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RESEARCH ARTICLE

Impact of organics on microbial activity and soil organic carbon build-up under rice in sodic soil

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Abstract

Salt-affected soils cover 6.73 M ha in India, with ~56 % being sodic and 44 % saline. Sodic soils, particularly in the Indo-Gangetic plains, form due to alternate wetting and drying, leading to alkali hydrolysis, sodium saturation and high pH. Soil organic matter (SOM) turnover, primarily driven by microbial activity, is significantly impaired under these conditions. Reduced decomposition rates in salt-affected soils may enhance carbon (C) sequestration, lowering CO_2 emissions, provided soil organic carbon (SOC) inputs are adequate. Navathania biomass consists of biomass from nine different crop seeds, improving soil organic matter and fertility. In contrast, Sunhemp biomass (*Sesbania rostrata*), a nitrogen-fixing green manure, enhances soil structure and microbial activity. A field experiment was conducted in sodic soil with seven treatments: T_1- Navathania biomass @ 5.0 t ha^{-1}, T_2- Sunhemp biomass @ 6.25 t ha^{-1}, T_3- Crop residue @ 6.25 t ha^{-1}, T_4- Vermicompost @ 5.0 t ha^{-1}, T_5- Enriched Farmyard Manure @ 750 kg ha^{-1}, T_6- Gypsum @ 50 % GR and T_7- Control. Navathania biomass incorporation significantly increased grain yield (4950 kg ha^{-1}) and straw yield (7200 kg ha^{-1}), with a 24.3 % yield increase over control. It also improved microbial biomass carbon (Cmb) (246 µg g^{-1} soil), Cmb/SOC ratio (1.92 %), SOC stock (23.7 Mg C ha^{-1}), C buildup rate (4.73 Mg C ha^{-1} yr^{-1}), basal respiration rate (43.7 mg CO_2-C g^{-1} day^{-1}) and enzyme activities. This treatment can enhance SOC conservation and soil productivity under sodic conditions.

Keywords

basal respiration rate; C build up; microbial biomass carbon; navathania biomass; soil organic carbon

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Introduction

Sodic soils adversely impact agriculture by reducing crop productivity due to poor soil structure, water infiltration and nutrient availability. High sodium levels cause clay dispersion, compaction and restricted root growth. These soils exhibit high pH, which limits microbial activity and organic matter decomposition, further degrading soil health. Reduced permeability results in waterlogging, making cultivation difficult. Essential nutrients like calcium, magnesium and potassium become deficient, affecting plant growth. Effective management strategies, such as organic amendments and gypsum application, are crucial to restoring soil fertility and productivity (1, 2). Salt accumulation in soils significantly inhibits plant growth and increases the risk of soil erosion, thereby threatening agricultural productivity and ecosystem sustainability. One of the critical processes affected by soil salinity and sodicity is the turnover of soil organic matter (SOM), which is predominantly regulated by microbial activity. Soil microorganisms play essential roles in maintaining soil health, primarily through the decomposition of SOM and the cycling of nutrients. However, salinity-induced stress can suppress or eliminate sensitive microbial populations, leading to long-term reductions in microbial activity and impaired SOM decomposition (1, 2).

The turnover of SOM is a key determinant of soil quality, influencing water retention, ion exchange processes, greenhouse gas emissions, soil structural stability and overall ecosystem resilience. In salt-affected soils, both plant inputs and microbial activity tend to decline. The reduced decomposition rates under saline conditions can contribute to increased carbon (C) sequestration by limiting carbon dioxide (CO_2) emissions, provided that soil organic carbon (SOC) inputs remain comparable to those in non-saline environments. Studies have demonstrated that microbial respiration and biomass initially increase after adding organic material to highly saline-sodic soils. This suggests a transient enhancement of microbial activity before potential inhibition due to osmotic stress and ion toxicity(1-3). Long-term fertilization, primarily when NPK and manure are used together, can significantly increase the SOC, total nitrogen and accessible nutrients. The primary source of labile C is the root biomass and microbial biomass detritus at lower depths, which FYM may assist. Better crop development, leftover root biomass, more root exudation at the lower layer and more microbial biomass detritus were the primary sources of labile C in deep soil in the balanced treatment (3). Soil sodicity is characterized by a relatively high concentration of sodium in the exchange complex or the soil water, causing adverse effects on the soil's physical, chemical and biological properties. Among the soil microbial properties, the soil urease activity and acid and alkaline phosphatase activity in soils were reported to decrease with the increase in soil pH and Exchangeable Sodium Percentage (ESP) (4, 5). Similarly, the soil microbial biomass, dehydrogenase activity and carbon in soil microbial biomass decreased due to specific ion deficiencies and toxicities at high soil pH and ESP (6, 7). Excess exchangeable sodium in sodic soils has a marked influence on the physical soil properties. As the proportion of exchangeable sodium increases, the soil becomes more dispersed, which results in the breakdown of soil aggregates and lowers the soil's permeability to air and water. Although the high pH of sodic soils has no direct adverse effect on plant growth per se, it frequently results in lowering the availability of some essential plant nutrients.

The reclamation of sodic soils requires the addition of organic matter to improve soil structure, enhance nutrient availability and promote microbial activity. Organic amendments such as Navathania biomass, Sunhemp biomass, vermicompost and farmyard manure play a crucial role in restoring soil fertility. These materials enhance soil aggregation, increase water infiltration and facilitate the leaching of excess sodium, thereby reducing soil sodicity. Additionally, they provide essential nutrients, stimulate microbial diversity and improve enzymatic activity, which aids in better decomposition and nutrient cycling. These organic amendments support sustainable soil management and enhance crop productivity in degraded sodic soils. Hence, this study was conducted to understand the impact of various organics on yield, which affects soil microbial and enzyme activities, SOC stock and carbon buildup during wetland rice production under sodic soil conditions.

Materials and Methods

Experiment site details

A field experiment was conducted in late Samba, 2024, with the Co 55 rice variety and the trial was conducted at Sugarcane Research Station, Sirugamani, Tamil Nadu Agricultural University. The initial soil sample was taken and analyzed for its physicochemical characteristics (Table 1). The nutrient content of different organics was analyzed (Table 2).

Soil characterization

The experimental field's soil was sandy clay loam in texture with a pH range of 8.82 and EC of 0.47 and 0.17 dSm-1. (Table 1). The soil nutrient status was characterized by low available $KMnO_4$- nitrogen (184 kg ha–1), medium Olsen available phosphorus (21 kg ha^{-}1) and medium in available NH_4OAc-potassium (232 kg ha^{-1}), the ESP of the soil is 28.5 % and low in soil organic carbon (0.39 %).

Experimental design and treatment details

The soil belongs to the Alathur soil series, which includes seven treatments and three replications in the randomized block design experiment. The experimental plot size was 20 m^2 (5 m × 4 m). The sources are T_1 (Application of Navathania biomass at 5.0 t ha^{-1}), T_2 (Application of Sunhemp biomass at 6.25 t ha^{-1}), T_3 (crop residue at 6.25 t ha^{-1}) and T_4 (vermicompost at 5.0 t ha^{-1}), T_5 (Enriched Farm Yard Manure (EFYM) @ 750 kg ha^{-1}), T_6(Gypsum requirement at 50 % GR)

Table 1. Initial soil characteristics of the experimental field

S.No.	Initial Soil Properties	Values	Reference for analytical methods used
1	Soil texture	Sandy clay loam series	
2	ESP (%)	28.5	
3	Organic carbon (g kg^{-1})	3.9	(9)
4	Available Nitrogen (kg ha^{-1})	184	(11)
5	Available Phosphorus (kg ha^{-1})	21.0	(12)
6	Available potassium (kg ha^{-1})	232	(13)
7	Free $CaCo_3$ (%)	14.5	(14)
8	pH	8.82	(15)
9	EC(dSm^{-1})	0.17	(15)

Table 2. Initial nutrient content of different sources

Sources	Total N (%)	Total P (%)	Total K (%)
Navathania biomass	1.78	0.38	0.89
Sunhemp biomass	1.64	0.21	0.72
Vermicompost	1.52	0.25	0.58
FYM	0.68	0.08	0.42
Crop residues	1.62	0.14	0.55
Enriched FYM	1.21	0.18	0.68

and T_7 (Control). The seeds were sown in the field and 45 days green manures were incorporated and then paddy crop CO 55 planting was taken up. The grain and straw yield data was recorded. The soil organic carbon, microbial biomass carbon (Cmb), Cmb as a fraction of SOC, basal soil respiration (BSR) and enzyme activities like urease, dehydrogenase and phosphatase activity were analyzed.

Soil sampling and physicochemical analysis

The soil sample was collected and analyzed for its soil organic carbon (SOC) and the bulk density was determined using a core sampler (8). The wet oxidation method was used to determine the SOC content (9). The following Equation 1 formula was used to determine the total SOC stock in each soil.

$$\text{SOC stock} = \text{SOC} \times \text{BD} \times \text{D} \times 100 \qquad \text{(Eqn. 1)}$$

BD is bulk density in Mg m^{-3}, D is depth in m and SOC stock is soil organic carbon stock in Mg C ha^{-1}. SOC is soil organic carbon represented as a percentage. The following chemical characteristics of the soil were identified in the air-dried samples: soil pH and EC measured in a 1:2.5 soil-to-water suspension (10). Available nitrogen (N) by the alkaline potassium permanganate method, available phosphorus (P) spectrophotometrically, available potassium (K) flame photometrically and free $CaCO_3$ (11, 14)

Microbial activity parameters

The field moist soil samples measured the enzyme and soil microbial activity. Titration and incubation techniques were used to calculate the basal soil respiration (BSR). Ten grams of soil were put in an airtight conical flask with a volume of one litre. The conical flask was air-tightened and a vial holding 20 mL of 1 M NaOH was left inside. The amount of CO2-C developed and trapped in alkali was evaluated by titrating the soils against 0.5 M HCl after incubating them for 10 days at 28 ± 2°C. The fumigation extraction procedure was used to determine the Microbial biomass carbon (Cmb). 100 mL of 0.5 M K_2SO_4 were used to extract 20 grams of fumigated and non-fumigated soil. After oxidation, the extract's Cmb was calculated using 0.2 N. $K_2Cr_2O_7$ microbial activity characteristics for 30 minutes at 100°C. The Equation 2 formula was used to determine the Cmb.

$$\text{Cmb} = (\text{Cf} - \text{Cuf})\ \text{Kex}^{-1} \qquad \text{(Eqn. 2)}$$

A value of 0.45 has been considered for computation. Cmb is the soil microbial biomass carbon in µg g^{1} soil and Cf and Cuf are the 0.5 M extractable organic carbon in fumigated and non-fumigated soils, respectively. To calculate Cmb, the moisture content of the identical soil samples was measured concurrently.

Enzyme activities

The soil's dehydrogenase activity was assessed using the method described in (15). A screw-type airtight test tube containing 0.5 mL of 1 % glucose solution and 0.2 ml of triphenyl tetrazolium chloride was filled with soil (l g). After that, the tubes were incubated for six hours at 27°C. The absorbance of a clear, pink supernatant at a wavelength of 485 nm was used to measure the activity of the dehydrogenase enzyme. It was stated as µg TPF g^{1} day^{-1} (triphenyl tetrazolium formazan per gram of soil per day). The method determined the soil's acid phosphatase activity (16). After adding 1 g of soil to an Erlenmeyer flask, 0.2 mL of toluene, 1 mL of p-nitro phenol and modified universal buffer (pH 6.5) were added one after the other. After that, it was retained for incubation for one hour at 37 °C. Following incubation, the flasks were stirred and 1 mL of 0.5 M $CaCl_2$ and 4 mL of 0.5N NaOH were added. The intensity of the generated yellow colour was measured at a wavelength of 440 nm. The µg p-nitro phenol per gram per hour (µg PNP g^{-1} h^{-1}) denoted the acid phosphatase activity. The amount of urea hydrolyzed following incubation was used to quantify urease activity in soils (17). Five grams of soil were incubated for five hours at 37 °C with a known quantity of urea. After filtering the suspension, potassium chloride, phenylmercuric acetate and colouring agent were combined with 5 millilitres of the filtrate. After being heated over a hot water bath for 30 minutes, the solution was let to cool. The red colour's intensity was determined at 527 nm wavelength. The urease activity was expressed as mg urea per gram per hour.

2.7. Statistical analysis

The data collected on various parameters were statistically analyzed using R software, following a Randomized Block Design (RBD) principles. The analysis aimed to evaluate the treatment effects and determine the presence of statistically significant differences among the seven treatment means. Significance testing was conducted at a 5 % probability level ($p \leq 0.05$), ensuring robust inference regarding treatment variations. This approach facilitated an accurate assessment of the experimental outcomes while accounting for inherent variability within the data, thereby enhancing the reliability and validity of the results.

Results

Effect of organics on grain and straw yield

Applying 5.0 t ha^{-1} of Navathania biomass integration produced the significantly highest grain yield of 4950 kg ha^{-1} in sodic soil, followed by Sunhemp biomass with 4875 kg ha^{-1}. At the same time, the control recorded the lowest at 3980 kg ha^{-1}. The percentage yield increase over the control is 24.3 % (Fig 1). Regarding the straw yield, the same treatment recorded the highest yield of 7200 kg ha^{-1} in Navathania Biomass incorporation at 5.0 t ha^{-1}, followed by 6850 kg ha^{-1} in sun hemp incorporation, of 4850 kg ha^{-1} in control. The same treatment also showed a BC ratio 2.27, while the control had

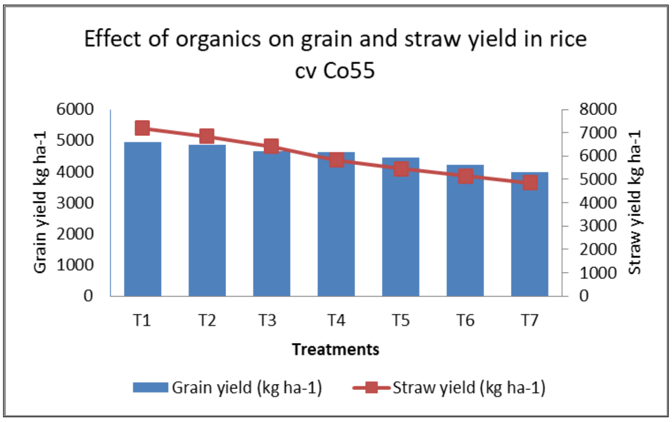

Fig. 1. Effect of different organics on grain and straw yield in rice cv Co55.

the lowest at 1.27. All the organic sources of nutrients were equally effective in increasing the grain yield over control. The beneficial effect of organics and their integrated use increased the grain and straw yield with Navathania and Sunhemp biomass incorporation, which can be attributed to improved soil fertility, enhanced microbial activity and better soil structure. These organic amendments promote nutrient mineralization, increase organic carbon content and enhance moisture retention, supporting plant growth. Additionally, improved root proliferation and reduced sodium toxicity likely contributed to higher nutrient uptake, resulting in greater yield (18-20).

Effect of organics on post-harvest soil characteristics

The addition of organic sources of nutrients changed the soil pH and EC significantly ($p < 0.05$) (Table 3). Treatments significantly increased the amount of available N compared to the control and their performance was comparable. The Navathania incorporation treatment had the most significant amount of available N (250 kg ha-1), 19.0 % more than the control. Available P was significantly lower in control-treated plots (10.7 kg ha^{-1}) and more significant in Navathania (14.4 kg ha-1) among the investigated treatments. When organic nutrient sources were applied, the soil's K availability significantly increased compared to the control and Navathania biomass performed (84.7 kg ha-1 higher), followed by Sunhemp incorporation (73.9 kg ha-1). In comparison, the control recorded 59.01 kg ha-1.

The entire organic nutrient sources used in this study were equally successful in raising grain production over control. Organics' positive effects and integrated use were previously documented by (18-20). The Navathania biomass-included field had the highest soil available N (250 kg ha^{-1}). Increased biomass output and the bulk of organic sources that contain nitrogen may have enhanced the soil's available nitrogen status. It's possible that the increase in soil available K in Navathania biomass (21.5 % greater than control) results from the input of K through Navathania biomass, which causes soil K buildup. In rice-soybean-rice cropping systems, the long-term use of composted paddy straw increases soil K availability and buildup more than inorganic fertilizers alone (21).

The nutrient content of different sources was analyzed for its N, P and K content. The significant highest was noticed in Navathania biomass with N (1.78 %), P (0.38 %) and K (0.89 %), followed by sun hemp biomass. The lowest were recorded in the control group, with 0.68 % N, 0.08 % P and 0.42 % K (Table 2). The higher availability of N, P and K in Navathania biomass-treated soil is due to enhanced microbial activity, organic matter decomposition and improved soil structure. Decomposition releases nitrogen gradually, while organic acids chelate phosphorus, making it more available. Additionally, increased cation exchange capacity (CEC) reduces sodium interference, enhancing potassium retention. These mechanisms collectively improve nutrient availability, leading to better plant uptake, higher yields and improved soil health in sodic conditions (21).

Effect of different organics on SOC content, stock and C buildup rate in the post-harvest soil

The application of various fertilizer sources resulted in substantial ($p < 0.05$) differences in soil BD, SOC content, stock and buildup rate (Table 4). Soil BD decreased significantly ($p < 0.05$) when organic sources were applied compared to the untreated control treatment. The Navathania Biomass inclusion treatment had the lowest BD (1.22 Mg m^{-3}), whereas the control group had the highest (1.38 Mg m^{-3}). With contents of 1.28 %, 1.21 % and 1.18 %, respectively, applying navathania, sun hemp and crop residual biomass could result in a significantly higher SOC than the control. The control had the lowest SOC content (0.75 %). Therefore, consistent use of Navathania biomass has the potential to improve SOC matter. Plots treated with Navathania biomass had the highest ($p < 0.05$) SOC stock (23.7 Mg C ha^{-1}), followed by plots treated with Sunhemp biomass (22.4 Mg C ha^{-1}), while the control treatment recorded the lowest (16.5 Mg C ha^{-1}). (Table 5). Although all treatments improved the SOC stock to a similar degree, it was evident that the application of organic sources of nutrients had a significantly ($p < 0.05$) greater SOC stock than the control.

According to the current study, applying organic sources lowers the soil BD in wetland rice soil. This may result from increased root biomass from applying organic material, enhanced soil aeration and C inputs (22). Because SOC concentration affects soil's physical, chemical and biological characteristics, it is frequently used in research to measure soil quality and agronomic sustainability (23). Though all of the nutrient sources were equally successful in increasing the SOC stock, it was evident that the application of various nutrient sources had a much higher SOC stock than the control. The ratio of rice crop leftovers may have caused the large SOC stock and buildup rate. These findings are consistent with those that have been published (24). The addition of C through degraded material containing a higher proportion of chemically resistant chemicals may also cause the higher SOC stock and C sequestration in Navathania biomass incorporation (25).

Incorporating organic amendments, such as Navathania biomass, significantly increases soil organic

Table 3. Effect of different organic sources on physio-chemical properties of post-harvest soil

Treatment	pH 1:2.5	EC (dS m^{-1})	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
T_1 (Navathania incorporation @ 5.0 t ha^{-1})	7.44	0.25	250	14.4	84.7
T_2 (Sunhemp incorporation @ 6.25 t ha^{-1})	7.85	0.32	242	13.5	73.9
T_3 (Crop residue incorporation @ 6.25 t ha^{-1})	8.10	0.38	238	13.4	70.6
T_4 (Vermicompost @ 5.0 t ha^{-1})	7.95	0.30	230	12.8	69.4
T_5 (EFYM @ 750 kg ha^{-1})	7.35	0.28	228	12.0	64.0
T_6 (Gypum @ 2.0 t ha^{-1})	8.23	0.24	230	10.9	65.4
T_7 (Control)	8.45	0.38	210	10.7	59.0
Mean	7.91	0.31	232.5	12.5	69.7
SEd	0.01	0.01	10.48	0.57	3.18
CD	0.02	0.02	22.8	1.28	6.95

Table 4. Effect of different organic sources on bulk density (BD), soil organic carbon (SOC), SOC stock and C buildup

Treatment	BD (Mg m^{-3})	SOC (%)	SOC stock (Mg C ha^{-1})	C buildup rate (Mg C ha^{-1} yr^{-1})
T_1 (Navathania incorporation @ 5.0 t ha^{-1})	1.22	1.28	23.7	4.73
T_2 (Sunhemp incorporation @ 6.25 t ha^{-1})	1.24	1.21	22.4	4.52
T_3 (Crop residue incorporation @ 6.25 t ha^{-1})	1.25	1.18	21.6	4.31
T_4 (Vermicompost @ 5.0 t ha^{-1})	1.23	1.11	21.8	4.57
T_5 (EFYM @ 750 kg ha^{-1})	1.28	1.02	18.9	3.74
T_6 (Gypum @ 2.0 t ha^{-1})	1.34	1.04	20.1	3.66
T_7 (Control)	1.38	0.75	16.5	3.30
Mean	1.28	1.08	7.67	4.12
SEd	0.05	0.06	0.95	0.20
CD	0.12	0.11	2.18	0.41

Table 5. Effect of organic nutrient sources on microbial biomass carbon (Cmb), Cmb as a fraction of SOC, basal soil respiration (BSR)

Treatment	C_{mb} (µg g^{-1})	C_{mb}/SOC (%)	BSR (mgCO_2- Cg^{-1} day^{-1})
T_1 (Navathania incorporation @ 5.0 t ha^{-1})	246	1.92	43.7
T_2 (Sunhemp incorporation @ 6.25 t ha^{-1})	195	1.61	42.5
T_3 (Crop residue incorporation @ 6.25 t ha^{-1})	198	1.68	42.0
T_4 (Vermicompost @ 5.0 t ha^{-1})	112	1.01	41.1
T_5 (EFYM @ 750 kg ha^{-1})	97.1	0.95	41.7
T_6 (Gypum @ 2.0 t ha^{-1})	89.7	0.86	41.0
T_7 (Control)	89.5	1.19	40.2
Mean	146.75	1.32	4174
SEd	0.19	0.06	1.87
CD	0.42	0.14	4.08

carbon (SOC) content, stock and carbon buildup rates in post-harvest soils. Organic materials decompose slowly, increasing SOC levels and enhancing nutrient cycling. This process also accelerates the carbon buildup rate by stimulating microbial activity and biomass. Organic amendments improve soil aggregation and stabilize organic matter, leading to sustained carbon retention. These amendments play a vital role in long-term soil health and carbon sequestration (25, 26).

3.4. Effect of different organics on Microbial properties

The microbial biomass Cmb and Cmb/SOC were significantly ($p < 0.05$) influenced by the various organic sources (Table 5). There were no discernible variations in Cmb between the control and all treatments, except for Navathania biomass (246 µg g^{-1} soil). The Cmb/SOC pattern tends to resemble the Cmb pattern. The Navathania biomass treatment had the most pronounced Cmb/SOC (1.92 %). A higher Cmb/SOC indicates a more significant amount of mineralized organic matter, which increases the amount of accessible substrate and the percentage of total SOC that is immobilized in the microbial cells (25, 27). Others have shown higher Cmb in organically applied treatments than untreated or fertilizer treatments (28-30). The higher Cmb under the imposed FYM could be ascribed to many things, such as increasing soil moisture content, improving soil aggregation, increasing root biomass and providing a steady supply of organic C to maintain the microbial population. The increase in Cmb brought about by adding organic amendments indicates that the experimental site's soil is C-limited and that the microbes used the C from the organic supplements provided as a source of energy.

The significantly higher microbial biomass carbon (Cmb) and Cmb/SOC ratios in Navathania biomass-treated soils are due to increased organic matter, which provides an abundant substrate for microbial growth. The decomposition of Navathania biomass releases nutrients, enhancing microbial activity and diversity. Improved soil structure also creates better conditions for microbial proliferation by enhancing aeration and water retention. The elevated Cmb/SOC ratio reflects more efficient microbial use of organic carbon, with a more significant proportion retained in microbial biomass rather than lost through mineralization. This promotes stable carbon pools, enhancing soil fertility and long-term carbon sequestration (26-30).

Effect of different organics on soil enzyme activities

The application of various nutrient sources resulted in a substantial ($p < 0.05$) response from all soil enzymatic activities; however, the trend varied for each enzyme (Table 6). Under Navathania biomass treatment, urease, phosphatase and dehydrogenase activities were significantly increased. Navathania biomass had the highest dehydrogenase enzyme activity (20.5 µg TPF g^{-1} day^{-1}), whereas the control had the lowest and non-significant values (7.50 µg TPF g^{-1} day^{-1}). Phosphatase activity was significantly ($p < 0.05$) improved in Navathania biomass (659 µg PNP g^{-1} h^{-1}), Sunhemp (643 µg PNP g^{-1} h^{-1}) and crop residue (559 µg PNP g^{-1} h^{-1}) treatments compared to control (501 µg PNP g^{-1} h^{-1}). The application of Navathania biomass resulted in significantly greater urease activity (0.29 µg urea g^{-1} h^{-1}.) compared to all other treatments. The control recorded the lowest of 0.22 µg urea g^{-1} h^{-1}. The amount of organic matter in the soil strongly correlates with its enzyme activity (25). In the current study, the Navathania biomass incorporation treatment had the highest ($p < 0.05$) dehydrogenase activity, while the untreated control had the lowest.

The positive and strong association between the dehydrogenase and SOC ($r = 0.76$, $p < 0.01$) and the dehydrogenase and Cmb ($r = 0.92$, $p < 0.01$) (Table 7) provides strong support for the dehydrogenase activity findings. The increased microbial activity and diversity of phosphate-solubilizing bacteria in the Navathania biomass incorporation-treated plot may cause higher phosphatase activity. Additionally, the SOC content ($r = 0.97$, $p < 0.01$) and Cmb ($r = 0.81$, $p < 0.01$) were strongly correlated with the phosphatase

Table 6. Effect of organic nutrient sources on dehydrogenase, phosphatase and urease activity

Treatment	Dehydrogenase (µg TPF g^{-1} day^{-1})	Phosphatase (µg PNP g^{-1} h^{-1})	Urease (µg urea g^{-1} h^{-1})
T_1 (Navathania incorporation @ 5.0 t ha^{-1})	20.50	659	0.29
T_2 (Sunhemp incorporation @ 6.25 t ha^{-1})	16.40	643	0.25
T_3 (Crop residue incorporation @ 6.25 t ha^{-1})	12.42	559	0.27
T_4 (Vermicompost @ 5.0 t ha^{-1})	10.60	542	0.26
T_5 (EFYM @ 750 kg ha^{-1})	10.54	514	0.27
T_6 (Gypum @ 2.0 t ha^{-1})	9.75	510	0.26
T_7 (Control)	7.50	501	0.22
Mean	12.53	561	0.26
SEd	1.87	25.7	0.01
CD	4.07	57.6	0.02

activity. Research indicates that similar observations in during the course of study (30,31). The application of Navathania biomass resulted in significantly increased urease activity (0.29 µg g^{-1} soil h^{-1}) compared to all other treatments. The organic carbon and Cmb increased due to the balanced application of nutrients and manures, which was in line with increased microbial activity and enzyme. The SOC significantly impacts soil biological activity, as evidenced by the strong (positive) correlation it has with all other indices.

Navathania biomass consistently led to the highest enzyme activities due to its ability to enhance SOC content, microbial activity and functional diversity. The high organic matter content is a carbon and nutrient source, stimulating microbial growth and enzyme synthesis. Increased SOC supports microbial metabolism, boosting key enzymes like dehydrogenase, urease and phosphatases, which are essential for nutrient cycling. Enhanced microbial activity drives enzyme production, aiding organic matter decomposition and nutrient release. Additionally, improved soil structure and moisture retention create optimal microbial colonization and diversity conditions, further increasing enzymatic functions. The broader functional diversity of microbes ensures efficient nutrient mineralization and carbon turnover. Consequently, Navathania biomass-treated soils exhibit superior enzyme activities, reinforcing their role in enhancing soil fertility and microbial stability in sodic conditions (31, 32).

Conclusion

The incorporation of Navathania biomass at 5 t ha-1 emerged as the most effective organic amendment for improving soil health and crop productivity in sodic soils. It significantly enhanced SOC stock, microbial biomass carbon (Cmb), Cmb/SOC ratio and enzymatic activity, leading to a 24.3 % increase in grain yield over the control, with grain and straw yields of 4950 kg ha-1 and 7200 kg ha-1, respectively. It demonstrated superior potential for improving soil fertility, microbial diversity and nutrient cycling compared to other organic sources. These findings confirm its role in sustaining long-term soil productivity and ecosystem resilience in salt-affected areas, making it a highly efficient and sustainable soil amendment. However, practical challenges, such as sourcing large quantities and uniform field application, may limit its widespread adoption. Overcoming these challenges requires efficient supply chains and mechanized application methods.

Future research should assess the long-term sustainability of Navathania biomass in different soils and cropping systems, focusing on SOC dynamics, microbial diversity and enzyme activities over multiple seasons. Studies on its effects on salt-sensitive and high-value crops can expand its applicability. Optimizing biomass processing, efficient application methods and cost-effective transportation will support large-scale adoption. Comparative research with other organic amendments and evaluating their interaction with irrigation and fertilization regimes will further enhance their role in sustainable soil management.

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Authors' contributions

DJ conducted the experiment and drafted the manuscript and KA helped in providing valuable insights. AS helped edit the manuscript, NP assisted in manuscript preparation and MK helped with KGA and contributed to the lab analysis. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

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