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RESEARCH ARTICLE

Soil health under the *in-situ* cereal residue management of rice-wheat cropping system in the Indo-Gangetic Plain of Eastern India

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Abstract

The Indo-Gangetic Plains (IGP) of Eastern India are raising the widespread cereal residue burning rendering low soil productivity thereby threatening a sustainable environment. *In-situ* cereal residue management is a promising approach. In the present experiment conducted in Eastern India *i.e.,* Pusa, Bihar under the rice-wheat cropping system (RWCS), the treatment T_5 under the *in-situ* incorporation of cereal residue (CR), and green manure (GM) along with cereal residue decomposer (CRD) showed the significantly highest soil health indicators such as AWC, WAS, WHC, DHA, FDA, ALP, active C, SOC, available Ca, available Mg, available Fe, and available Cu followed by the treatment T_4 under CR and GM and the lowest was reported by the control treatment T_8 among all the treatments. Moreover, treatment T_5 also showed the highest Soil Health Index (SHI) followed by treatments T_4 and T_3. As per Pearson's coefficient correlation between soil health indicators and SHI, the soil health indicator *i.e.*, FDA had the highest and strongest positive correlation with SHI and the lowest with WAS, however, BD, pH, and free $CaCO_3$ were strongly and negatively correlated with SHI. Based on the above experimental findings, the *in-situ* cereal residue management under RWCS along with GM and CRD would be dual-benefits such as reducing cereal residue burnings and enhancing soil health for achieving a sustainable environment in the IGP of Eastern India.

Keywords: Indo-Gangetic plains, Soil productivity, Soil health index, Sustainable environment.

Introduction

India's Indo-Gangetic Plains (IGP) extend from Punjab in the North-Western to West Bengal in the Eastern Region of India (Jat *et al*., 2005). The IGPs are bestowed with the most fertile alluvial soil extending to a total area of 43.7 Mha of which 12.3 Mha is predominantly Rice-Wheat Cropping System (RWCS) (Ladha *et al*., 2003) contributing 50% food grain production for approximately 40% of the total population from only 27% of the total net cultivated area of the country (Dhillon *et al*., 2010). The RWCS generates around 121.2 Mt $yr.^{-1}$ of rice residue and 141 Mt $yr.^{-1}$ of wheat residue out of the total crop residue production *i.e.*, 521 Mt $yr.^{-1}$ in the country (Devi *et al*., 2017). However, they are subjected to *on-farm* burning of 92.8 Mt $yr.^{-1}$ in the country, especially in the IGPs. As the RWCS is extensively practiced under an intensive farming system, it renders a very short window period between the *kharif*-rice and *rabi*-wheat *i.e.*, 15 to 20 days. This causes the farmers to opt for cereal residue burning as the cereal residue is unable to decompose in soil within the short window period because of a wider C: N ratio *i.e.,* 80:1 and even a week delay in wheat crop sowing reduces its productivity. The continuous burning of cereal residues affects soil properties, deteriorates air quality, and induces climate change. In contrast to cereal residue burning, cereal residue management through the incorporation of the residue into the soil along with a cereal residue decomposer (CRD) is a promising task for a sustainable environment. Various CRDs in India are introduced, which can decompose the cereal residue within the short window period of RWCS. Besides, the RWCS is the most nutrient-exhaustive system and retains 25% each of N and P, 75% K, and 50% S in the residues which are lost into the atmosphere when burning rendering a loss of soil nutrient content. However, *in-situ*

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cereal residue management facilitates the return of the nutrient content in the residue into the soil. It enhances the SOM (soil organic matter), N, P, and K content (Singh and Singh 2001) thereby approaching a sustainable environment.

The Eastern India comprises Bihar, Jharkhand, Odisha, and West Bengal. Among them, the state of Bihar has a predominant RWCS. The rainfed rice cultivated area in the state is 3.2 Mha and for wheat is 2.1 Mha generating a total of 19.9 Mt per annum of cereal residues of the rice and wheat crops. Among the total crop residues being burnt in the country (92.8 Mt/yr.$^{-1}$), Bihar produced 3.19 Mt yr.$^{-1}$ of crop residues of which rice crop shares 7t ha^{-1} and wheat crop by 5t ha^{-1} and the range of the *on-farm* burning is approximately 1.48-3.91 Mt yr.$^{-1}$ (Pathak *et al*., 2010; Jain *et al*., 2014). This lack of cereal residue management reduces the soil quality such as physical, chemical, and microbiological indicators of RWCS. Generally, the alluvial calcareous soil of Bihar has a low content of soil organic carbon (SOC) and indigenous soil N, and the incorporation of cereal residue having a wider C:N ratio may further decrease the soil N content due to immobilization of soil available N during decomposition and reducing soil productivity. This N-immobilization lasts for 4 to 6 weeks when cereal residue is incorporated, and a basal dose of inorganic N sources can compensate for this. However, the minimum utilization of inorganic fertilizers is more appreciated in approaching a sustainable environment. The inorganic N-sources can be substituted with green manure, an organic source of N, at the flowering stage (Singh and Singh 2001) to optimize the immobilized soil's available N content during the decomposition of cereal residues (CR). Moreover, incorporating CR along with green manure (GM) fastened the decomposition of CR (Zhou *et al*., 2021). Even though Bihar state is bestowed with the most fertile alluvial soil, generally, the soil productivity is low. It is very crucial to hypothesize in this region whether the introduction of CRD can appreciate cereal residue management under RWCS having a short window period or not. Besides, it is highly expected that the enhancement in the decomposition rate of CR under the RWCS can increase soil health. Moreover, *in-situ* cereal residue management is a promising approach for dual benefits such as reducing cereal residue burning and improving soil health for a sustainable environment.

Materials and Methods

Experimental site

An experimental study was conducted for a cropping system of rice and wheat from 2021-22 in the Soil Science field of RPCAU, Pusa (Bihar). The location was between 25^0 59′ N latitude and 85^0 40′ E longitude with an altitude of 170.6 ft. above the mean sea level. The region lies near the Burhi Gandak River, a tributary of the Ganga River. The average rainfall of the site is 1200 cm per annum. During the experiment, the temperature range was between 33.3 and 22.4^{0}C, rainfall was between 24.6, and 36.3 mm (Fig. 1). The site's soil is alluvial calcareous soil with alkaline soil pH (8.3), SOC content (0.39%), low in the soil available N (96 kg/ha), P_2O_5 (13.9 kg/ha), medium content of available K_2O (83.5 kg/ha), and low in Zn contents (0.63 ppm).

Experimental details

The experiment was conducted in moderate upland soil with no stagnation of rainwater for long periods during the *kharif season,* and the *rabi season* received minimum rainfall. There were eight (8) different treatments and replicated thrice under *in-situ* cereal residue management, as shown in Table 1 and the plot size of each treatment was 12m^2 (3 × 4m). The k*harif*-rice was selected as the Rajendra Bhagwati variety and was transplanted for a duration of 105-110 days with a spacing of 20 ×15cm, and r*abi*-wheat as Rajendra Gehu-2 and was direct and line-seeded for 115-118 days with a spacing of 20 cm between rows. The green manure crop, *Sesbania aculeata* (Dhaincha), was broadcasted @40 kg seeds/ha as per the treatment details (Table 1) after *rabi*-wheat and before *kharif*-rice for 40-45 DAS or till before flowering initiation. The recommended dose of fertilizers (RDF) of this region under RWCS is 120:60:40 of N:P_2O_5:K_2O and applied through urea, single superphosphate (SSP), and muriate of potash (MOP); and $ZnSO_4$ fertilizer @ 25kg/ha for only in inorganic treated plot. The urea was applied at three splits of both crops in which basal dose, early vegetative growth and panicle initiation stages for rice and basal dose, tillering and before flowering stages of wheat crop. The amount of application of the 5 cm length chopped cereal residue (CR) and green manure (GM) was based on the total nitrogen (N%) content (100% N in CR should be equivalent to 120 kg N/ha) which was analyzed chemically through the acid-digestion method in the Kjeldahl apparatus in the laboratory. The cereal residue decomposer (CRD) was chosen as Pusa Decomposer, introduced by the Division

Table 1: Treatment details under the *in-situ* cereal residue management

Sl. No	*Treatments*
T_1	100% recommended dose of fertilizer
T_2	50% N cereal residue + 50% recommended dose of fertilizer
T_3	50% N cereal residue + 50% recommended dose of fertilizer + cereal residue decomposer
T_4	50% N cereal residue + 50% N green manure
T_5	50% N cereal residue + 50% N green manure + cereal residue decomposer
T_6	100% N cereal residue + cereal residue decomposer
T_7	100% N cereal residue
T_8	Control

of Microbiology, IARI, New Delhi. The preparation of the Pusa Decomposer was followed as per the method given by AICRP and applied through spraying @10 litre/acre. The wheat residue was incorporated in the soil manually through spading and rice residue was applied as mulching on the soil. The experiment was conducted under complete *in-situ* cereal residue management. During the cropping system, hand weeding was conducted whenever necessary. 2,4-D ethyl ester controlled the *Chenopodium album* weed of the *rabi*-wheat crop through spraying.

Observations to be recorded

Soil samples were collected from 0 to 15 cm depth after the RWCS through the auger method. Then it was air-dried and ground and sieved through 2 mm size for analyzing soil physical, chemical, and microbiological indicators.

Soil physical indicators

The core sampling method determined the soil bulk density (BD) (Blake 1965). The available water content (AWC) was determined with the help of the pressure plate apparatus method (Tuller and Or 2004). The water stable aggregate (WAS) and water holding capacity (WHC) were also determined as per the procedure given by Moebius-Clune *et al*. (2016) and Singh *et al*. (2005) respectively.

Soil chemical indicators

The soil pH was examined in a soil:water suspension ratio of 1:2.5 (Jackson *et al*., 1973), and electrical conductivity (EC) was estimated through a conductivity meter (Jackson *et al*., 1973). The soil organic carbon (SOC) content was estimated by rapid titration method (Walkley and Black 1934), available N by alkaline permanganate method (Subbiah and Asija, 1956), available P by Olsen's method (Olsen *et al*., 1954), available K by neutral ammonium acetate method (Jackson *et al*., 1973), extractable micronutrients (Fe, Mn, Zn, and Cu) by DTPA method (Lindsay and Norvell 1978), available B by hot-water method (Gupta 1967), available S by 0.15% $CaCl_2$ method (William and Steinbergs 1959), available Ca and Mg by neutral ammonium acetate method (Cheng and Bray 1951), and free $CaCO_3$ by rapid titration method (Puri 1930).

Soil microbiological indicators

The soil dehydrogenase (DHA) assay was determined by 2,3,5-TTC (3%) method (Klein *et al*., 1971), fluorescein diacetate (FDA) by FDA hydrolysis method (Schnurer and Rosswall 1982), alkaline phosphatase (ALP) by colorimetric method (Tabatabai and Bremner 1969), and active carbon (C) by potassium permanganate oxidation method (Weil *et al*., 2003).

Soil Health Index

Soil health index (SHI) was calculated using the average factorial deviation from the soil health indicators determined in the experiment (Brink *et al*., 1991; Wanshnong *et al*., 2013).

Statistical analysis

The experimental data obtained from randomized block design (RBD) was analyzed using ANOVA and the "F' test computed the significance between the mean of the treatments. The value of the standard error of the mean of critical differences (CD) at 0.05 (5%) level of significance was evaluated, and the difference of mean between the two treatments obtained higher than the CD value was considered significant. The covariance between the indicators was estimated through Pearson's correlation coefficient.

Result and Discussion

Soil physical indicators

The soil physical indicators such as AWC, WAS, and WHC were recorded as significantly highest by treatment T_5 *i.e.,*

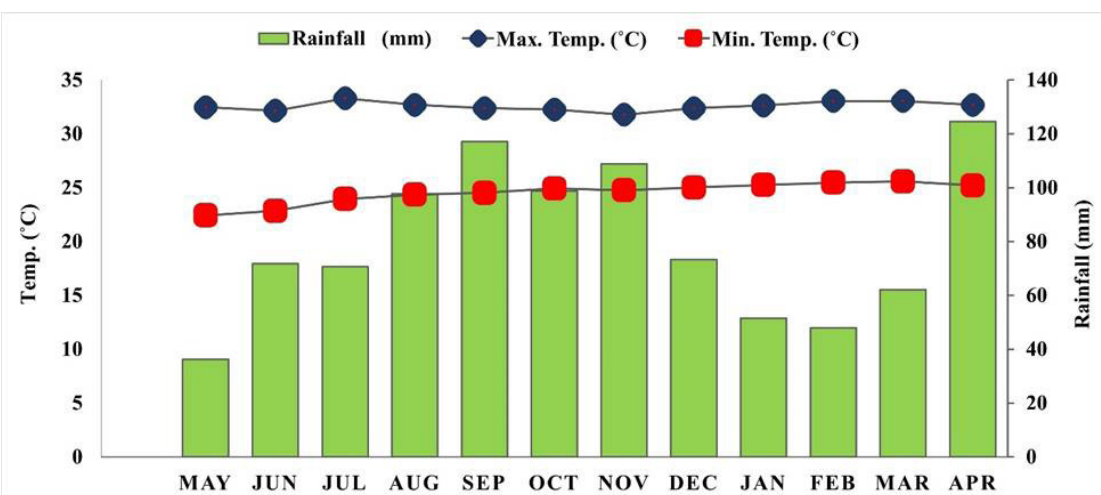

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Fig.1: Average monthly weather report of rainfall (mm), maximum temperature (°C), and minimum temperature (°C) during the experiment (2021-22)

23.3, 59.5, and 51.4% respectively followed by T_4 treatment and the lowest by T_8 treatment as compared with the other treatments (Table 2). This may be due to the proliferation of CRD facilitated by the CR and GM enhancing the soil organic matter (SOM) content to build up better soil physical indicators. The higher the SOM content, the higher the AWC and WHC (Minasny and McBratney 2017). The role of soil microbes is immense in improving the soil aggregate stability as they release organic molecules, extracellular polymeric materials, and biofilm and humus formations while the decomposition of organic matter which acts as a binding agent for soil aggregation (Martens 2000; Totsche *et al*., 2018; Strujik *et al*., 2020). Again, the soil aggregation is positively correlated with AWC and WHC. However, the control treatment lacked organic matter for proliferating the soil microbial population to facilitate soil aggregation. However, treatment under 100% CR with CRD without any N-sources might have immobilization of N nutrient while decomposing the CR and so minimum proliferation of soil microbial population for enhancing the soil physical indicators. Ultimately, the results show that diverse soil organic matters (CR, GM, and CRD) play a pivotal role in the enhancement of soil physical indicators.

Soil microbiological indicators

The soil microbial population was determined indirectly by DHA and FDA analysis. The quantity of triphenyl formazan (TPF) and fluorescein secreted from 2, 3, 5-triphenyl tetrazolium chloride and 3′6′-diacetyl-fluorescein respectively through microbial dissolution indicates a soil microbial population *i.e.,* the higher the secretion, the more the soil microbial population. The treatment T_5 significantly recorded the highest DHA and FDA *i.e.,* 144 mg/g soil/day and 22.1 µg/g soil/hr, respectively followed by the treatment T_4 *i.e.,* 141 mg/g soil/day and 21.1 µg/g soil/hr. and the lowest was recorded by the treatment T_8 *i.e.,* 82.3 mg/g soil/day and 15.8 µg/g soil/hr. When comparing among the treatments (Table 2). The result showed that the treatment under the applied CRD with CR and GM showed the highest soil microbial population which may be because the inherent alluvial calcareous soil has a low content of microbial population and the exogenous application of soil microorganisms as CRD potentially proliferated with carbon energy and nutrient sources from the organic matters of CR and GM. This also showed the abundance of decomposition of CR with N-source support from GM from immobilization. The application of green manure supplies soil nutrients helps stimulate soil microbial activities and affects the microbial population (Nivelle *et al*., 2016). The treatment with GM can record a higher total soil microbial biomass as compared with the treatment with no organic amendments (Elfstrand *et al*., 2007). The soil microbial dissolution of soil available phosphorus (P) from an insoluble form of P *i.e.,* tri-calcium phosphate was determined by ALP activity. The significantly highest ALP activity was recorded by treatment T_5 *i.e.,* 128 µg/g soil/hr followed by treatment T_4 *i.e.,* 120 µg/g soil/hr and the lowest was recorded by treatment T_8 *i.e.,* 85.1 µg/g soil/hr. as compared with the other treatments (Table 2). However, a similar CRD to the present study is composed of four tablets containing eco-friendly fungus and decomposes within 15 to 30 days (Debangshi and Ghosh 2022; Bhasker *et al*., 2022). The enhancement of ALP activity with the application of this decomposer requires further study. The soil microbial activities such as DHA, FDA, and ALP were significantly higher in the treatment under chemically diverse organic matters than in the control treatment (Sharma et al., 2023). The chemically diverse organic matters include CR, GM, FYM, compost, microbial consortia, *etc*. Moreover, the treatment applied with CRD showed a higher ALP indicating they have the potential to secrete phosphatase enzyme to dissolve the insoluble P-forms into soil-available P-forms. Similarly, the significantly highest and lowest active C was recorded by

Table 2: Influences on the soil physical and microbiological indicators for 0-15 cm depth under the *in-situ* cereal residue management of RWCS.

Treatment	*Soil physical indicators*				*Soil microbiological indicators*				
	BD (g/cc)	*AWC (%)*	*WAS (%)*	*WHC (%)*	*DHA (mg/g soil/day)*	*FDA (µg/g soil/hr.)*	*ALP (µg/g soil/hr.)*	*Active C (ppm)*	*Urease (ppm)*
T_1	1.44	17.1	51.4	47.4	84.8	16.9	88.3	804	21.0
T_2	1.42	18.3	51.9	47.5	103	18.7	93.5	923	14.5
T_3	1.40	19.5	53.7	48.8	128	20.2	100	1008	15.4
T_4	1.38	21.3	55.8	49.9	141	21.1	120	1044	13.4
T_5	1.37	23.3	59.5	51.4	144	22.1	128	1162	14.0
T_6	1.40	20.3	54.6	49.3	137	20.5	114	1010	12.3
T_7	1.41	18.7	52.4	48.5	93.3	17.6	89.5	881	11.1
T_8	1.45	15.3	50.4	46.3	82.3	15.8	85.1	792	10.5
SEm ±	0.02	0.20	0.50	0.56	0.98	0.23	1.27	10	0.13
CD (p=0.05)	NS	0.60	1.52	1.69	2.97	0.71	3.84	30	0.38

treatment T_5 *i.e.,* 1162 ppm, and treatment T_8 *i.e.,* 792 ppm, respectively (Table 2). This shows that the inclusion of CRD with CR and GM facilitates instantly available C-sources as energy sources for the proliferation of the soil microbial population. Contradictorily, the active C content under cereal residue management in calcareous soil with 10 kg Zn application per hectare was reported as 299.2 ppm (Laik *et al*., 2025) which is significantly lower than the present study. However, the significantly highest urease activity was recorded by treatment T_1 *i.e.,* 21.0 ppm followed by treatment T_3 *i.e.,* 15.4 ppm as compared with the other treatments, and the lowest was recorded by treatment T_8 *i.e.,* 10.5 ppm (Table 2). This result was supported by Paulson and Kurtz 1969 that the introduction of urea fertilizer facilitates the production of urease enzymes to dissolve the urea. In the present experiment, the treatments under 100% CR with or without CRD reported less soil microbial activities due to the immobilization of N nutrients and less inherent soil microbial population in the alluvial calcareous soil of the region, respectively.

Soil chemical indicators

The soil EC, available N, available P_2O_5, available K_2O, available S, and available Zn were recorded significantly highest by the treatment T_1 *i.e.,* 0.49 dS/m, 142, 25.4, 116 kg/ha, 25.8, and 1.0 ppm, respectively followed by the treatment T_3 as compared with the other treatments and the lowest by the treatment T_8 (Table 3). This might be due to the application of NPK and $ZnSO_4$ fertilizers significantly increasing the soil available N, P, K, and Zn nutrients and a similar result was also reported by Adekiya *et al*. 2020. Whereas the treatments with incorporation of CR might be experiencing immobilization of soil available N, P_2O_5, and K_2O. The application of CR of rice and wheat as surface applied or incorporated immobilized the soil mineral-N (Ali and Nabi 2016). Moreover, it is highly expected that the immobilization of other available soil nutrients such as P, K, Ca, Mg, S, and micronutrients along with N-immobilization under cereal residue decomposition. Besides, the application of $ZnSO_4$ fertilizer in the RWCS as low content of Zn in calcareous soil allows more availability of Zn and S in soil. The recommendation of Zn-based fertilizers (*e.g.* $ZnSO_4$) in calcareous soil as basal dose has a higher return (Khan *et al*., 2008). As the $ZnSO_4$ fertilizer is highly soluble in water (Beig *et al*., 2022) dissociates into Zn^{2+} and SO_4^{2-} facilitating enhancement of their availability in soil. Besides, the soil available Ca, available Mg, available B, available Fe, and available Cu were recorded as the significantly highest by the treatment T_5 *i.e.,* 10.3 Meq./lit., 24.8 Meq./lit., 0.85, 29.5, and 3.5 ppm, respectively followed by treatment T_4 and the lowest was recorded by the treatment T_8 (Table 3). However, the soil available Mn was statistically comparable among T_4, T_5, and T_6 *i.e.,* 15.9, 16.1, and 15.8 ppm, respectively, and the lowest by T_8 *i.e.,* 13.9 ppm (Table 3). The soil availability of Ca and Mg in the calcareous soil is inversely correlated with the pH of the soil. This means that decreasing soil pH allows for the dissolution of the insoluble forms of Ca and Mg and increases the soil available forms. The dissolution of insoluble forms of Ca (*e.g.* apatites) in acid is hugely important for the species on earth (Dorozhkin 2012). The reduction in soil pH is possible with the release of organic acids when decomposing organic matter and is directly dependent on the proliferation of soil microbial population and activities rendering organic matter a factor influencing soil pH (McCauley *et al*., 2009). The soil's

Table 3: Influences on the soil chemical indicators for 0-15 cm depth under the *in-situ* cereal residue management of RWCS.

Treat-ment	*Soil chemical indicators*														
	pH (1:2.5)	*EC (dS/m)*	*SOC (%)*	*Avl. N (kg/ha)*	*Avl. P_2O_5 (kg/ha)*	*Avl. K_2O (kg/ha)*	*Avl. Ca (Meq /lit)*	*Avl. Mg (Meq /lit)*	*Avl. S (ppm)*	*Avl. B (ppm)*	*Avl. Fe (ppm)*	*Avl. Mn (ppm)*	*Avl. Zn (ppm)*	*Avl. Cu (ppm)*	*Free $CaCO_3$ (%)*
T_1	8.24	0.49	0.40	142	25.4	116	7.88	20.4	25.8	36.2	22.5	13.9	1.00	2.70	36.2
T_2	8.25	0.47	0.43	126	18.7	95.2	8.74	21.1	22.7	36.5	23.8	15.2	0.88	2.75	36.5
T_3	8.24	0.48	0.46	128	21.6	101	8.96	21.3	24.0	36.0	24.9	15.3	0.91	2.82	36.0
T_4	8.26	0.46	0.49	117	17.3	81.4	9.85	23.5	21.5	37.0	25.4	15.9	0.81	3.28	37.0
T_5	8.25	0.48	0.50	124	17.6	94.8	10.3s	24.8	21.7	36.7	29.6	16.1	0.85	3.46	36.7
T_6	8.26	0.45	0.47	116	15.5	92.2	9.15	21.5	18.9	37.0	25.2	15.8	0.72	2.84	37.0
T_7	8.26	0.45	0.45	116	14.7	90.3	8.59	20.8	18.4	37.1	23.2	15.1	0.68	2.71	37.1
T_8	8.32	0.45	0.39	97	14.1	85.1	7.09	19.4	16.8	37.2	22.1	13.9	0.66	2.33	37.2
SEm ±	0.05	0.01	0.00	1.31	0.15	0.99	0.12	0.31	0.26	0.33	0.31	0.19	0.01	0.04	0.33
CD (p= 0.05)	NS	0.02	0.01	3.96	0.45	2.99	0.36	0.95	0.78	NS	0.95	0.58	0.02	0.13	NS

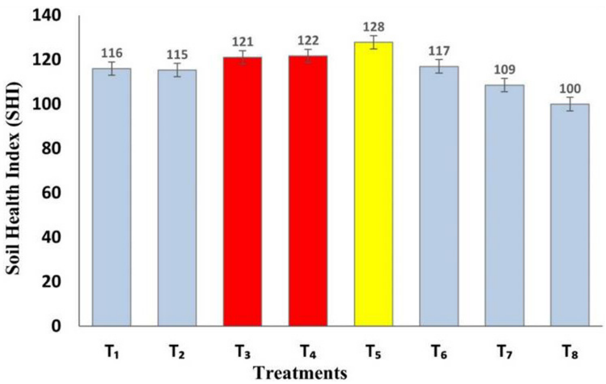

Fig. 2: Soil Health Index (SHI) for 0-15 cm depth of soil under the *in-situ* cereal residue management of RWCS.

sole source of micronutrients (B, Fe, Mn, and Cu) is organic matter (Dhaliwal *et al*., 2019). The release of organic form of micronutrients to the available form of micronutrients *i.e.,* mineralization depends on the soil microbial population and the activity as well. Soil microbes are responsible for organic matter decomposition rendering availability of soil nutrients (Furtak and Gajda 2018). The content of free $CaCO_3$ is directly dependent on the soil pH. In the infancy of the experiment, the soil pH and free $CaCO_3$ were non-significant among the treatments. The above results clearly show that the addition of CRD under *in-situ* cereal residue management along with GM made possible for decomposition of CR and made available various essential soil nutrients that are involved in soil health.

Soil health index (SHI) and Pearson's correlation coefficient

The quantified soil health indicators of soil physical, chemical, and microbiological properties were the inputs for estimating the soil health index (SHI). Among the treatments, the highest SHI was recorded by treatment T_5 *i.e.,* 128 followed by T_4 and T_3 at par, and the lowest by treatment T_8 *i.e.,* 100 (Fig. 2). This shows that the *in-situ* cereal residue management with CRD and GM provided the best soil health among other management practices in the study. Moreover, the immobilized soil available nutrients during the decomposition of CR were compensated with basal doses of nutrients either through GM or inorganic sources however GM is prioritized in approaching a sustainable environment. The inclusion of GM in cereal residue management under RWCS enhances soil health, and reduces the requirement for inorganic N fertilizers (Singh *et al*., 2007; Parihar *et al*., 2016; Chauhan *et al*., 2012). Moreover, conservation agriculture *i.e.,* retention of cereal residues, application of GM, and minimum tillage enhances the soil microbial properties and improves soil health (Das *et al*., 2014; Huang *et al*., 2013).

Pearson's correlation coefficient between the soil health index (SHI) under *in-situ* cereal residue management of RWCS and soil health indicators is shown in Table 4. This shows the soil health indicators that highly contributed to enhancing soil health expressed as SHI. The result demonstrated that the AWC, WAS, WHC, FDA, active C, available Ca, available Mg, available B, and available Zn were strongly and positively correlated with SHI, and the highest held by FDA ($r=0.896^{**}$) and the lowest by WAS ($r = 0.837^{**}$). The soil health parameters such as BD, pH, and free $CaCO_3$ were negatively correlated with SHI (Table 4). This showed that a higher proliferation of soil microbial population indicated through FDA analysis under treatment T_5 is the key to enhancing soil health as supported by soil physical and chemical indicators. The soil microbial enzymatic functions regulate soil health which is further influenced by soil physical and chemical indicators (Khati *et al*., 2017; Dasgupta and Brahmaprakash 2021).

Conclusion

The adoption of *in-situ* cereal residue management is crucial in the IGP of Eastern India for its dual benefits of reducing cereal residue burning and enhancing soil health for a sustainable environment. The soil health parameters that showed the significantly highest T_5 treatment under the *in-situ* incorporation of cereal residue (CR), and green manure (GM) along with cereal residue decomposer (CRD) were AWC by 23.3%, WAS by 59.5%, WHC by 51.4%, DHA by144 mg/g soil/day, FDA by 22.1 µg/g soil/hr., ALP by 128 µg/g soil/hr., active C by 1162 ppm, SOC by 0.5 %, available Ca by 10.3 Meq./lit., available Mg by 24.8 Meq./lit., available Fe by 29.6 ppm, and available Cu by 3.46 ppm and the SHI by128 followed by the treatment under CR and GM comparing among the other treatments. The goal of a sustainable environment would be achieved when the management is followed over the years. The application of diverse soil organic matters such as CR, GM, and CRD is highly recommended in this region.

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Declaration of Interest

The authors declare there is no conflict of interest related to this research article.

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Table 4: Pearson's correlation coefficient between soil health indicators with soil health index (SHI) under *in-situ* cereal residue management of RWCS.

	BD	*AWC*	*WAS*	*WHC*	*DHA*	*FDA*	*ALP*	*Active C*	*Urease*	*pH*	*EC*
BD	1										
AWC	-0.982***	1									
WAS	-0.928***	0.965***	1								
WHC	-0.966***	0.988***	0.974***	1							
DHA	-0.924**	0.915**	0.884**	0.884**	1						
FDA	-0.954***	0.958***	0.914**	0.92**	0.98***	1					
ALP	-0.913**	0.939***	0.957***	0.926***	0.948***	0.94***	1				
Active C	-0.961***	0.967***	0.954***	0.942***	0.956***	0.982***	0.942***	1			
Urease	0.152	-0.055	-0.068	-0.054	-0.124	-0.029	-0.102	-0.123	1		
pH	0.466	-0.512	-0.361	-0.478	-0.382	-0.511	-0.304	-0.421	-0.651	1	
EC	-0.077	0.167	0.198	0.167	0.063	0.189	0.082	0.16	0.882**	-0.663	1
SOC	-0.994***	0.971***	0.909**	0.956***	0.932***	0.946***	0.91**	0.948***	-0.212	-0.434	-0.008
N	-0.122	0.21	0.123	0.191	0.072	0.21	0.051	0.121	0.905**	-0.899**	0.86**
P_2O_5	0.14	-0.072	-0.098	-0.075	-0.104	-0.012	-0.14	-0.108	0.976***	-0.668	0.902**
K_2O	0.301	-0.188	-0.196	-0.162	-0.288	-0.188	-0.294	-0.245	0.888**	-0.596	0.797*
Ca	-0.981***	0.986***	0.92**	0.952***	0.911**	0.963***	0.914**	0.955***	-0.037	-0.557	0.17
Mg	-0.924**	0.953***	0.965***	0.942***	0.84**	0.892**	0.93***	0.92**	0.003	-0.411	0.248
S	-0.099	0.159	0.104	0.128	0.102	0.22	0.061	0.127	0.926***	-0.797*	0.927***
B	-0.963***	0.955***	0.892**	0.909**	0.971***	0.988***	0.929***	0.972***	-0.139	-0.466	0.066
Fe	-0.888**	0.936***	0.981***	0.934***	0.858**	0.902**	0.918**	0.957***	-0.062	-0.365	0.255
Mn	-0.952***	0.928***	0.837**	0.881**	0.915**	0.934***	0.864**	0.928***	-0.285	-0.423	-0.091
Zn	-0.055	0.13	0.101	0.098	0.076	0.194	0.056	0.112	0.935***	-0.741*	0.951***
Cu	-0.925***	0.954***	0.943***	0.942***	0.838**	0.897**	0.916**	0.902**	0.105	-0.514	0.309
Free $CaCO_3$	-0.035	-0.008	0.031	0.013	-0.007	-0.111	0.115	-0.045	-0.815*	0.699	-0.891**
SHI	-0.833*	0.879**	0.837**	0.853**	0.82*	0.896**	0.813*	0.856**	0.396	-0.762*	0.575

*** Correlation is significant at 0.001 level (two tailed); ** Correlation is significant at 0.01 level (two tailed); * Correlation is significant at 0.05 level (two tailed)

SOC	*N*	*P_2O_5*	*K_2O*	*Ca*	*Mg*	*S*	*B*	*Fe*	*Mn*	*Zn*	*Cu*	*Free $CaCO_3$*	*SHI*
1													
0.069	1												
-0.202	0.897**	1											
-0.343	0.849**	0.876**	1										
0.968***	0.242	-0.045	-0.21	1									
0.891**	0.189	-0.035	-0.213	0.942***	1								
0.029	0.937***	0.955***	0.769*	0.21	0.198	1							
0.965***	0.128	-0.128	-0.294	0.971***	0.88**	0.12	1						
0.863**	0.144	-0.081	-0.142	0.891**	0.932***	0.127	0.875**	1					
0.967***	0.034	-0.274	-0.389	0.948***	0.824*	-0.021	0.975***	0.817*	1				
-0.02	0.918**	0.953***	0.782*	0.174	0.191	0.992***	0.088	0.138	-0.065	1			
0.891**	0.295	0.067	-0.13	0.952***	0.99***	0.297	0.88**	0.898**	0.817*	0.279	1		
0.096	-0.84**	-0.906**	-0.816*	-0.038	0.015	-0.905**	0	-0.046	0.123	-0.902**	-0.062	1	
0.793*	0.593	0.398	0.211	0.887**	0.857**	0.598	0.84**	0.829*	0.738*	0.577	0.902**	-0.444	1