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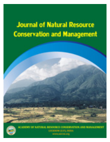

Wheat productivity and micronutrient uptake after 3 consecutive cycles of rice residue management and irrigation under rice-wheat cropping system in northwest India

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ABSTRACT

Tillage-residue management profoundly influences soil physicochemical properties, crop yield, water productivity, and micronutrient dynamics. A field experiment was conducted with a split-plot design to meticulously assess these interactions during the rabi season of 2018-19 in the wheat crop. Five tillage regimes were evaluated: rice residue incorporation with a mouldboard plough (T_1), Super Seeder (T_2), Happy Seeder (T_3), zero tillage without rice residue (T_4), and conventional tillage without rice residue (T_5). Subplots comprised three irrigation treatments: rainfed, 0.60 IW/CPE, or 0.90 IW/CPE. After three consecutive cycles of residue incorporation, soil was sampled for DTPA-extractable and fractionated Zn, Cu, Fe, and Mn. Incorporation of rice residues resulted in a significant increase in the available micronutrient fractions. Notably, the highest wheat grain yield was attained under 0.90 IW/CPE (4.83 t ha^{-1}), followed by 0.60 IW/CPE (4.71 t ha^{-1}) and rainfed conditions (4.40 t ha^{-1}). These findings underscore that strategic incorporation of rice residues not only enhances soil micronutrient bioavailability and crop uptake but also improves key soil physicochemical properties, offering a sustainable pathway to intensify rice-wheat production systems.

Keywords: Super Seeder, DTPA extractable, Residue incorporation, Happy Seeder.

INTRODUCTION

The rice-wheat cropping system (RWCS) in Punjab occupies over 60% of the cultivated area, spanning approximately 5 million hectares (Anonymous, 2025). Annually, this system generates about 51 MT of crop residues, with 22.9 MT derived from paddy and 23.1 MT from wheat (Bimbraw, 2019). Large-scale residue removal disrupts nutrient recycling and accelerates depletion of essential micronutrients in cereal-based systems (Bhardwaj *et al.*, 2018; Malik *et al.*, 2020). The adoption of high-yielding varieties, advanced machinery, and improved irrigation has boosted productivity, it has concurrently led to emergent micronutrient deficiencies (Fe, Mn, and Zn) and contributed to declining water tables, soil health deterioration, and environmental degradation (Sandhu *et al.*, 2011; Singh *et al.*, 2017). Sustained productivity of the rice–wheat system is increasingly constrained by emerging micronutrient deficiencies and soil quality deterioration under intensive cultivation (Bhardwaj *et al.*, 2016; Bhardwaj *et al.*, 2017). Imbalanced fertilization and continuous cereal cultivation have intensified micronutrient mining across Indo-Gangetic soils (Bhardwaj *et al.*, 2019; Kumar *et al.*, 2020). Long-term nutrient imbalance significantly alters soil biochemical properties and reduces nutrient use efficiency (Bhardwaj *et al.*, 2020; Malik *et al.*, 2021). The prevalence of micronutrient deficiencies in agroecosystems is exacerbated by practices such as residue burning, erosion, leaching, reduced application of organic amendments, liming of acid soils, and cultivation on marginal lands (Fageria *et al.*, 2002). A nationwide assessment by the AICRP on Micro- and Secondary Nutrients and Pollutant Elements revealed Zn, Fe, Cu, Mn, and B deficiencies in 43%, 14.4%, 6.1%, 7.9%, and 20.6% of Indian soils, respectively, based on GPS coordinated sampling of 127,752 sites (Shukla *et al.*, 2014).

Prolonged use of inorganic nitrogen and phosphorus fertilizers has been implicated in the depletion of available S, Mn, B, Zn, and Fe, whereas the integration of organic manures can enhance the content and bioavailability of these essential elements (Gao *et al.*, 2000). Exclusive reliance on chemical fertilizers without organic recycling further aggravates micronutrient deficiencies (Bhardwaj *et al.*, 2021). In situ retention of crop residues has been shown to elevate both the concentration and availability of micronutrients (Li *et al.*, 2010; Leghari *et al.*, 2015; Parr and Papendick, 1978).

Residue management practices significantly affect soil chemical properties (e.g., cation exchange capacity, organic carbon, pH), physical parameters (e.g., compaction, moisture, structure, erosion, temperature, runoff) (Singh *et al.*, 2023a), and biological attributes (e.g., microbial biomass, biodiversity) (Turmel *et al.*, 2015; Singh *et al.*,2023b). Residue-mediated nutrient recycling plays a vital role in sustaining soil productivity under intensive cropping systems (Bhardwaj *et al.*, 2018; Singh *et al.*, 2022). Incorporation of residues can replenish 50-80% of the Cu, Mn, Zn, and Fe removed by wheat and rice crops (Prasad and Sinha, 1995), and also increases soil storage of organic carbon, N, K, P, and Si (Turmel *et al.*, 2015). Residue incorporation enhances soil organic carbon and supports gradual micronutrient release through decomposition processes (Kumar *et al.*, 2020; Singh *et al.*, 2022). Enhancement of soil organic matter through residue management improves micronutrient availability and buffering capacity (Bhardwaj *et al.*, 2020; Chejara *et al.*, 2022). Improved microbial activity under residue retention promotes nutrient mineralization and soil fertility restoration (Chejara *et al.*, 2022). The efficacy of residue return in sustaining micronutrient status is contingent on factors such as residue composition, soil temperature, and microbial activity, which govern decomposition, mineralization, and nutrient cycling (Parr and Papendick, 1978).

Integrating rice residue into the soil matrix holds promise for improving micronutrient sustainability, conserving resources, and enhancing yields within the rice-wheat production system. Integrated residue and nutrient management strategies are therefore essential for restoring micronutrient balance in RWCS soils (Bhardwaj *et al.*, 2022). Against this backdrop, the present experiment was undertaken to evaluate the effects of residue management, tillage, and irrigation practices on crop growth, yield, and micronutrient dynamics in the rice-wheat cropping system.

MATERIALS AND METHODS

A comprehensive field experiment was established during the rabi season of 2018-19 at the Research Farm, PAU Regional Research Station, Gurdaspur. The experimental site is situated in the sub-mountainous agro-ecological zone at the foothills of the Shivalik range (32°03′ N, 75°25′ E; altitude: 219 m above mean sea level). The region is characterised by a semi-arid, subtropical climate with marked seasonality: summers (April-June) are typified by intense heat and aridity, with temperatures ranging from 38°C to 44°C, while the monsoon (July-September) brings a transition to hot, humid conditions. Winters (November-January) are notably cold, featuring fog and frost, with minimum temperatures reaching 2.9°C. The site receives an annual precipitation of 800-1000 mm, of which 70-80% is concentrated in the monsoonal period. This distinct climatic regime provides a representative platform for investigating the interactions between residue management and irrigation strategies on wheat productivity and soil health.

Following the harvest of the preceding rice crop, field plots were established on October 31, 2021, to facilitate the implementation of diverse tillage and residue management regimes (Thind *et al.*, 2023). The experimental treatments comprised: (T_1) soil inversion with residue incorporation via mould board plough, followed by cultivation and wheat sowing using a conventional drill; (T_2) residue incorporation and sowing with a Super Seeder; (T_3) residue retention and direct wheat sowing using a Happy Seeder (Sidhu *et al.*, 2015); (T_4) residue removal and zero-tillage wheat establishment; and (T_5) conventional tillage involving two-disc harrowings, two cultivator passes, and planking. Three distinct irrigation regimes-rainfed, 0.60 IW/CPE, and 0.90 IW/CPE were applied, where IW denotes irrigation water and CPE represents cumulative pan evaporation. Treatments were organized in a factorial randomized block design with three replications to ensure robust statistical analysis and minimize experimental error.

The experimental site's soil is classified as fine loamy, non-calcareous, and developed under a hyperthermic regime, corresponding to USDA typic Haplustalfs (Soil Survey Staff, 2003). The surface texture is silt loam, comprising 41.0% sand, 39.0% silt, and 20.0% clay. Bulk density measurements ranged from 1.45 Mg m^{-3} in the 0-15 cm horizon to 1.68 Mg m^{-3} at 60-90 cm depth, indicative of moderate compaction with increasing depth. The soil exhibited slight salinity (EC 0.21-0.28 dS m^{-1}) and was near neutral in reaction (pH 7.11-7.85). Organic carbon content was moderate (0.43%) in the uppermost layer (0-15 cm) and decreased to low levels (0.31%) in the 15-30 cm stratum. Available macronutrient concentrations also declined with depth: nitrogen ranged from 129 kg ha^{-1} (0-15 cm) to 106 kg ha^{-1} (15-30 cm), phosphorus from 18.9 kg ha^{-1} to 11.5 kg ha^{-1}, and potassium from 85.5 kg ha^{-1} to 76.2 kg ha^{-1}, respectively. This comprehensive characterization establishes the baseline soil fertility and physicochemical status before treatment imposition.

Before wheat sowing in April 2022, following the completion of three cycles of crop residue management, soil samples were collected at random across the experimental plots. Core samples were extracted at incremental depths of 0-15, 15-30, 30-60, and 60-90 cm to capture vertical variation in soil properties. Each sample was air-dried in shade, passed through a 2 mm sieve, and subsequently analyzed for a suite of physicochemical properties to assess treatment effects on soil quality.

Wheat (cultivar Unnat PBW 343) was established in the final week of October with a row spacing of 20 cm and a seeding rate of 100 kg ha^{-1}. Basal fertilizer application comprised 162 kg ha^{-1} diammonium phosphate (DAP) and 100 kg ha^{-1} muriate of potash, both incorporated at sowing. Nitrogen was supplied as urea at a total rate of 245 kg ha^{-1}, split equally between the first and second irrigations to optimize nutrient uptake. Irrigation scheduling was strictly aligned with the respective experimental treatments. Integrated weed, insect, and pest management practices were implemented in accordance with the recommended agronomic guidelines for wheat (Anonymous, 2023).

At crop harvest, key agronomic parameters, including plant height, number of productive tillers, and thousand-grain weight, were systematically measured. Grain and straw yields were determined post-threshing and standardized to a 12% w/w moisture content. Grain samples were finely ground, subjected to di-acid digestion, and analyzed for zinc, iron, manganese, and copper concentrations using atomic absorption spectroscopy, ensuring precise quantification of micronutrient uptake.

Experimental data were analyzed according to a factorial randomized complete block (RCB) design, following the methodology of Gomez and Gomez (1983), utilizing SAS software version 9.1 (SAS Institute, CA). Treatment means were compared using the least significant difference (LSD) test at the 5% probability threshold to determine statistical significance among treatments.

RESULTS AND DISCUSSION

Effect of tillage and residue management practices and irrigation regimes on growth and yield

Effects of rice residue incorporation, tillage practices, and irrigation regimes on wheat plant height at key growth stages (30, 60, 90 days after sowing [DAS], and harvest) in Table 1. While plant height did not differ significantly among treatments at harvest, notable differences were evident at earlier stages. Across all growth intervals, treatments involving rice residue incorporation-particularly with mould board plough (T_1) and Super Seeder (T_2) consistently produced greater plant height compared to treatments without residue incorporation. At 30 DAS, the tallest plants were recorded in T_1 (25.2 cm) and T2 (25.0 cm), followed by Happy Seeder (T_3, 24.6 cm), with the lowest in conventional tillage without residues (T5, 24.1 cm). At 60 DAS, maximum height occurred with T_2 (46.6 cm), followed by T_3 (45.6 cm), and the minimum in zero tillage without residues (T_4, 36.2 cm). By 90 DAS, T_1 (87.5 cm) and T_2 (85.8 cm) again led, whereas T_3 recorded the lowest height at both 90 DAS (83.9 cm) and harvest (88.1 cm). At harvest, the tallest plants were observed with T_2 (105.1 cm) and T_1 (104.4 cm). The superior plant growth with residue incorporation, especially using the Super Seeder, can be attributed to improved nutrient availability and soil moisture (Memon *et al*., 2013; Leghari *et al*., 2015). Notably, a significant interaction between irrigation regimes and tillage treatments was observed at harvest.

Table 1. Effect of tillage-residue management practices and irrigation regimes on plant height (cm)

Tillage practices	30 DAS	60 DAS	90 DAS	At harvest
T_1 (rice residue incorporation with Mould board plough)	25.2	42.3	87.5	104.4
T_2 (rice residue incorporation with Super seeder)	25.0	46.6	85.8	105.1
T_3 (rice residue retention with Happy seeder)	24.6	45.6	83.9	88.1
T_4 (Zero tillage sowing without rice residue)	24.4	36.2	85.4	90.8
T_5 (Conventional sowing without rice residue)	24.1	36.4	84.9	99.2
LSD ($P<0.05$)	NS	4.31	NS	NS
I_1 (Rainfed)	24.8	41.4	84.4	95.3
I_2 (0.60 IW/CPE)	24.6	41.7	86.0	103.3
I_3 (0.90 IW/CPE)	24.5	41.2	86.1	99.0
LSD ($P<0.05$) Irrigation	NS	NS	NS	2.35
LSD ($P<0.05$) T × I	NS	NS	NS	NS

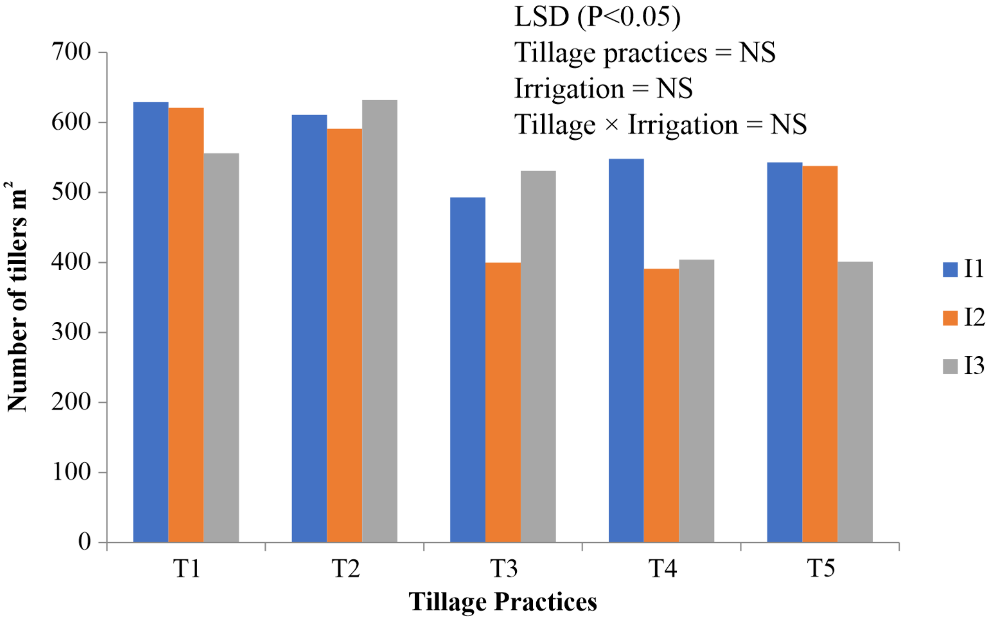

Fig. 1. Effect of tillage-residue management practices and irrigation regimes on productive tillers

Analysis of tillage practices revealed that the highest number of productive tillers at harvest occurred in treatments involving rice residue incorporation with the mould board plough (T_1) and Super Seeder (T_2). These treatments substantially outperformed conventional tillage and zero-tillage wheat without residue incorporation, as depicted in Figure 1. The enhanced tillering in these systems is likely attributable to improved nutrient cycling and soil structure associated with residue incorporation.

Thousand grain weight (TGW) was maximized in treatments involving rice residue incorporation using the Super Seeder (38.9 g) and mould board plough (38.9 g), with comparatively lower values observed for the Happy Seeder (37.7 g) and the lowest in zero-tillage wheat without rice residues (36.9 g). Irrigation regimes exerted a significant influence on TGW (Figure 2), with the highest values recorded in I_1 (38.4 g), followed by I_2 (38.1 g) and I_3 (37.4 g). Notably, TGW was consistently enhanced under tillage practices that incorporated rice residues via the Super Seeder and mould board plough. The superior TGW and grain yield associated with these treatments are likely attributable to improved water uptake and enhanced root proliferation in deeper soil layers (Qamar *et al.*, 2015), resulting in bolder and heavier grains under deep-tilled conditions (Singh and Hadda, 2015). Statistical analysis indicated no significant interaction between irrigation regimes and tillage practices for TGW.

Grain yield was maximized in treatments involving rice residue incorporation with the Super Seeder (5.06 t ha^{-1}), followed closely by the mould board plough (4.96 t ha^{-1}), whereas the lowest yield

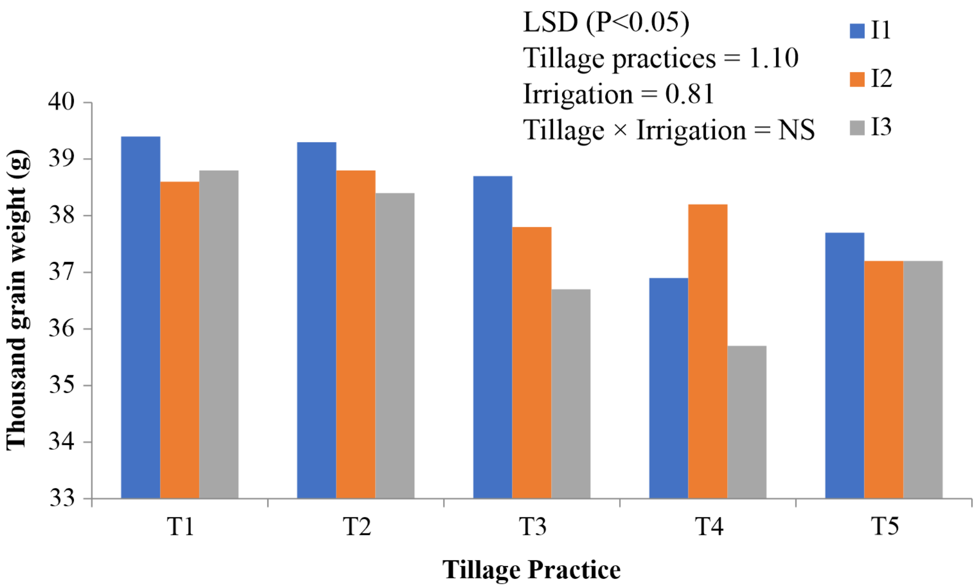

Fig. 2. Effect of tillage-residue management practices and irrigation regimes on thousand grain weight

was recorded under zero tillage without residue incorporation (4.28 t ha^{-1}) (Table 2). Deep tillage systems consistently outperformed conventional tillage, likely due to superior soil moisture retention, increased water uptake, and enhanced root proliferation in subsurface layers (Kumar *et al.,* 2024). Specifically, grain yields in T_1 and T_2 were 15% and 18% higher, respectively, compared to T_4. Among irrigation regimes, the highest yield was observed under 0.90 IW/CPE (I_3; 4.83 t ha^{-1}), followed by 0.60 IW/CPE (I_2; 4.71 t ha^{-1}), with the lowest yield under rainfed conditions (I_1; 4.40 t ha^{-1}). The improved yields under higher irrigation frequencies can be attributed to increased soil moisture availability, as supported by previous findings (Singh and Sharma, 2024).

Biological yield reached its maximum in treatments involving rice residue incorporation with the mould board plough (13.0 t ha^{-1}), followed closely by incorporation using the rotavator (12.9 t ha^{-1}), and was lowest under zero tillage without residue incorporation (11.5 t ha^{-1}). Notably, biological yield in T_1 exceeded that of T_4 by 13%, likely due to greater nutrient and moisture availability resulting from residue incorporation. Across irrigation regimes, the highest biological yield was observed under I_1 (12.6 t ha^{-1}), followed by I_2 (12.4 t ha^{-1}) and I_3 (12.1 t ha^{-1}), reflecting the influence of water management on crop biomass production.

Effect of tillage and residue management practices and irrigation regimes on grain Fe, Zn, Mn and Cu concentration and uptake

Micronutrient concentrations in wheat grain exhibited distinct patterns in response to tillage and residue management practices. Zinc (Zn)

Table 2. Effect of tillage-residue management practices and irrigation regimes on grain yield of wheat

Tillage practices	Grain yield (t ha^{-1}) I_1	I_2	I_3	Mean	Biological yield (t ha^{-1}) I_1	I_2	I_3	Mean
T_1	4.52	4.94	5.43	4.96	12.8	12.8	13.5	13.0
T_2	4.64	5.27	5.28	5.06	12.4	13.1	13.3	12.9
T_3	4.44	4.24	4.49	4.39	11.5	11.9	12.3	11.9
T_4	4.04	4.60	4.21	4.28	11.4	10.8	12.2	11.5
T_5	4.37	4.53	4.75	4.55	12.0	12.2	12.9	12.4
Mean	4.40	4.71	4.83		12.0	12.2	12.8	
LSD (P<0.05)	Tillage practices= 0.35 Irrigation= 0.19 Tillage × Irrigation = 0.44				Tillage practices= NS Irrigation= 0.615 Tillage × Irrigation=NS			

Table 3. Effect of tillage-residue management practices and irrigation regimes on concentration of Zn, Cu, Mn, and Fe in wheat grain

	Zn (mg kg^{-1})	Cu (mg kg^{-1})	Mn (mg kg^{-1})	Fe (mg kg^{-1})
Tillage practices				
T_1	41.3	3.9	20.7	96.4
T_2	40.2	3.8	21.2	94.8
T_3	41.4	3.9	20.6	96.1
T_4	40.8	3.7	21.9	93.2
T_5	40.9	3.4	21.3	93.0
LSD ($p<0.05$)	NS	NS	NS	1.38
Irrigation regimes				
I_1	40.9	3.7	20.5	94.3
I_2	40.6	3.7	21.5	95.5
I_3	39.3	3.8	21.5	94.3
LSD ($p<0.05$)- I	2.65	NS	NS	NS
LSD ($p<0.05$)- T × I	NS	NS	NS	2.99

Table 4. Effect of tillage-residue management practices and irrigation regimes on uptake of Zn, Cu, Mn, and Fe in wheat

	Zn (g ha^{-1})	Cu (g ha^{-1})	Mn (g ha^{-1})	Fe (g ha^{-1})
Tillage practices				
T_1	204	19.1	103	478
T_2	204	19.3	107.2	480
T_3	182	16.9	90.7	422
T_4	175	15.8	93.6	399
T_5	186	15.6	97.1	423
Mean	190	17.3	98.2	440
LSD ($p<0.05$)-T	NS	NS	NS	36.3
Irrigation regimes				
I_1	180	16.4	90.0	415
I_2	201	17.2	101.3	450
I_3	189	18.3	103.7	455
Mean	190	17.3	98.2	440
LSD ($p<0.05$)- I	15.9	1.34	NS	18.7
LSD ($p<0.05$)- T × I	NS	NS	NS	44.9

concentrations ranged from 40.2 to 41.4 mg kg^{-1}, with the highest values observed under rice residue incorporation using the Happy Seeder (41.4 mg kg^{-1}) and mould board plough (41.3 mg kg^{-1}), while the lowest was recorded under conventional tillage without residue incorporation (40.8 mg kg^{-1}). Copper (Cu) concentrations varied between 3.4 and 3.9 mg kg^{-1}, with peak concentrations in T_3 and T_1 (3.9 mg kg^{-1}), and the lowest under conventional tillage without residue (3.4 mg kg^{-1}). For manganese (Mn), concentrations ranged from 20.6 to 21.9 mg kg^{-1}, with the highest observed in zero tillage without residue incorporation (21.9 mg kg^{-1}), followed by conventional tillage (21.3 mg kg^{-1}), and the lowest under the Happy Seeder (20.6 mg kg^{-1}). These differences were not statistically significant for Mn and Cu across tillage or irrigation regimes, although a significant interaction between tillage and irrigation was detected for Mn. Iron (Fe) concentrations ranged from 93.0 to 96.4 mg kg^{-1}, with significantly greater values in treatments with residue incorporation highest under the mould board plough (96.4 mg kg^{-1}) and Happy Seeder (96.1 mg kg^{-1}) and lowest under conventional tillage (93.0 mg kg^{-1}). Overall, retention and incorporation of rice residues at the soil surface consistently enhanced micronutrient concentrations in grain, as summarized in Table 3.

Micronutrient uptake by wheat grain demonstrated clear effects of tillage and residue management. Zinc (Zn) uptake ranged from 175 to 204 g ha^{-1}, with the highest values observed in plots managed with the Super Seeder (204 g ha^{-1}) and mould board plough (T_1), and the lowest under zero tillage without residue incorporation (175 g ha^{-1}; Table 4). No significant interaction was detected between tillage and irrigation for Zn uptake. Copper

(Cu) uptake was greatest in treatments with residue incorporation via the Super Seeder (19.3 g ha^{-1}), followed by the mould board plough (19.1 g ha^{-1}); tillage effects were statistically significant for Cu. For manganese (Mn), maximum uptake was recorded in the Super Seeder treatment (T_2; 107.2 g ha^{-1}), followed by the mould board plough (102.9 g ha^{-1}), with the lowest in the Happy Seeder (90.7 g ha^{-1}). Iron (Fe) uptake was highest in the Super Seeder (479 g ha^{-1}), closely followed by the mould board plough (478 g ha^{-1}), and lowest in zero tillage without residue (399 g ha^{-1}). These results underscore the role of residue incorporation-particularly with the Super Seeder-in enhancing micronutrient acquisition by wheat, likely through improved nutrient cycling and elevated soil organic matter (Singh *et al.*, 2000; Torbert *et al.*, 1999). Notably, while Zn and Cu concentrations in grain were highest under the Happy Seeder, the greatest overall uptake of Zn, Cu, Mn, and Fe was achieved with the Super Seeder, highlighting the importance of both concentration and yield in determining total micronutrient removal.

CONCLUSIONS

Plant height and effective tiller number were maximized under tillage systems employing a mouldboard plough. The highest thousand grain weight was achieved in treatments incorporating rice residue with either the Super Seeder or mould board plough. Zinc uptake in wheat grain was highest in plots with residue incorporation using the Super Seeder (204 g ha^{-1}) and mould board plough. Copper uptake in wheat showed no statistically significant differences among tillage practices, although the highest value was observed in the Super Seeder treatment. Manganese uptake peaked with the Super Seeder (107.2 g ha^{-1}), followed by the mould board plough (102.9 g ha^{-1}), and was lowest in the Happy Seeder (T_3; 90.7 g ha^{-1}). Iron (Fe) uptake was highest in the Super Seeder (479 g ha^{-1}), closely followed by the mould board plough (478 g ha^{-1}). The superior grain yield observed in T_2 relative to T_4 can be attributed to enhanced nutrient acquisition and improved root system development, underscoring the agronomic advantages of residue incorporation with advanced tillage implements.

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