosphorus concentration in both grain and straw was higher in treatment T_6 where combined use of organic and inorganic amendments was applied but the difference between T_5 and T_6 was not statistically significant. Maximum K content in wheat grain (0.37%) and straw (2.2%) was recorded in treatment where gypsum at 25% GR was used in conjunction with enriched MSW compost and minimum (0.27% and 1.4%) with control and 0.28% and 1.8% where only gypsum was used. Ponnamperuma (1972) [45] and Bhattacharyya et al. (2003) [46] reported that P content of grain and straw was significantly correlated with the bound P of MSWC probably due to the reason that P became soluble under stress conditions.

3.3. Effect of Enriched MSW Compost and Gypsum on Nutrient Uptake in Grain and Straw of Rice and Wheat

The integrated use of organic and inorganic amendments significantly influenced the N uptake in grain and straw of rice. Maximum N uptake in rice grain and straw was recorded in treatment T_6, which was at par with T_5 but significantly higher over the rest of the treatments. The results are in line with the work carried out by Kropisz and Wojciechowsky

1978 [47]. Similar to N uptake, the P uptake was also found significantly increased in rice grain (15.26 kg ha^{-1}) and straw 9.77 kg ha^{-1}) in treatment T_6 over T_1, T_2, T_3, and T_4 but at par with T_5. The results can be evident from the findings of Ali et al., 2003 [48] and King et al., 1977 [49]. In rice grain, maximum potassium uptake (20.16 kg ha^{-1}) was observed in treatment T_6 but it was not significantly higher over the rest of the treatments. However, in rice straw, K uptake in treatment T_6 was significantly higher than treatment T_1, T_2, T_3, and T_4 with a value of 195.43 kg ha^{-1} (Figure 4). Lowest K uptake in rice grain and straw was recorded in T_1 (control) treatment. Our results could also be proved by the reports of Ali et al., 2003 [48] and Duggan and Wiles 1976 [50], which suggested that the incorporation of garbage compost leads to a significant increase in plant potassium content.

Data shown in Figure 4 demonstrate that N uptake in wheat grain and straw was significantly higher in treatment T_6 over the other treatments. Similarly, P uptake in wheat grain was recorded as significantly higher in treatment T_6 but at par with combined use of un-enriched MSW compost and gypsum. The P uptake in wheat straw was not significantly affected due to the application of organic and inorganic amendments (Figure 4). These findings of the present study are similar to Imran et al., 2011 [51] who reported the highest P uptake in maize with rock phosphate enriched compost. The potassium uptake by wheat plant revealed that there was significant increase in K uptake by the combined application of gypsum and EMSWC (T_6) over rest of the treatments. Our findings are in agreement with Han et al., 2006 [52], who reported maximum K uptake in pepper with application of microbial enriched compost. The quantity of nutrient uptake is dependent on yields and nutrient contents in grain and straw. In this study, highest grain yields in wheat were obtained in treatment T_6 where gypsum was used in conjunction with enriched MSW compost.

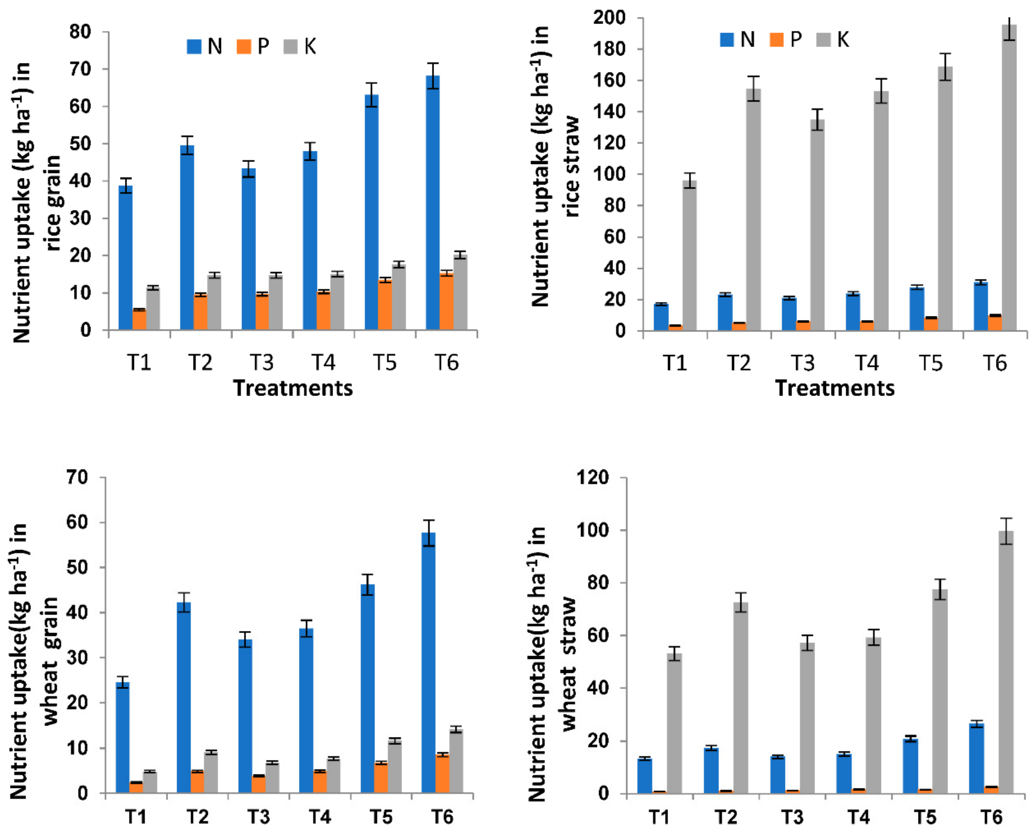

Figure 4. Effect of organic and inorganic amendments on nutrient uptake in grain and straw of rice and wheat.

4. Grain Qualities

4.1. Ionic Accumulation

In different plant parts, the ionic accumulation (Na, K, and Na:K ratio) varied under different treatments. The highest sodium content in rice root was observed in treatment T_1 and the lowest in T_6. The Na: K ratio in rice plant parts was higher in treatment T_2 followed by T_1 and the lowest in T_6. The K content in these plant parts increased with the addition of an organic source of amendments. Similarly, in stem, leaf, and grain Na content was higher in treatment T_1 and T_2 and the lowest in treatment T_6. Similar results pertaining to Na content have also been reported by Cha-um et al., 2007 [53]. In our study, Na^+ in rice grown in sodic soil treated with the conjoint use of enriched MSW compost and gypsum was lower than that of control and gypsum-treated plots.

In the case of wheat, the highest Na:K ratio in all plant parts was observed in Treatment T_2 and the lowest in T_6. The maximum Na ionic content was accumulated in stem followed by root, leaf, and grain. This shows that the level of sodicity plays an important role in ionic accumulation in rice and wheat plant parts (Figure 5). Cha-um et al., 2011 [39] reported that sodium ion accumulation in both root and shoot organs of rice and wheat cultivated in the soil treated with gypsum and enriched MSW compost was lower than control (T_1) and gypsum alone, while the potassium ion level was enriched. Addition of organic matter through enriched MSW compost and gypsum may function as salt-ion chelating agents which detoxify the toxic ions, especially Na^+ [54–57].

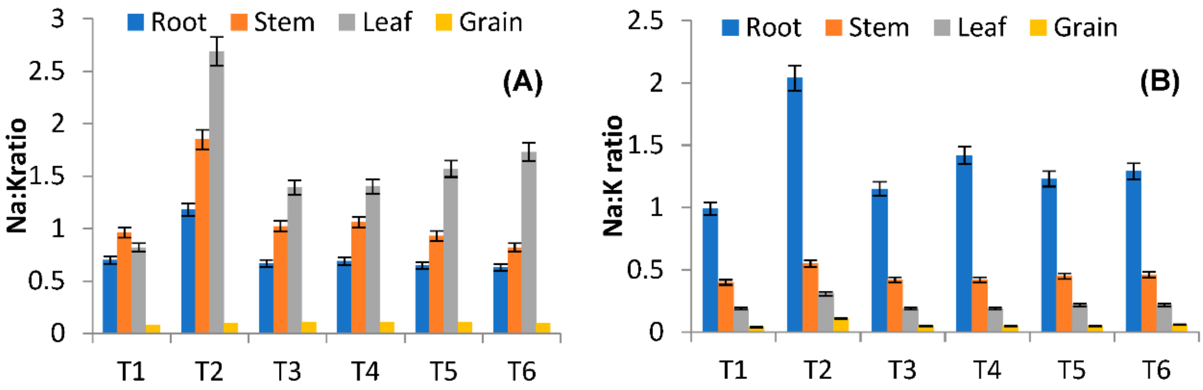

Figure 5. Sodium and potassium ratio (Na:K) in (**A**) rice and (**B**) wheat plant parts under different treatments.

4.2. Nutrient Contents and Heavy metals

The occurrence of heavy metals (i.e., Cd, Cu, Zn, Pb etc.) in MSW compost is always a matter of concern, as they may accumulate in the soil that can be assimilated in the agricultural crops grown and that may cause a variety of human health issues when shifted at high levels through the progression of food chain [58–63]. The data given in Table 6 revealed that highest Zn, Cu, and Fe contents in rice grain were recorded with T_3, T_2, and T_4, respectively. However, higher concentration of these nutrients in wheat was recorded in treatments T_5, T_5, and T_6. The higher concentration of these nutrients in these treatments over the application of gypsum may be due to addition of MSW compost. Hargreaves et al., 2008 [60] and Nayak et al., 2009 [64] assessed and compared the effect of MSWC and inorganic fertilizer on grain quality and reported that the mineral concentration increased significantly with MSW compost over inorganic fertilizer.

Table 6. Effect of organic and inorganic amendments on micronutrient and heavy metal content in rice and wheat grain.

Treatments	Rice			Wheat		
	Zn (ppm)	Cu (ppm)	Fe (ppm)	Zn (ppm)	Cu (ppm)	Fe (ppm)
T_1	10.93	3.66	147.04	34.20	12.36	38.62
T_2	10.36	3.90	197.45	34.52	14.20	40.20
T_3	11.22	4.23	233.43	36.20	16.20	42.32
T_4	11.91	4.30	242.53	38.42	13.50	40.60
T_5	12.80	4.90	296.06	41.30	117.20	41.20
T_6	12.87	6.26	537.96	42.10	18.20	43.20

5. Economics of Technology

After the first year of reclamation by use of different amendments, followed by the cultivation of rice and wheat, a small positive net return was calculated with treatment T_3 and T_4 where no inorganic amendment was used and only organic amendments were used. The net economic return was negative in all the remaining treatments. Highest negative return was obtained in treatment T_2 followed by T_5 and T_6. This was obviously due to higher reclamation cost including the cost of gypsum at 50% GR and 25% GR, respectively. During the second and third years, the highest positive cumulative net return was observed in treatment T_6 followed by T_5 and the lowest in treatment T_1, whereas a negative return was calculated in treatment T_2. Although, the current study did not account for the carryover residual fertilizer or nutrients present in soil [65]. This shows that the cost of sodic soil reclamation with addition of gypsum is not recovered even after the second year of cultivation (Figure 6). On the basis of cost economic analysis, the highest B/C ratio was observed in T_6 which was at par with T_5 but significantly higher over the rest of the treatments.

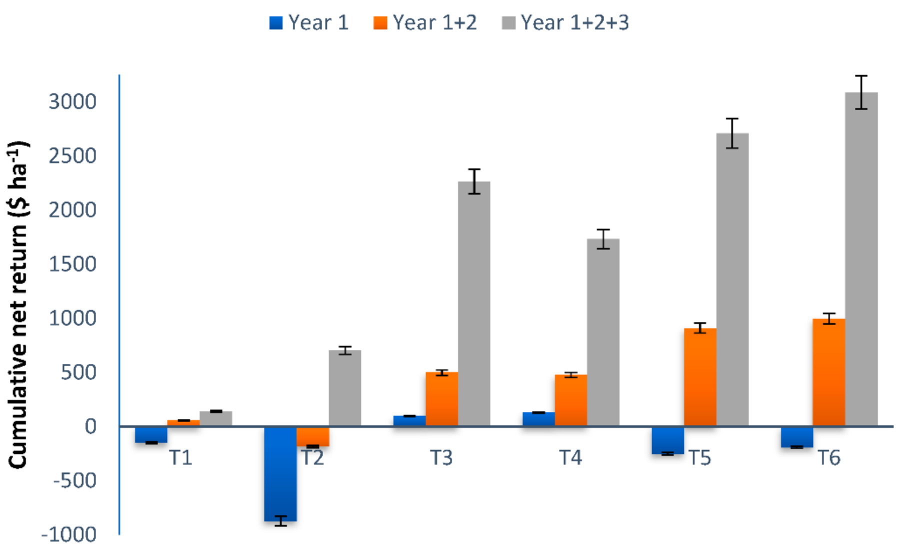

Figure 6. Cumulative net returns of the rice-wheat cropping system over a two year period with organic and inorganic amendments of sodic soil.

6. Conclusions

The bio-chemical and nutritive value of the MSW compost is generally enhanced with enrichment by halophilic plant growth-promoting microbes. The plant growth, yield-attributing characteristics and yield of rice and wheat were favorably influenced with the combined use of enriched MSW compost and gypsum. Synergistic use of microbial enriched MSW compost at 10 t ha^{-1} with 50% reduction in gypsum dose significantly influenced the productive tillers, panicle density, and dry matter contents. The grain yield of rice and wheat with enriched MSW compost at 10 t ha^{-1} along with gypsum @25% GR was 29.45% and 110.75% higher over control and 3.41% and 20.61% over sole application of gypsum @50% GR. The uptake of N, P, and K level in different parts of plants were enhanced to a significant level with combined use of reduced dose of gypsum and microbial-enriched MSW compost. Grain quality of rice and wheat also improved with the addition of an organic source of amendment in sodic soils. Application of microbial-enriched MSW compost in conjunction with a reduced dose of gypsum reduced 35.6% reclamation cost on account of saving of gypsum and improved soil fertility status than the application of gypsum alone. This saved the quantity of mineral gypsum that can be utilized to bring more area under reclamation. Thus, it can be concluded that the combined use of gypsum and microbial-enriched MSW compost in sodic soils and cultivation of salt-tolerant varieties of rice and wheat were proved as cost-effective sustainable sodic soil reclamation technology which can also be helpful for the efficient utilization of municipal solid waste.

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