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Effect of major wheat (*Triticum aestivum*)-based cropping system and long-term residue management practices on soil carbon and nutrient availability in both plant and soil system in Inceptisol of sub-tropical India

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ABSTRACT

Residue management has emerged as a critical agronomic strategy for enhancing crop productivity while reducing the environmental footprint of agricultural practices. A long-term field experiment initiated in 2010 at ICAR-Indian Agricultural Research Institute was conducted to evaluate the effects of different cropping systems, viz. maize (*Zea mays* L.)–wheat (*Triticum aestivum* L.), pearl millet (*Pennisetum glaucum* L.)–wheat, and rice (*Oryza sativa* L.)–wheat; and residue management practices, namely residue incorporation, biochar application, residue burning, and residue removal. Soil organic carbon (SOC), major nutrients availability (N, P and K), and nutrients uptake by grains were assessed during 2022 and 2023. The results indicated that the maize–wheat system consistently outperformed the pearl millet–wheat and rice–wheat systems in terms of soil health and productivity. Among residue management practices, residue incorporation proved most effective, significantly enhancing SOC and improving soil N, P and K availability, which subsequently increased nutrients uptake by grains and overall system productivity. On average, residue incorporation increased total soil nitrogen by 27.4% and grain nitrogen uptake by 35% compared to residue removal. Additionally, a notable 23% improvement in system productivity was observed under residue incorporation relative to no-residue treatments. A strong and significant positive correlation was established between soil available nutrients and grain yield across cropping systems. Overall, the findings highlighted the importance of sustainable residue management practices, particularly residue incorporation and biochar application, in improving soil health, nutrient dynamics, and productivity of intensive cereal-based cropping systems.

Keywords: Maize–wheat cropping system, Nutrient uptake, Residue management, System productivity

Maintaining current levels of agricultural productivity under changing climatic conditions is increasingly associated with higher production costs, which threaten farmers' net returns and may discourage further investment in agriculture (Thakur and Gudade 2018). In this context, the National Institution for Transforming India (NITI Aayog) has emphasised to double farmers' real income by 2022–23, which would require an annual growth rate of 10.41% in farm income. Achieving this target necessitates not only sustaining agricultural production but also reducing input costs to enhance farmers' net income and long-term economic resilience. Crop residues represent the most abundant and readily available biomass resource in agricultural systems. The biomass remaining after crop harvest is a valuable source of organic carbon and plays a multifunctional role in regulating soil processes and agro-ecosystem functioning (Choudhary *et al.* 2018). In India alone, approximately 500 million tonnes of crop residues are generated annually (NPMCR 2020). Recycling cereal crop residues have, therefore, become a crucial component of environmentally oriented sustainable agriculture (Ghimire *et al.* 2017). However, despite their agronomic and ecological value, crop residues are often burned *in situ* by farmers due to operational constraints and the need for rapid field preparation for subsequent crops (Sharma and Dhaliwal 2020). Residue burning adversely affects soil health, contributes to air pollution, poses fire hazards, and accelerates the loss of soil biodiversity, including beneficial flora and fauna (Lohan *et al.* 2018).

The contrasting impacts of residue incorporation, burning, and removal, along with emerging practices such as biochar application, warrant systematic investigation to fully understand their long-term implications for soil health and crop productivity. Moreover, the widespread adoption of the rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.) cropping system has raised serious sustainability concerns, particularly due to excessive groundwater depletion and increased greenhouse gas emissions, especially methane

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(CH_4), from flooded rice cultivation. These challenges have intensified the need to evaluate alternative wheat-based cropping systems that are both environmentally sustainable and economically viable for farming communities.

Against this backdrop, a long-term field experiment was initiated in 2010 at the ICAR-Indian Agricultural Research Institute, New Delhi. The primary objective of this study was to assess the long-term effects of different residue management practices on soil organic carbon, availability and uptake of primary nutrients (N, P and K), and overall system productivity under three wheat-based cropping systems. The study aimed to provide scientific evidence to support sustainable residue management and cropping system diversification for enhancing soil health, productivity, and farm profitability under intensifying climatic and resource constraints.

MATERIALS AND METHODS

Experimental site: Soil samples were collected from an ongoing long-term field experiment established in 2010 at ICAR-Indian Agricultural Research Institute, New Delhi (28°38'07.4"N, 77°09'09.0"E; at an elevation of 228.61 m amsl), focusing on various residue management practices within rice–wheat (RW), maize–wheat (MW), and pearl millet–wheat (PW) cropping systems. The climate in the area can be characterised as sub-tropical and semi-arid, with an average annual precipitation of 650 mm, primarily concentrated during the rainy season (July–September). The mean annual minimum and maximum temperatures stand at 18ºC and 35ºC, respectively. The soil, classified as an Inceptisol (Holambi series, hyperthermic family, Typic Haplustepts), is non-calcareous, alkaline, and exhibits a sandy clay loam texture typical of subtropical regions in India.

Treatment details: The long-term residue management involving crop residue incorporation (an average amount of 6.6 t/ha of residues was incorporated), open burning of the same amount of crop residues in the field, crop residue converted into biochar (4.0, 4.6 and 5.3 t/ha of biochar were generated from the residues of rice, pearl millet, and maize, respectively) and complete removal of crop residues in three wheat based cropping system (Table 1). Biochar was produced from maize stover, pearl millet stalks, and rice and wheat straw using a 200 L oil barrel placed in a thermally insulated enclosure. About 8 kg feedstock was pyrolysed at ~400°C, monitored at different barrel depths. After 30 min at peak temperature, heating was stopped, the biochar was quenched with water, removed the next day, and sun-dried (Antal and Gronli 2003). The average biochar recovery from crop residues ranged between 30–40%. The total carbon content of the produced biochar was 66% for maize, while pearl millet, rice, and wheat biochar contained approximately 64% carbon each. The recommended fertiliser application rates were 150 kg N, 60 kg P_2O_5, and 60 kg K_2O/ha for rice; 100 kg N, 40 kg P_2O_5, and 40 kg K_2O/ha for pearl millet; 180 kg N, 80 kg P_2O_5, and 80 kg K_2O/ha for maize; and 150 kg N, 60 kg P_2O_5, and 60 kg K_2O/ha for wheat.

Soil sampling and analysis: A composite surface of soil samples was collected (0–15 cm) from each plot for two years (2022 and 2023) after harvesting of wheat crop. Air-dried soil samples were analysed for soil organic carbon (SOC) (Walkley and Black 1934), available nitrogen (Subbiah and Asija 1956), available P (Olsen *et al.* 1950), and available K (Jackson 1973). Upon reaching physiological maturity, the crop underwent harvesting, and grain yields were documented determined at a moisture level of 14%. The grain samples underwent digestion using a di-acid mixture (HNO_3:$HClO_4$ in a 10:1 volume ratio). Subsequently, the digested samples were analysed for P using the Vanado Molybdate yellow colour method, K via flame photometer, and N through digesting with H_2SO_4. The nutrient uptake in the grains was determined by multiplying the nutrient content in the grain by the corresponding grain yield. To evaluate system productivity, the grain yield of three wheat-based cropping systems (maize–wheat, pearl millet–wheat, and rice–wheat) was converted into wheat equivalent yield. This conversion was based on their respective Minimum

Table 1 Treatment details of the experiment

Serial no.	Treatment	Cropping systems	Residue management
1	MW-BC	Maize–Wheat (MW)	Biochar (BC)
2	MW-RI	Maize–Wheat (MW)	Residue incorporation (RI)
3	MW-RB	Maize–Wheat (MW)	Residue burning (RB)
4	MW-NR	Maize–Wheat (MW)	No residue (NR)
5	PW-BC	Pearl millet–Wheat (PW)	Biochar (BC)
6	PW-RI	Pearl millet–Wheat (PW)	Residue incorporation (RI)
7	PW-RB	Pearl millet–Wheat (PW)	Residue burning (RB)
8	PW-NR	Pearl millet–Wheat (PW)	No residue (NR)
9	RW-BC	Rice–Wheat (RW)	Biochar (BC)
10	RW-RI	Rice–Wheat (RW)	Residue incorporation (RI)
11	RW-RB	Rice–Wheat (RW)	Residue burning (RB)
12	RW-NR	Rice–Wheat (RW)	No residue (NR)

Support Prices (MSP) for the years 2022 and 2023, as outlined by Jat *et al.* (2014).

Statistical methods: The data derived from the estimated parameters underwent analysis utilising the Windows-based SPSS software (version 25). The least significant difference (LSD) values were then subjected to testing at a 5% level of significance (*p*=0.05).

RESULTS AND DISCUSSION

Effect of wheat-based cropping system on soil available N, P, K and soil organic carbon: The pooled data for two years (2022 and 2023) showed that the highest concentration of available N, P and K was found under the MW system followed by PW whereas the lowest content was recorded in the RW system (Fig. 1). The average content of available N, P and K was 13.1%, 12.78% and 5% higher under the MW system in comparison to the RW, respectively. Likewise, the content of SOC was highest under the MW system (6.91 g/kg) followed by PW (6.70 g/kg) and the lowest under (6.44 g/kg) RW system, which was significantly different from each other. The heightened SOC and other available nutrients (N, P and K) content in the MW system could be attributed to the larger maize biomass and increased recycling of residues in this system compared to the other two (Chen *et al.* 2017). Conversely, rice grown under submerged conditions experienced a reduced loss of SOC due to combination of intensive soil disturbance, residue management constraints, and enhanced carbon losses driven by alternating redox conditions. One of the primary factors contributing to SOC depletion in RW systems is the practice of puddling during rice cultivation, which disrupts soil aggregates and exposes physically protected organic matter to microbial decomposition (Six *et al.* 2002, Lal 2004). The breakdown of macroaggregates during puddling reduces aggregate-associated carbon protection, accelerating SOC mineralisation (Ghimire *et al.* 2017). Also, long-term studies across the Indo-Gangetic Plains have consistently reported lower SOC under RW systems compared to upland cereal-based systems, particularly when residue recycling is inadequate (Ghosh *et al.* 2021). Besides, the low C:N ratio in maize and pearl millet straw facilitated faster decomposition in comparison to the high C:N ratio in rice straw.

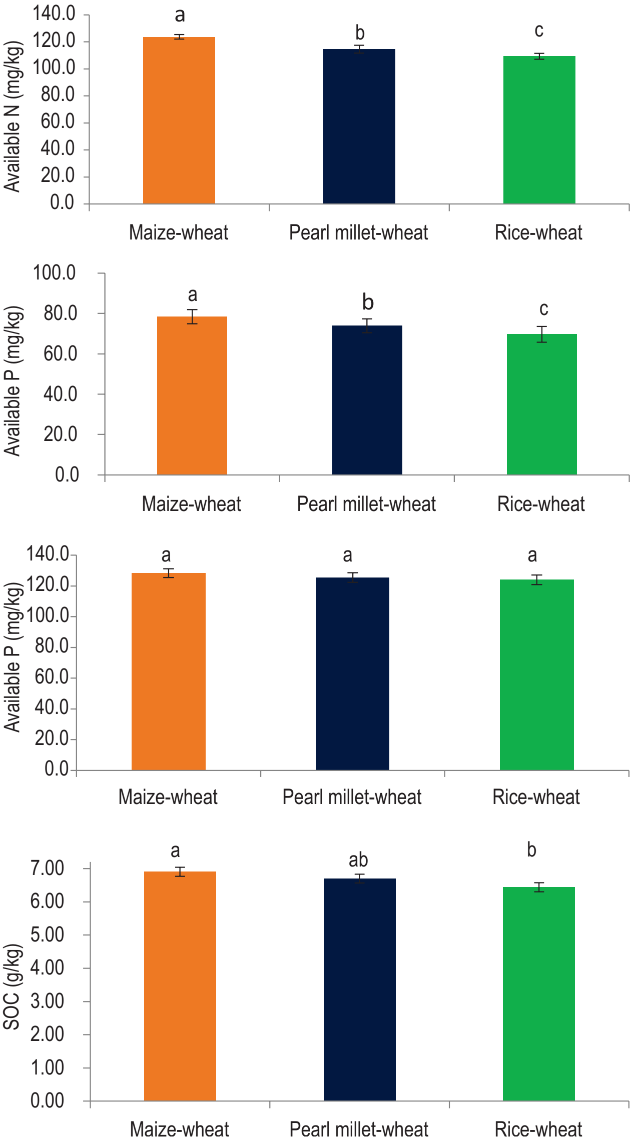

Fig. 1 Effect of wheat-based cropping systems on the available N, P, K and SOC content (mg/kg) in soil (Pooled data for 2022 and 2023).

Histograms followed by different lowercase letters are significant at *p*=0.05 and the error bar indicates the standard error of the mean. SOC, Soil organic content.

Effect of long-term residue management on available N, P, K and SOC in soil: The pooled data across two years indicated that residue incorporation significantly enhanced soil available N, P and K contents, closely followed by biochar application across all cropping systems, whereas residue burning markedly reduced nutrient availability. Residue incorporation increased available N, P and K by 27.4%, 38.7% and 19.7%, respectively compared with treatments without residue application, while biochar application increased these nutrients by 14.0%, 31.5%, and 10.3%, respectively (Fig. 2). This improvement could be attributed to the rich nutrient composition of cereal residues, containing essential elements such as N, P, K, S, Ca and Mg, which upon decomposition release nutrients into the soil, thereby enhancing nutrient accumulation and crop productivity (Krishnaprabu 2019). Biochar provided an additional benefit by adsorbing ammonium and nitrate onto its reactive surfaces, thereby reducing nitrogen losses through volatilisation (Chintala *et al.* 2014). The soil organic carbon content was associated with the combined application of crop residues and biochar. Although biochar is relatively deficient in P and did not directly increase soil P levels, it likely minimised P leaching losses by adsorbing phosphate onto its surface (Singh *et al.* 2010, Chintala *et al.* 2014). In contrast, residue burning significantly reduced available N, P and K contents by 18.3%, 23.5% and 16.0%, respectively, compared with residue incorporation. Residue decomposition increased soil available P through the release of soluble organic compounds, such as organic acids, which promote phosphate desorption and improve

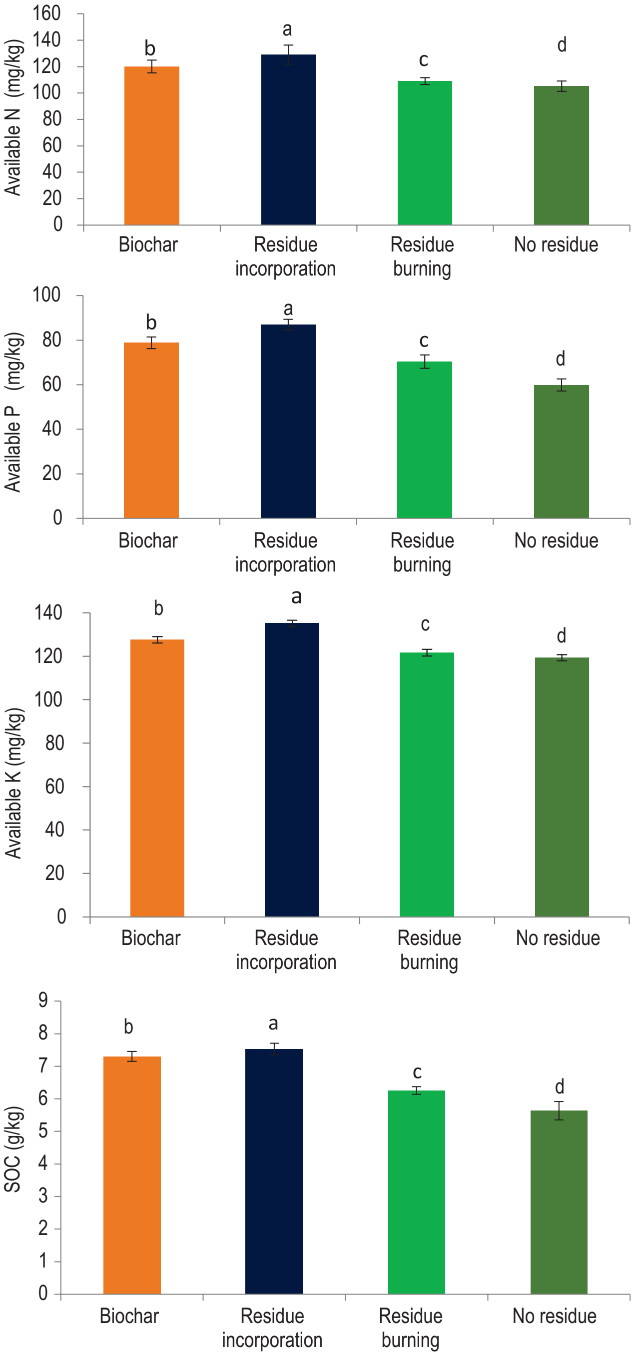

Fig. 2 Effect of residue management practices on available N, P, K and SOC (Pooled data for 2022 and 2023). Histograms followed by different lowercase letters are significant at p=0.05 and the error bar indicates standard error of the mean. SOC, Soil organic content.

soil P availability (Kumar and Singh 2021). Furthermore, crop residues serve as important reservoirs of potassium, resulting in a noticeable increase in soil available K with continuous residue application (Jat *et al.* 2019). Owing to higher carbon inputs, SOC content increased by 29.6% with biochar application and by 33.7% with residue incorporation compared with no-residue treatments across cropping systems (Fig. 2). This enhancement in SOC could be largely attributed to the protective effect of residues against carbon oxidation (Xue *et al.* 2015). Additionally, long-term incorporation of wheat straw had been reported to improve SOC stocks in rice–wheat systems (Duxbury *et al.* 2004), which corroborated the findings of the present study.

Interaction effect of cropping system and residue management on N, P and K uptake by grains: The pooled data over two years showed that residue incorporation significantly enhanced grain uptake of N, P and K by 35%, 155% and 87%, respectively, compared with residue removal. The increased availability of soil nutrients resulting from residue mineralisation likely contributed to greater nutrient uptake by crops (Kumari *at al.* 2018, Sharma and Dhaliwal 2020). In addition, the release of organic acids during residue decomposition increased labile P concentrations in the soil solution, thereby directly enhancing grain P uptake (Lu *et al.* 2009). Following residue incorporation, biochar application further improved the uptake of N, P and K by 30.7%, 70% and 49%, respectively, relative to residue removal (Table 2). The beneficial effects of biochar could be attributed to its high cation exchange capacity and large specific surface area, which enhance nutrient retention and availability in soil (Mukherjee and Zimmerman 2013). Biochar also improves nitrogen uptake by reducing losses through volatilisation and denitrification processes (Clough *et al.* 2013). Conversely, open burning of residues resulted in a decline in grain uptake of N, P and K by 26.0%, 46.5%, and 46.6%, respectively, compared with residue incorporation (Table 2), primarily due to substantial nutrient losses during the burning process (Choudhary *et al.* 2018). Among the treatment combinations, the highest grain uptake of N, P and K was recorded under MW with residue incorporation (116.7, 24.4 and 52.1 kg/ha, respectively), while the lowest uptake was observed under RW with no residue (76.4, 76.7 and 70.47 kg/ha, respectively) (Table 2).

Interaction effect of cropping system and residue management on system productivity: The data indicated that the MW system recorded the highest system productivity, followed by the RW and PW systems. During 2022, average system productivity under MW, PW, and RW systems was 10.95, 8.07, and 10.53 t/ha, respectively, whereas in 2023 the corresponding values were 11.16, 8.33, and 10.78 t/ha (Table 2). The superior performance of the MW system can be attributed to greater crop residue recycling and improved soil edaphic conditions compared to the other two systems (Bhattacharyya *et al.* 2015). Enhanced nutrient supply within the root zone through residue incorporation facilitates nutrient movement in the soil solution, thereby improving nutrient uptake and utilisation by crops and ultimately resulting in higher yields (Xu *et al.* 2019). Nevertheless, residue burning exerted a negative effect on nutrient availability in both soil and grain in the present study. However, a marginal increase in system productivity (4.43%) under residue burning compared to residue removal was observed, which may be due to the short-term availability of certain nutrients released from burned residues (Paul *et al.* 2014). Among the treatment combinations, the highest system productivity was recorded under MW with residue

Table 2 Interaction effects of residue managements and cropping systems on the grain uptake of N, P and K and system productivity under wheat-based cropping systems (Pooled data for 2022 and 2023)

Cropping system	Residue management	Nutrient uptake (kg/ha)			System Productivity (t/ha)	
		N	P	K	2022	2023
Maize–Wheat	Biochar	100.17b	16.52d	41.44c	11.52b	11.57b
	Residue incorporation	116.74a	24.40a	52.15a	12.22a	12.26a
	Residue burning	83.85d	12.63f	31.59f	10.41d	10.29d
	No residue	76.47de	9.70h	25.854i	10.03f	9.88f
Pearl millet–Wheat	Biochar	97.25b	14.87e	39.27d	8.50h	8.58h
	Residue incorporation	114.09a	23.30b	51.20a	9.44g	9.41g
	Residue burning	84.68cd	12.5f	31.89f	7.53i	7.75i
	No residue	76.73de	8.96i	25.44i	7.08j	7.22j
Rice–Wheat	Biochar	95.23bc	14.38e	37.89e	10.85c	10.84c
	Residue incorporation	101.97b	21.08c	45.93b	11.54b	11.66b
	Residue burning	77.71de	11.59g	29.45g	10.28e	10.26e
	No residue	70.47e	8.25j	28.30h	10.06f	9.90f

The values followed by different lower-case letters in a particular column are significant according to LSD at *p*=0.05.

incorporation (12.26 t/ha), while the lowest productivity was observed under PW with no residue (7.22 t/ha) (Table 2).

Correlations between soil available nutrients and grain yield: The correlation analysis between soil available nutrient concentrations (N, P and K), soil organic carbon (SOC), and grain yield demonstrated a strong positive influence of available N, P, K, and SOC on grain yield. Among these parameters, soil available K and P showed the highest correlation with grain yield, each recording a correlation coefficient of 0.94. In contrast, the correlation coefficients for SOC and available N were 0.92 and 0.88, respectively (Table 3). Available K plays a crucial role in regulating source-sink relationships during starch synthesis, including the synthesis, transport, and transformation of photosynthates, ultimately resulting in enhanced grain yield (Li *et al.* 2014). N strongly influences grain yield by increasing crop growth rate, leaf area, and leaf area index, thereby improving photosynthetic efficiency (Kibe *et al.* 2006). P is essential for plant growth and development, participating in starch metabolism and cellular respiration; thus, higher soil P availability and uptake contribute to yield enhancement (Setia and Sharma 2004). SOC accelerates nutrient cycling and improves soil physical, chemical, and biological properties, which collectively promote better plant growth and increased grain yield.

Table 3 Pearson correlation between soil organic content, available nutrients (N, P and K) and grain yield under wheat-based cropping system

	SOC (g/kg)	Avail N (mg/kg)	Avail P (mg/kg)	Avail K (mg/kg)	Grain yield (t/ha)
SOC (g/kg)	1	.820**	.953**	.929**	.926**
Avail N (mg/kg)		1	.841**	.890**	.887**
Avail P (mg/kg)			1	.956**	.943**
Avail K (mg/kg)				1	.945**
Grain yield (t/ha)					1

SOC, Soil organic content.

Long-term residue management significantly influenced the nutrient contents in soil and as well as their uptake by grain irrespective of the cropping systems. However, MW cropping system could be a promising alternative to conventional unsustainable RW system in terms of improvement of the system productivity and nutrients uptake by grains when it comes to long term residue management. In view of burning of cereals crop residues and its associated negative impact, residue incorporation/biochar could be alternative promising residue management strategies which should be promoted and popularised among the farming community for enhanced nutrient uptake and to improve the overall system productivity. It has been proved from the study that long-term burning of residues *in situ* can drastically deteriorate nutrient availability for both soils and plants and therefore, this practice must be stopped immediately to preserve the vital natural resources like soil.

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