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Effect of tillage and weed management practices on soil micronutrients availability in post-harvest under aerobic rice-wheat cropping system

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Abstract
The present investigation was carried out at the Research Farm of the Department of Agronomy, CSKHPKV, Palampur during the *kharif* 2022 to *rabi* 2023-24 seasons, as part of an ongoing long-term experiment initiated in 2013-14. The study comprised fifteen treatment combinations involving five tillage practices CT-CT, CT-ZT+R, ZT-ZT, ZT-ZT+R, and ZT+R-ZT+R (CT: conventional tillage; ZT: zero tillage; ZT+R: zero tillage with residue retention) and three weed management strategies H-H (herbicide), IWM-IWM (integrated weed management), and HW-HW (hand weeding) within an aerobic rice-wheat cropping system. The experimental soil was silty clay loam in texture, classified under the Alfisol order and Typic Hapludalf subgroup. Post-harvest soil samples were collected from a 0-15 cm depth following wheat harvests in 2022-23 and 2023-24 and analyzed for chemical properties, particularly micronutrient availability. The treatment involving zero tillage with crop residue retention in both rice and wheat (ZT+R-ZT+R) significantly enhanced the availability of micronutrients such as Cu, Fe, Mn, and Zn. In contrast, the conventional tillage system for both crops (CT-CT) recorded the lowest levels of these micronutrients. Among weed management practices, significant differences were observed in DTPA-extractable Fe and Zn content, whereas Cu content remained unaffected.

Keywords: Zero Tillage with Residue Retention (ZT+R), aerobic rice-wheat cropping system, weed management strategies, micronutrient availability (Cu, Fe, Mn, Zn), Conventional Tillage (CT), DTPA-extractable micronutrients, post-harvest soil analysis

Introduction

Rice and wheat are two of the most vital food crops globally, forming the dietary cornerstone for billions of people. Among the various cereal-based production systems, the rice-wheat cropping sequence is not only the most extensive but also the most technologically advanced. It spans approximately 13.5 million hectares across Asia, with nearly 57% concentrated in South Asia, predominantly within the Indo-Gangetic Plains (IGP), which includes major agricultural states such as Uttar Pradesh, Bihar, Punjab, Haryana, West Bengal, Madhya Pradesh, Rajasthan, and parts of Himachal Pradesh (Banjara *et al*., 2021; Balasubramanian *et al*., 2012) [4, 3]. India, despite being the second-largest rice producer after China, leads in terms of area under rice cultivation. As of 2023, rice and wheat in India are cultivated on 47.83 and 31.40 million hectares, respectively, with total productions of 135.7 and 110.55 million tonnes (Anonymous, 2023) [2].

In recent decades, the intensification of cereal-based systems in the IGP has led to concerns over declining soil health, particularly due to unsustainable tillage and weed management practices. Tillage intensity plays a pivotal role in influencing the dynamics of soil nutrients, especially micronutrients. Conventional Tillage (CT), while effective for seedbed preparation and early weed suppression, tends to accelerate the decomposition of Soil Organic Matter (SOM), often resulting in nutrient depletion particularly in light-textured soils with poor organic matter retention (Feller and Beare, 1997; Alam *et al*., 2013) [6, 1]. In contrast, conservation tillage methods such as Zero Tillage (ZT) or permanent raised bed planting, when coupled with crop residue retention, are known to improve SOM, enhance soil moisture retention, and maintain soil structure (Govaerts *et al*., 2007) [7].

The availability of micronutrients such as Zinc (Zn), Iron (Fe), Manganese (Mn), and Copper (Cu) is closely associated with SOM content and biological activity in the soil (Boggs *et al*., 2003) [5]. However, the majority of tillage-related research has primarily focused on macronutrients such as Carbon (C), Nitrogen (N), and Phosphorus (P), with comparatively limited attention given to micronutrient dynamics. This gap is significant, as micronutrients are essential not only for optimal crop growth and yield but also for enhancing the nutritional quality of grains, which has direct implications for human and animal health. Notably, Zn deficiency has been widely reported as a limiting factor for productivity in many soils of the IGP (Kaushik *et al*., 2018) [8]. Simultaneously, weed management plays an equally important role in shaping the nutrient-use efficiency and productivity of cereal systems. Tillage influences weed seed distribution and germination, thus altering weed flora composition over time. Conventional tillage often promotes annual weeds adapted to disturbed soils, whereas zero tillage favors perennial and surface-germinating species. The growing reliance on herbicides in conservation systems has led to concerns about herbicide resistance (Norsworthy *et al*., 2012) [12], making Integrated Weed Management (IWM) which combines cultural, mechanical, and chemical methods a more sustainable approach for long-term weed suppression. In light of these considerations, the present study was undertaken to evaluate the effects of conservation tillage and weed management practices on the availability of micronutrients in the soil under an aerobic rice-wheat cropping system in the mid-Himalayan conditions of Palampur. The outcomes of this research are expected to contribute toward enhancing nutrient management strategies and sustainability in cereal-based production systems.

Materials and Methods

The present study, entitled “Effect of conservation tillage and weed management practices on nutrients and microbial dynamics in aerobic rice-wheat system”, was conducted at the Experimental Farm of the Department of Agronomy, College of Agriculture, CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur, during *kharif* 2022 to *rabi* 2023-24. The experiment forms part of a long-term trial initiated in 2013. Geographically, the research site is situated at 32°06′ N latitude and 76°03′ E longitude, at an elevation of approximately 1290 meters above mean sea level. The farm is located in the Palam Valley of Kangra district, Himachal Pradesh, and falls under the mid-hill wet temperate agro-climatic zone of the state. Climatically, the site experiences mild summers (March to June) and severe winters (December to February). It receives an average annual precipitation ranging from 2500 mm to 3000 mm, with nearly 80% of the total rainfall concentrated during the monsoon period (June to September). Weather data, including daily precipitation, minimum and maximum temperatures, and solar radiation during the experimental period, were recorded at the meteorological observatory of CSKHPKV, Palampur. A graphical representation of these weather parameters was used to support analysis of crop and soil responses.

The field experiment was conducted using a split plot design with three replications. The main plot treatments consisted of five tillage practices:

T1: CT-CT (Conventional Tillage in both rice and wheat)
T2: CT-ZT+R (Conventional Tillage in rice followed by Zero Tillage with Residue retention in wheat)
T3: ZT-ZT (Zero Tillage in both crops)
T4: ZT-ZT+R (Zero Tillage in rice followed by Zero Tillage with Residue retention in wheat)
T5: ZT+R-ZT+R (Zero Tillage with Residue retention in both rice and wheat)

The sub-plot treatments comprised three weed management practices:

W1: H-H (Application of recommended herbicides in both seasons)
W2: IWM-IWM (Integrated Weed Management in both seasons)
W3: HW-HW (Manual hand weeding in both crops)

Soil samples were collected from each treatment plot after the harvest of both rice and wheat crops at a depth of 0-15 cm. The available micronutrient content (Zn, Fe, Mn, and Cu) was determined using the Diethylene Triamine Pentaacetic Acid (DTPA) extraction method as outlined by Lindsay and Norvell (1978). The extracted samples were analyzed using appropriate instrumentation for quantification of micronutrient concentrations.

The recorded data were statistically analyzed using the OPSTAT software. Treatment means were compared using the Least Significant Difference (LSD) test at a 5% level of significance ($p<0.05$) to determine the significance of treatment effects.

Result and Discussions

DTPA-extractable iron (Fe)

The available Fe content in soil was significantly influenced by the various tillage and weed management practices during both the 2022-23 and 2023-24 cropping seasons (Table 1). The highest DTPA-extractable Fe concentrations 28.2 mg kg^{-1} in 2022-23 and 28.9 mg kg^{-1} in 2023-24 were recorded under the ZT+R-ZT+R treatment, where zero tillage was combined with crop residue retention in both rice and wheat. This enhancement in Fe availability can be attributed to the increased Soil Organic Matter (SOM) associated with residue retention and minimal soil disturbance. Organic residues promote microbial activity and the formation of natural chelating agents, such as organic acids, which in turn increase the solubility and mobility of micronutrients like iron. This finding aligns with the earlier observations of Kaushik *et al*., (2018) [8], who reported improved Fe availability under zero tillage compared to conventional systems. Among other tillage treatments, the ZT-ZT (zero tillage without residue retention) also maintained relatively higher Fe concentrations (25.6 mg kg^{-1} and 26.0 mg kg^{-1} across two years), likely due to reduced oxidation and enhanced SOM conservation under minimal tillage. Weed management practices also exerted a significant effect on Fe availability. The Integrated Weed Management (IWM-IWM) approach resulted in higher Fe content compared to herbicide-only or manual weeding treatments. This may be due to a reduction in nutrient competition between crops and weeds, as well as more balanced nutrient recycling through diversified weed suppression strategies. Similar findings were reported by Kavita *et al*., (2021) [9], who noted enhanced micronutrient availability under integrated weed management regimes. Overall, the combined use of conservation tillage with residue retention and integrated weed management proved most effective in improving DTPA-extractable Fe availability in soil under the rice-wheat cropping system.

Table 1: Effect of tillage and weed management practices on DTPA extractable iron and manganese (mg kg^{-1}) in soil after wheat harvest

Treatment (Rice - Wheat)	DTPA- extractable iron		DTPA- extractable manganese	
	2022-23	2023-24	2022-23	2023-24
Tillage				
T_1: CT-CT	23.1	23.0	20.52	20.51
T_2: CT-ZT+R	26.0	26.6	22.82	22.63
T_3: ZT-ZT	25.6	26.0	21.90	21.92
T_4: ZT-ZT+R	26.9	27.5	23.10	22.78
T_5: ZT+R-ZT+R	28.2	28.9	24.70	24.75
LSD (P=0.05)	2.08	2.10	1.40	1.29
Weed management				
W_1: H-H	25.5	25.6	21.74	21.75
W_2: IWM-IWM	26.6	27.2	23.63	23.51
W_3: HW-HW	25.8	26.3	22.46	22.27
LSD(P=0.05)	0.73	0.82	0.94	NS
Interaction (T*W)	NS	NS	NS	NS

CT: Conventional Tillage, ZT: Zero Tillage, ZTR: Zero Tillage + Residues, H: Herbicides (clodinafop 60 g ha^{-1} + MSM 4 g ha^{-1}), IWM: Integrated Weed Management [Wheat + Mustard (2:1) + Herbicide (clodinafop 60 g ha^{-1}) + Hand Weeding (45-50 DAS)], HW: Hand Weeding (30 DAS)

DTPA-extractable manganese (Mn)

The available Mn content in soil was significantly affected by the tillage and weed management practices during the study period (Table 1). The highest DTPA-extractable Mn values 24.70 mg kg^{-1} in 2022-23 and 24.75 mg kg^{-1} in 2023-24 were recorded under the ZT+R-ZT+R treatment, which combined zero tillage with residue retention in both cropping seasons. The enhancement in Mn availability under conservation tillage can be attributed to improved organic matter status and reduced oxidation of Mn^{2+} ions under minimal soil disturbance. Zero tillage without residue retention (ZT-ZT) also exhibited a significant increase in Mn content, showing 6.72% and 6.87% higher values compared to the Conventional Tillage (CT-CT) system in the first and second year, respectively. These results are in agreement with findings reported by Santiago *et al*., (2008) [13] and Kaushik *et al*., (2018) [8], who also documented enhanced Mn availability under conservation tillage practices. Among weed management treatments, significant variation in Mn content was observed only in the first year (2022-23), with Integrated Weed Management (IWM-IWM) showing relatively higher Mn availability. This is likely due to better nutrient recycling and reduced weed competition. Similar outcomes were reported by Kavita *et al*., (2021) [9]. The interaction between tillage and weed management practices, however, remained statistically non-significant for Mn availability during both years.

DTPA-extractable Copper (Cu)

The influence of tillage practices on available soil Cu content was statistically significant, though the magnitude of change remained modest (Table 2). The highest Cu concentration was observed under the ZT+R-ZT+R treatment, with values of 0.86 mg kg^{-1} in 2022-23 and 0.89 mg kg^{-1} in 2023-24. Conversely, the CT-CT plots recorded the lowest values at 0.70 and 0.67 mg kg^{-1}, respectively. Zero Tillage without residue retention (ZT-ZT) also showed a moderate increase in Cu availability, with values of 0.75 and 0.76 mg kg^{-1} across the two years. Although organic matter improves Cu retention and availability, the inherently low mobility of Cu in soil and its strong adsorption to soil colloids could explain the relatively limited response across tillage treatments. Similar observations of non-significant or limited influence of tillage on Cu content were also reported by Govaerts *et al*., (2008) [20] and Shiwakoti *et al*., (2019) [14]. Weed management practices did not show any significant effect on Cu availability during either year of the study. However, a numerically lower Cu concentration was recorded under herbicide-based treatment involving clodinafop (60 g ha^{-1}) + metsulfuron-methyl (4 g ha^{-1}), possibly due to reduced biomass recycling. The interaction effects between tillage and weed management for Cu availability were also found to be non-significant.

DTPA-extractable Zinc (Zn)

Significant differences were observed in Zn availability as influenced by tillage and weed management strategies (Table 2). The ZT+R-ZT+R and ZT-ZT+R treatments recorded the highest concentrations of DTPA-extractable Zn, with statistically similar values, while the lowest Zn content was reported under CT-CT. The improved Zn availability in conservation tillage with residue retention is attributed to the recycling of Zn-rich vegetative biomass, as approximately 50-80% of micronutrient cations taken up by rice remain in the vegetative parts, which, when incorporated back into the soil, contribute to nutrient enrichment (Singh *et al*., 2009) [16]. These findings are further corroborated by Zahid *et al*., (2020) [19], who reported enhanced micronutrient concentrations under residue incorporation compared to residue removal or burning. Weed management practices significantly influenced Zn availability during both years. Integrated Weed Management (IWM-IWM) led to higher Zn content, which may be attributed to reduced nutrient uptake by weeds and better synchrony of nutrient release and crop demand. These results are consistent with the findings of Kavita *et al*., (2021) [9] and Singh *et al*., (2016) [15], who reported higher micronutrient availability under IWM in wheat-based systems. However, the interaction effect between tillage and weed management on Zn availability was statistically non-significant, indicating their independent contributions to soil Zn dynamics.

Table 2: Effect of tillage and weed management practices on DTPA- extractable copper and zinc (mg kg^{-1}) in soil after wheat harvest

Treatment (Rice -Wheat)	DTPA- extractable copper		DTPA- extractable zinc	
	2022-23	2023-24	2022-23	2023-24
Tillage				
T_1: CT-CT	0.70	0.67	1.53	1.50
T_2: CT-ZT+R	0.78	0.79	1.61	1.63
T_3: ZT-ZT	0.75	0.76	1.59	1.61
T_4: ZT-ZT+R	0.83	0.85	1.65	1.67
T_5: ZT+R-ZT+R	0.86	0.89	1.68	1.73
LSD (P=0.05)	0.03	0.05	0.06	0.05
Weed management				
W_1: H-H	0.77	0.78	1.58	1.59
W_2: IWM-IWM	0.80	0.81	1.65	1.67
W_3: HW-HW	0.79	0.79	1.60	1.62
LSD (P=0.05)	NS	NS	0.04	0.05
Interaction	NS	NS	NS	NS

CT: Conventional Tillage, ZT: Zero Tillage, ZTR: Zero Tillage + Residues, H: Herbicides (clodinafop 60 g ha^{-1} + MSM 4 g ha^{-1}), IWM: Integrated Weed Management [Wheat + Mustard (2:1) + Herbicide (clodinafop 60 g ha^{-1}) + Hand Weeding (45-50 DAS)], HW: Hand Weeding (30 DAS)

Conclusion

The results of the present long-term study clearly indicate that the continuous adoption of conservation tillage practices over an eleven-year period has led to a significant improvement in soil micronutrient status, particularly with respect to DTPA-extractable Iron (Fe), Manganese (Mn), Copper (Cu), and Zinc (Zn). Among the evaluated weed management strategies, Integrated Weed Management (IWM) proved more effective in enhancing the availability of Fe and Zn compared to herbicide-based or manual weeding approaches. These findings underscore the importance of a combined approach involving zero tillage with crop residue retention and integrated weed management as a sustainable soil management strategy to improve micronutrient availability, enhance soil health, and support long-term productivity in aerobic rice-wheat cropping systems.

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