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Research Article

Integration of Organics in Nutrient Management Improves Micronutrient Profile of Soil and Plants: A Case Study of Rice-Wheat Systems in Indo-Gangetic Plain

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Abstract

Incidences of micronutrient in human beings is an emerging challenge at global scale. Crop plants are the major source of micronutrients in the human diet via either direct consumption of plant parts or indirectly through the use of dairy and meat from animals fed on fodder and crop residues. In a 10-year long experiment on soil nutrient management for the rice-wheat cropping systems, the effects of six common managements on the daily plant availability of Zn, Fe, Cu, their stocks in soil, and the translocation into grain and straw were studied. The management included: 1) F=100% inorganic macronutrient (N, P, K) and micronutrient (Zn) fertilizers compared to reduced macronutrient fertilizer (55% of N, P, K; *no micronutrient*) application supplemented with organic inputs from 2) LE=opportunity legume crop (Green gram; *Vigna radiata*) biomass incorporation, 3) GM=green manuring with *Sesbania aculeata*, 4) FYM=farmyard manure incorporation, 5) WS=wheat stubble incorporation, and 6) RS=rice stubble incorporation. In the case of 100% inorganic nutrient management (F), significant soil buildup of micronutrient Zn neither translated into proportionate availability in soil solution during crop growth nor improved translocation to plant parts. All organic supplemented management, particularly legume-based, resulted in higher availability of Zn, Fe, and Cu in soil solution during crop growth, and better translocation into plants, compared to 100% inorganic fertilizer use. Total zinc harvests in legume based organics integration in nutrient management are comparable with zinc fertilization. Rice and wheat serve, almost in the whole world, as a staple food and their straw serves as feed for animals in many regions. The study indicated to considerable improvement in micronutrient status of rice-wheat crops when grown with integration of organics in nutrient management. Thus, integration of organic inputs has the potential to improve the micronutrient nutritional quality of rice-wheat crops and may contribute to addressing micronutrient deficiency, while recognizing that confirmation of effects on human nutrition would require dedicated dietary and nutritional studies.

Keywords: Copper, iron, malnutrition, micronutrient, organic management, zinc

1. Introduction

The Indo-Gangetic Plains (IGP) of South Asia support nearly one billion people, with about 40% living in extreme poverty (Balasubramanian *et al.*, 2013). In the Indian IGP, the rice-wheat (R-W) system is dominant, covering about 10.3 Mha and accounting for 23% and 40% of India's rice and wheat areas, respectively (Ladha *et al.*, 2003). Rice is grown during the kharif season (June-October), followed by wheat during rabi (November-March/April), leaving a short fallow period between crops (Gathala *et al.*, 2013). This fallow period offers an opportunity to grow short-duration legumes or green manure crops during May-June to improve soil health and sustain crop productivity.

The soil is a large reservoir of nutrients that not only plays a role in plant growth but also serves as an essential nutrient source for human-beings indirectly. Increased population pressure, particularly in developing countries, has led to intensive crop production systems which have deprived the soil of the nutrients essential in the human diet, while crop fertilization is skewed mostly towards nitrogen (N), phosphorus (P), and potassium (K) use to increase crop growth and productivity (Vitousek *et al.*, 2009). This has resulted in rapidly growing micronutrient malnutrition (Gardner and Halwell, 2000). Micronutrient deficiency in the diet affects more than half of the world's population (Akhtar and Ashgar, 2011). More than 30% of the world's population is zinc (Zn) deficient and more than 60% is Iron (Fe) deficient (WHO, 2002; White and Broadley, 2005). Fortification of foods with micronutrients like Zn and Fe, therefore, is a global priority program (Joy *et al.*, 2015, Dimpka and Bindraban, 2016). More and more countries are including expensive micronutrient supplementation and fortification in their nutritional health policies to combat Zn, Fe, and other micronutrient malnutrition (WHO, 2018).

In Indo Gangetic plains occurrence of zinc deficiency in crops under soils of alkaline reaction is due to the low solubility of zinc, rather than zinc content in the soil. In north India zinc deficiency decreased from 66% in 1988 to 24.2% in 2008 because of regular use of zinc sulphate. Zinc sulphate consumption has been increased from 1752 to 22600 t yr^{-1} in Uttar Pradesh, 1692 to 11470 t yr^{-1} in Haryana and 16292 to 48,000 t yr^{-1} in Punjab during the years of 1988 to 2008 (Singh *et al.*, 2009). Iron Deficiency in soils of North India zone are not extensively observed (Singh *et al.*, 2009).

Fertilizers have an immense effect on crop growth and yield, and therefore, are most adopted for crop production. However, excessive and imbalanced use of any fertilizers have serious environmental pollution-related issues, and therefore, organic manuring has been encouraged for maintaining sustainability of agro ecosystem. Though organic manures improve the supply of nutrients to soils and plants grown on such soils, they have other issues such as labor and energy-intensive operations, inadequate availability of organic materials, and uncertainty of nutrient release characteristics when applied (Goenadi *et al.*, 2017). In most cases, especially for grain crops, sole organic fertilization has limitations in meeting crop macro-nutrient (N, P, K) requirement and maintaining the desired productivity (Nelson *et al.*, 2004; De Ponti *et al.*, 2012; Seufert *et al.*, 2012). The availability of organic manures has declined, particularly in the developing world, due to shifting from integrated (animal-based) farming to labor-saving mechanized farming. Application of farmyard manure (FYM) is one of the oldest practices, particularly in South Asia, yet it has become less viable due to the limited availability of FYM at the farm level. These reasons discourage farmers to adopt purely organic fertilization options (Goenadi *et al.*, 2017).

Integrated nutrient management (INM) programs (inorganic fertilizers plus organic amendments) have recently found increased success due to the availability of a diversity of new options, like retaining a part of crop residue/stubble on the surface or plowing it in as agricultural waste management strategy. Even a high C/N ratio of these materials would not pose much a problem in integrated use with inorganic fertilizers. Options also include diversification of cereal-based systems to include legumes which can fix atmospheric N and have low C/N biomass, to counter declining soil fertility. Government-supported programs have particularly encouraged the adoption of legumes in cropping cycles. Recently, retention and incorporation of crop residues into arable soil have been vigorously encouraged as an environment-friendly practice, particularly as an option to burning stubble, in the Indian subcontinent (Gupta, 2014). Crop residues are a rich source of organic carbon and improve microbial activity in the soil (Changitny, 2003; Bhardwaj *et al.*, 2019; Bhardwaj *et al.*, 2020). When decomposed, these residues foster the release of micronutrients as well as promote their mobilization by forming soluble metal-organic complexes (Strobel *et al.*, 2001; Ashworth and Alloway, 2004).

While organic or INM programs advocate benefits in terms of soil health and environmental pollution reduction, yet benefits in terms of nutrient release in soil and their plant availability have not been thoroughly explored, especially for micronutrients. Furthermore, the relationship between soil stocks, periodic release and plant availability, and translocation to plant parts has rarely been investigated. Therefore, in this study, we investigated effects of 10 years of management under six integrated nutrient management options for rice-wheat cropping on three micronutrients: zinc (Zn), iron (Fe), and copper (Cu), with particular regard to their daily plant availability in soil solution, translocation to grain and straw, and effects on soil available-stocks. We report the temporal dynamic of several INM options on micronutrient availability in soil solution at a daily scale and its relation with grain and straw micronutrient status.

2. Materials and Methods

2.1 Study site and experimental layout

A long term experiment on soil nutrient management for rice-wheat cropping systems was started in 2005 on a sandy loam textured soil at ICAR-Central Soil Salinity Research Institute (CSSRI), Karnal, India, located at 29.43 ^{o}N and 76.58 ^{o}E. At the initiation of the experiment, the soil (0-15 cm) pH= 8.7 (1:2, soil to water), cation exchange capacity = 9.5 cmol kg^{-1}, and organic carbon = 3.2 g kg^{-1}(Yaduvanshi *et al.*, 2013). The experimental area has a semi-arid subtropical climate with a mean annual precipitation of 750 mm.

The treatments included six combinations of different inorganic and organic fertilizers. With the treatments enforced for 14 years, the present examination of nutrient availability in soil solution, using ion-exchange resin (IER) strips, was carried out during 2017-18 and 2018-19, over four full growing seasons. The treatments included five management with combinations of organic amendments and reduced inorganic fertilizer (55% of recommended) i.e., GM-green manure (*Sesbania aculeata*), FYM- farmyard manure, LE- legume (*Vigna radiata*), WS- wheat straw, and RS-rice straw, compared to 100% of recommended inorganic fertilizer (F). The plot size was 5 x 4 m. The treatments were implemented with four replications in a completely randomized block design.

Following management schedules were followed for different treatments:

1. **F**: Rice followed by wheat was grown with only inorganic macronutrient fertilizer inputs (N, P, K, @ 180, 26, 42, kg ha^{-1} respectively, for both rice and wheat). Only Zn as micronutrient fertilizer (as $ZnSO_4$ salt) was applied @7 kg ha^{-1} for both rice and wheat. No organic inputs were given. Rice and wheat crop residues were completely removed at the harvest.

2. **LE**: Legume crop, green gram (*Vigna radiata*), was grown in the summer lean period between wheat and rice as an "*opportunity crop*". The *Vigna* seeds were sown in the last week of April, after wheat harvest. No fertilizers or inoculants were applied to the legume crop, and the seeding rate was 25 kg ha^{-1}. Sowing was done in 30 cm spaced rows. In the first week of July (after 60-70 days of sowing) pods were harvested and the remaining plant biomass was dry plowed into the soil during the first week of July, followed by puddling (30 cm) and transplanting of rice. Only 55% of inorganic macronutrient (N, P, K) fertilizers were applied to both rice and wheat crops in the same manner as in F. No micronutrient fertilizers were applied in this management. Rice and wheat crop residues were completely removed at the harvest.

3. **GM**: A green manure crop, *Sesbania aculeata*, was grown in the lean period between wheat and rice. No fertilizers were applied to the green manure crop. The green manure crop was sown @ 25 kg ha^{-1} on or around the 20th of May every year. No fertilizers were applied to the green manure crop. After 35-40 days of sowing, the green manure crop was dry plowed into the soil during the first week of July, followed by puddling (30 cm) and transplanting of rice. Only 55% of inorganic macronutrient (N, P, K) fertilizers were applied to both rice and wheat crops in the same manner as in F. No micronutrient fertilizers were applied in this management. Rice and wheat crop residues were completely removed at the harvest.

4. **FYM**: Farmyard manure (FYM) at the rate of 10 Mg ha^{-1}was dry plowed into the soil during the first week of July, followed by puddling (30 cm) and transplanting of rice. Only 55% of inorganic macronutrient fertilizers (N, P,

K) were applied to both rice and wheat crops in the same manner as in F. No micronutrient fertilizers were applied in this management. Rice and wheat crop residues were completely removed at the harvest.

5. **WS**: 30 cm standing stubble of wheat was retained at the time of harvesting. The standing stubble was dry plowed into the soil during the first week of July, followed by puddling (30 cm) and transplanting of rice. Only 55% of inorganic macronutrient (N, P, K) fertilizers were applied to both rice and wheat crops in the same manner as in F. No micronutrient fertilizers were applied in this management.

6. **RS**: 30 cm standing stubble of rice was retained at the time of harvesting of rice. It was dry-plowed into the soil (30 cm) at the time of wheat sowing in 2nd week of November. Only 55% of inorganic macronutrient fertilizers were applied to both rice and wheat crops in the same manner as in F. No micronutrient fertilizers were applied in this management.

Rice-wheat cropping system has rice crop grown from July to October (summer monsoon), followed by wheat crop from November to April (winter). Rice is grown during the rainy season which receives 70-80% of total annual rainfall followed by wheat during the relatively drier winter season. For transplanting of rice crop, dry plowing was carried out in all of the treatments followed by puddling under water-flooded conditions, during the first week of July. For treatments with organic inputs, the materials were mixed in the soil during dry plowing with power tiller (VST Shakti 130, V.S.T. Tillers Tractors Ltd., Bengaluru, India). Around 7th July, 30 days old nursery-raised rice seedlings (var. Pusa 44) were transplanted in the treatment plots. Inorganic fertilizers were applied immediately before transplanting. Wherever applicable, the N fertilizer application was in three equally split doses. The first 1/3 dose was immediately before transplanting, the second 1/3 dose was at 21 days after transplanting (DAT), and the third 1/3 dose was at 42 DAT. Rice crop was maintained under flooded conditions with nearly 10 cm of water head for one month with daily irrigation if needed, around 5 cm head for the next one month, and saturated conditions with no surface-standing water in the third month. Flooded to saturated (1 month) conditions existed in the rice crop until the last 15 days when irrigation was stopped and soils dried before harvesting. After harvesting the rice crop in the third week of October, the treatment plots were dry-plowed and wheat seeds (var. HD 2967) were sown in the second week of November. The wheat crop under different treatments received only inorganic fertilizers, in the same doses as rice crop. The wheat crop was harvested in the second week of April.

2.2 Plant available micronutrients in soil solution

Micronutrient availability in the different managements was determined throughout the cropping period using the ion exchange resin (IER) membranes. Membrane strips (cation and anion, separately) of 2.5 cm x10 cm size were cut out from commercially available large sheets (General Electricals, Watertown, MA, USA). The strips were charged by dipping and shaking in 0.5 mol /L HCl for 1.2 h, and then in 0.5 mol/L $NaHCO_3$ for 5 h. Following this, strips were rinsed with deionized water and placed directly in vertical apertures made in treated soils. Two strips (1 anion and 1 cation in each plot) were inserted into soil covering up to 15 cm depth. Each aperture was firmly closed to allow instant contact with soil. Both cation and anion strips were placed 5 cm apart in the soil for ~ 15 days interval and were replaced with new ones immediately after removing the previous set of strips. The new strips were always installed 15-30 cm away from the previous spot, in the clockwise direction. One pair of strips was installed per plot, constituting four pairs per treatment at a particular point of time. This process was continued for the entire period of study. After removal from the soil, the strips were rinsed with deionized water to eliminate any adhering soil. For analysis, both strips (cation and anion) put together in a vial for extracting micronutrients in the laboratory. For extraction, 70 ml of 2mol L^{-1}KCl was added to the vials containing strips, shaken for 1 h, and decanted into a scintillation vial. The filtered extracts were analyzed using Atomic Absorption Spectrophotometer (AAS) (ZEENIT 700P, Analytik Jena, Germany).

The availability of micronutrients was calculated as:

2.3 Micronutrient content of soil, grain, and straw

Two random soil samples per plot (four replications) were collected from 0-15 cm depth at the harvest of both rice and wheat crop, from 0-15 cm depth, using a soil auger. The two soil samples were aggregated together to represent one plot. The replication-wise samples were air-dried, ground, and sieved through a 2 mm sieve. Toa

10 g of the soil sample, 20 ml of the DTPA solution [0.05 M diethylene triamine penta acetic acid, 0.01 M calcium chloride ($CaCl_2$), and 0.10 M triethanolamine adjusted to pH 7.3] was added to extract micronutrients (Zn, Fe, Cu) (Lindsay and Norvell, 1978). The extracts were analyzed using AAS (ZEENIT 700P, Analytic Jena Germany).

Grain and straw samples of rice and wheat, for each treatment, were collected at the harvest, replication-wise, using 1 m^2 quadrat. The location of the quadrat was positioned at the center of the plot to eliminate edge effects and away from other observation-spots. 100 g subsamples were further drawn and oven-dried (at 60°C) to constant weight. These dried samples were ground, and a further subsample of 0.5 g was digested with concentrated HNO_3 and $HClO_4$ mixture in the ratio of 5:1. Each digest was transferred to 50 ml volumetric flask to make volume using double distilled water, and finally, filtered. The concentrations of micronutrients i.e., Zn, Fe, and Cu in the samples were determined using the AAS (ZEENIT 700P, Analytic Jena Germany). The concentration of micronutrients in the organic amendments is provided in Table 1.

Table 1. Micronutrient (Zn, Fe, Cu) concentrations of organic materials under different nutrient management systems for rice-wheat. Numbers in brackets indicate ± *1 SE*.

Management	Organic amendment	Concentration (mg per kg dry matter)		
		Zn	Fe	Cu
F	**None**	-	-	-
LE	**Legume crop (*Vigna radiata*) biomass**	0.48 (*0.02*)	1.97 (*0.24*)	0.09 (*0.00*)
GM	**Green manure crop (*Sesbania aculeata*) biomass**	0.42 (*0.01*)	3.44 (*0.42*)	0.16 (*0.01*)
FYM	**Farmyard manure**	0.56 (*0.01*)	18.50 (*1.79*)	0.13 (*0.01*)
WS	**Wheat stubble**	0.26 (*0.01*)	3.24 (*0.12*)	0.27 (*0.02*)
RS	**Rice stubble**	0.29 (*0.02*)	1.33 (*0.08*)	0.22 (*0.01*)

2.4 Statistical Analysis

The micronutrient availability data was found to be normally distributed and separation of means was subjected to Tukey's t-test. Correlation analysis was conducted to delineate relationships between the measured parameters. All tests were performed at the 0.05 significance level. Statistical analysis was performed using JMP v. 9.0 (SAS Inc., Cary, NC, USA) and graphing was done using Origin v.8.5 (OriginLab Corp., Northampton, MA, USA). The straw, grain, and soil micronutrient contents represent averages of four plot replicates and two cropping cycles (2013-14 and 2014-15).

3. Results

Assessment of Zn stocks in soil and translocation to plant parts (Fig. 1) revealed significant effects of integrated management. The F management had fertilizer application of $ZnSO_4$ while other INM management had no application. On one hand, significant stocks of Zn (DTPA extractable) in the soil in F (100% inorganic fertilizers only) revealed a buildup of Zn in soil. On the other hand, LE which had the removal of green gram pods had the lowest soil Zn (DTPA extracts). Amongst integrated management, all except LE maintained similar levels of Zn in soil. Zn translocation to grains was maximum in GM and F treatments for wheat grains and non-significantly different for rice grains. For straw (wheat as well as rice) there were no significant differences except LE which had lower Zn content in wheat compared with F treatments.

In the case of Fe, no significant differences amongst management were noted for soil stocks (Fig. 2). For both grain and straw of rice, LE and GM management resulted in the highest availability of Fe amongst all management. For Cu, no significant differences were noted amongst management, for soil stocks (Fig. 3). GM had maximum translocation of Cu in rice grain and straw. Further, LE and GM treatments significantly enhanced Fe content in grain and straw of wheat, while no significant differences was observed for straw.

In terms of total micronutrient Zn, Fe, and Cu which were harvested (concentration x grain and straw harvested)

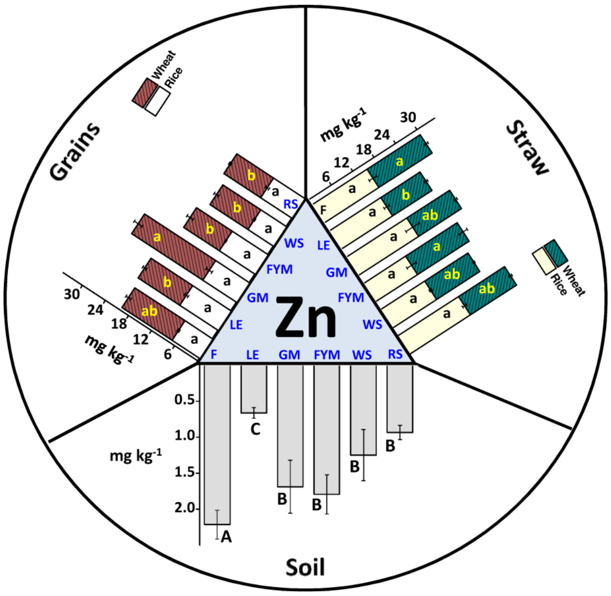

Fig. 1: Concentrations of zinc (Zn) in soil (DTPA extractable), grains (total), and straw (total) under different management. F=100% inorganic macronutrient(N, P, K) fertilizers + 100% Zn fertilizer, LE= 55% inorganic macronutrient (N, P, K) fertilizers + opportunity legume crop (*Vigna radiata*) biomass incorporation, GM=55% inorganic macronutrient (N, P, K) fertilizers + green manuring with *Sesbania aculeata*, FYM=55% inorganic macronutrient (N, P, K) fertilizers + farmyard manure incorporation, WS=55% inorganic macronutrient (N, P, K) fertilizers + 30 cm wheat stubble *in situ* retention & incorporation, RS= 55% inorganic macronutrient (N, P, K) fertilizers + 30 cm rice stubble *in situ* retention & incorporation. Error bars denote ± 1 SE. Managements with the same letters are not significantly different at p≤0.05. Dark small letters designated statistical differences for rice (grain and straw), and light small letters for wheat (grain and straw). Capital letters designated statistical differences for soil.

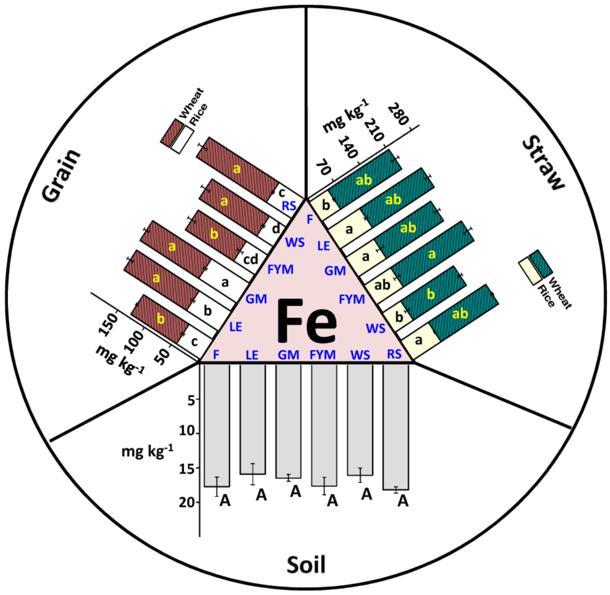

Fig. 2: Concentrations of iron in soil (DTPA extractable), grains (total), and straw (total) under different management. F=100% inorganic macronutrient(N, P, K) fertilizers + 100% Zn fertilizer, LE= 55% inorganic macronutrient (N, P, K) fertilizers + opportunity legume crop (*Vigna radiata*) biomass incorporation, GM=55% inorganic macronutrient (N, P, K) fertilizers + green manuring with *Sesbania aculeata*, FYM=55% inorganic macronutrient (N, P, K) fertilizers + farmyard manure incorporation, WS=55% inorganic macronutrient (N, P, K) fertilizers + 30 cm wheat stubble *in situ* retention & incorporation, RS= 55% inorganic macronutrient (N, P, K) fertilizers + 30 cm rice stubble *in situ* retention & incorporation. Error bars denote ± 1 SE. Managements with the same letters are not significantly different at p≤0.05. Dark small letters designated statistical differences for rice (grain and straw), and light small letters for wheat (grain and straw). Capital letters designated statistical differences for soil.

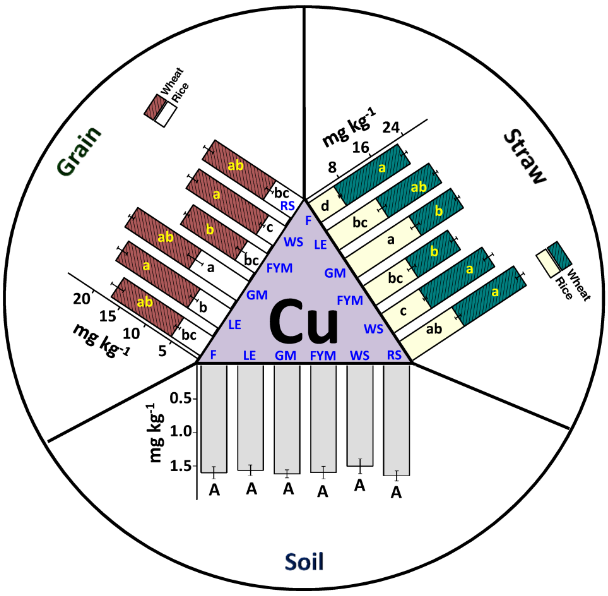

Fig. 3: Concentrations of copper (Cu) in soil (DTPA extractable), grains (total), and straw(total), under different management. F=100% inorganic macronutrient(N, P, K) fertilizers + 100% Zn fertilizer, LE= 55% inorganic macronutrient (N, P, K) fertilizers + opportunity legume crop (*Vigna radiata*) biomass incorporation, GM=55% inorganic macronutrient (N, P, K) fertilizers + green manuring with *Sesbania aculeata*, FYM=55% inorganic macronutrient (N, P, K) fertilizers + farmyard manure incorporation, WS=55% inorganic macronutrient (N, P, K) fertilizers + 30 cm wheat stubble *in situ* retention & incorporation, RS= 55% inorganic macronutrient (N, P, K) fertilizers + 30 cm rice stubble in situ retention & incorporation. Error bars denote ± 1 SE. Managements with the same letters are not significantly different at p≤0.05. Dark small letters designated statistical differences for rice (grain and straw), and light small letters for wheat (grain and straw). Capital letters designated statistical differences for soil.

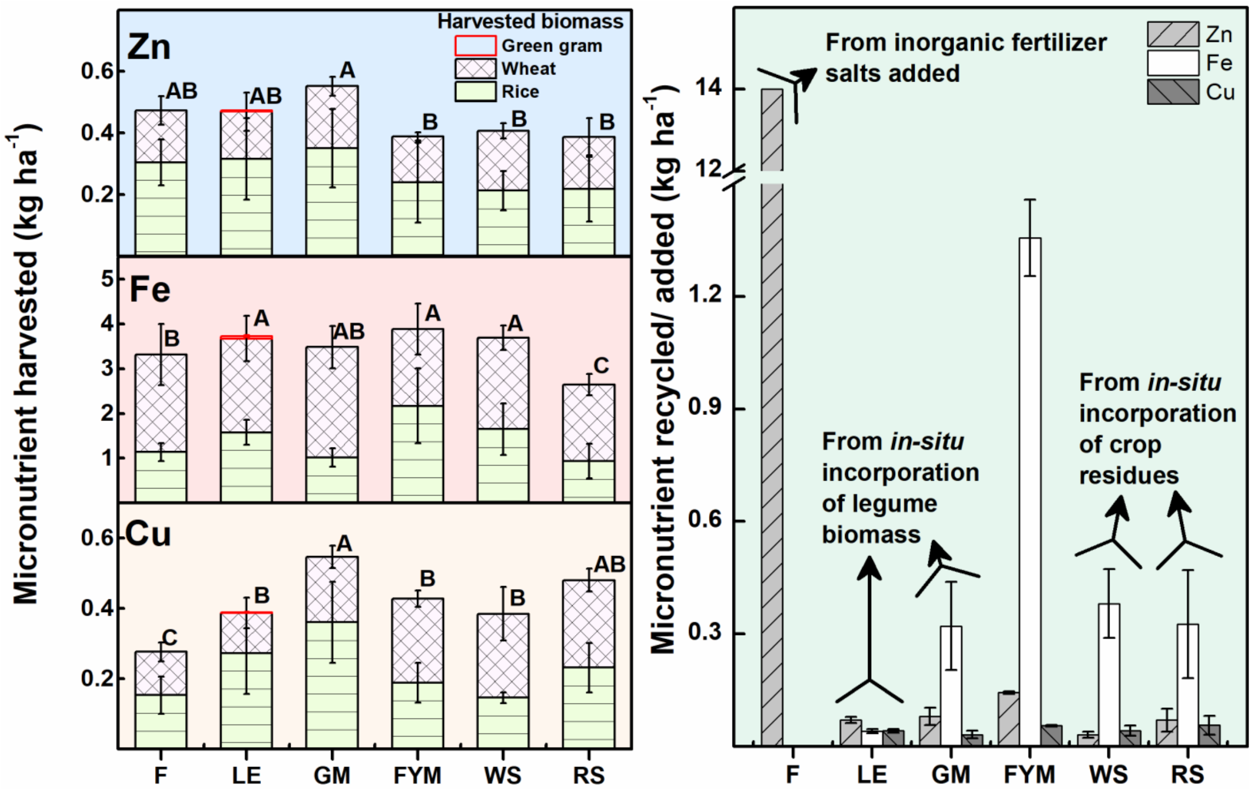

Fig. 4: Micronutrient zinc (Zn), Iron (Fe), Copper (Cu) annually harvested as grain and straw (and removed off the farm), and recycled/added (into the soil) under different management. F=100% inorganic macronutrient (N, P, K) fertilizers + 100% Zn fertilizer, LE= 55% inorganic macronutrient (N, P, K) fertilizers + opportunity legume crop (*Vigna radiata*) biomass incorporation, GM=55% inorganic macronutrient (N, P, K) fertilizers + green manuring with *Sesbania aculeata*, FYM=55% inorganic macronutrient (N, P, K) fertilizers + farmyard manure incorporation, WS=55% inorganic macronutrient (N, P, K) fertilizers + 30cm wheat stubble *in situ* retention & incorporation, RS= 55% inorganic macronutrient (N, P, K) fertilizers + 30 cm rice stubble *in situ* retention & incorporation. Error bars denote ± 1 SD.

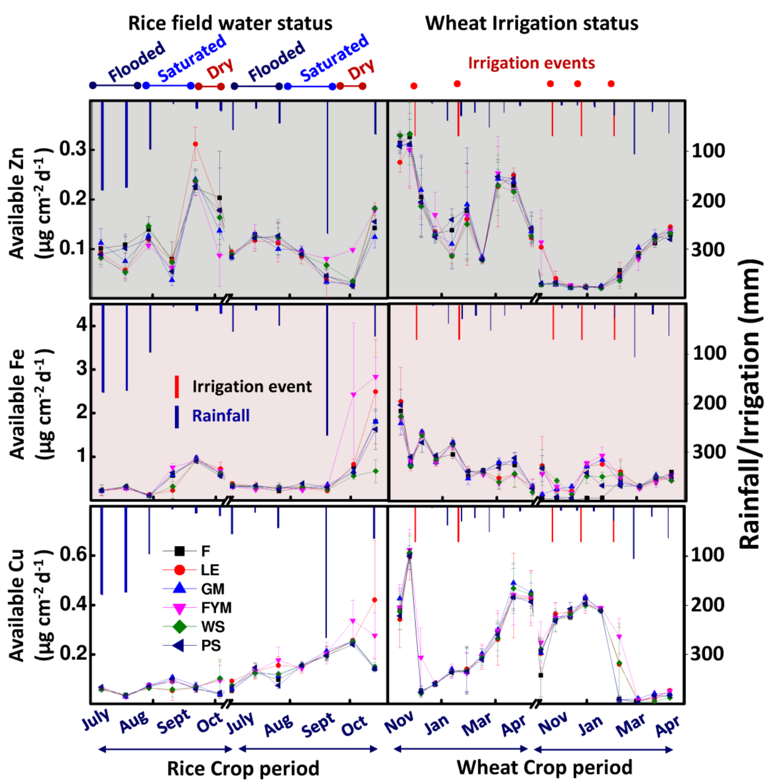

Fig. 5: Trends in plant-available zinc (Zn), iron (Fe), and copper (Cu) as determined with ion exchange resin (IER) strips during two rice-wheat cropping cycles. Hanging bars represent cumulative rainfall/ irrigation received/applied during the residence of strips in the soil (~15 days). F=100% inorganic macronutrient(N, P, K) fertilizers + 100% Zn fertilizer, LE= 55% inorganic macronutrient (N, P, K) fertilizers + opportunity legume crop (*Vigna radiata*) biomass incorporation, GM=55% inorganic macronutrient (N, P, K) fertilizers + green manuring with *Sesbania aculeata*, FYM=55% inorganic macronutrient (N, P, K) fertilizers + farmyard manure incorporation, WS=55% inorganic macronutrient (N, P, K) fertilizers + 30 cm wheat stubble *in situ* retention & incorporation, RS= 55% inorganic macronutrient (N, P, K) fertilizers + 30 cm rice stubble *in situ* retention & incorporation. Error bars denote ± 1 SE.

from a management system, GM showed higher harvest which was comparable with F and LE treatments and significantly superior from other management (FYM, WS and RS) (Fig. 4). In case of Fe, LE had significantly higher harvest compared with F and RS treatment while comparable with treatments of GM, FYM and WS. Even in the case of Zn, GM and LE exceeded F (where $ZnSO_4$ fertilizer @ 7 kg ha^{-1} was applied), and other management (FYM, WS, RS) matched F. For Fe and Cu, all organic management exceeded F.

Soil moisture conditions largely controlled micronutrient availability in soil solution (Fig. 5), though differences in amounts added through organics were also significant. For Zn, Fe, and Cu, soil moisture close to the saturation/field capacity favored higher availability compared to flooded conditions. Zn availability at field capacity was assessed 10-14% and 15-20% higher compared to saturated and flooded conditions, respectively. During the wheat season, daily available Zn concentration in all the treatments ranged from 0.10-0.31 µg cm^{-2} d^{-1} (2013-14) to 0.01-0.12 µg cm^{-2} d^{-1} (2014-15), year 1 being wetter than year 2. For Fe, soil conditions close to field capacity favored more release for both rice and wheat. In rice season, plant availability of Fe was observed higher under dry conditions (1.11 µg cm^{-2} d^{-1}) followed by saturated (0.31 µg cm^{-2} d^{-1}) and flooded (0.29 µg cm^{-2} d^{-1}) conditions, averaged for both the years. Likewise, in wheat, available Fe concentration decreased during irrigation and rainfall events but increased subsequently upon attaining field capacity conditions. Similar to Zn and Fe, daily available Cu in rice season was higher during field capacity conditions than saturated and flooded conditions under all treatments.

Total IER Zn showed variable trends amongst different integrated nutrient management (INM) in the rice-wheat cropping system (Fig. 6). Total available Zn in rice and wheat ranged from 9.6-16.0 µg cm^{-2} and 5.9-28.0 µg cm^{-2}, respectively. In the rice season, there was no significant variation among management in 2013-14, while FYM treatment had maximum availability in 2014-15. For wheat, there was a large variation between the two years. 2013-14 had an almost double amount of available Zn in soil solution than 2014-15, with no significant differences amongst treatments in the former year and maximum availability in LE and FYM, in the latter year. In general, FYM (rice) and LE (wheat) had 12.4% and 17.7% higher

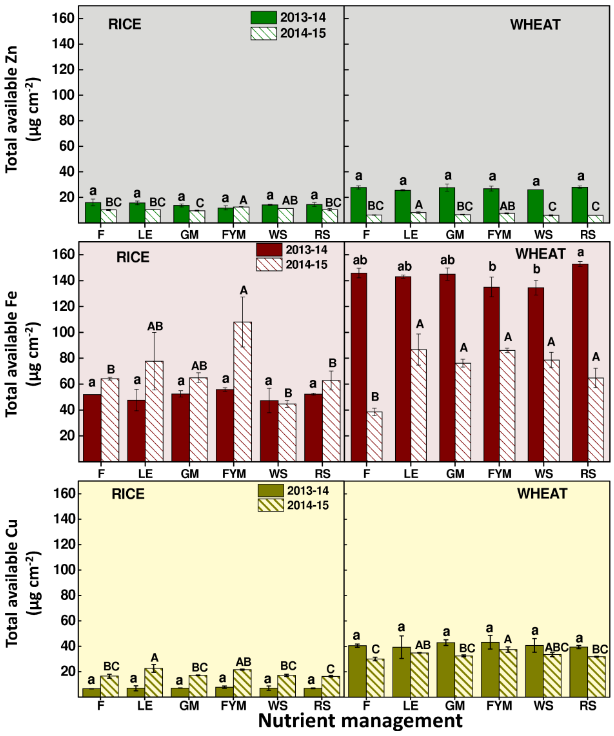

Fig. 6: Full-season plant-available zinc (Zn), iron (Fe) and copper (Cu) in soil solution, determined with ion exchange resin (IER) strips, under different management. F=100% inorganic macronutrient(N, P, K) fertilizers + 100% Zn fertilizer, LE= 55% inorganic macronutrient (N, P, K) fertilizers + opportunity legume crop (*Vigna radiata*) biomass incorporation, GM=55% inorganic macronutrient (N, P, K) fertilizers + green manuring with *Sesbania aculeata*, FYM=55% inorganic macronutrient (N, P, K) fertilizers + farmyard manure incorporation, WS=55% inorganic macronutrient (N, P, K) fertilizers + 30 cm wheat stubble *in situ* retention & incorporation, RS= 55% inorganic macronutrient (N, P, K) fertilizers + 30 cm rice stubble *in situ* retention & incorporation. Error bars denote ± 1 SE. Treatments with the same letters are not significantly different at P≤0.05. Small letters denote differences for the first cropping cycle and capital letters denote differences for the second cropping cycle.

availability, respectively, compared to F treatment. In rice, total IER Fe availability was observed in the order of FYM>LE=GM>WS=RS>F (p>0.05) during 2014 while no significant differences were noted in 2013 (Fig. 6). In wheat, all integrated management had higher Fe availability during 2014-15, while RS, GM, LS, and F had significantly higher availability compared to FYM and WS, during 2013-14. Ion exchange resin (IER) available Cu in the treatments varied from 6-22 µg cm^{-2} and 30-43 µg cm^{-2}, respectively, in both seasons of rice and wheat cropping. In rice, IER Cu in FYM during 2013 and LE during 2014 were recorded higher compared to the rest of the management. Availability in FYM (2013) and LE (2014) was observed 12% and 16% higher compared to F treatments. FYM incorporation resulted in higher

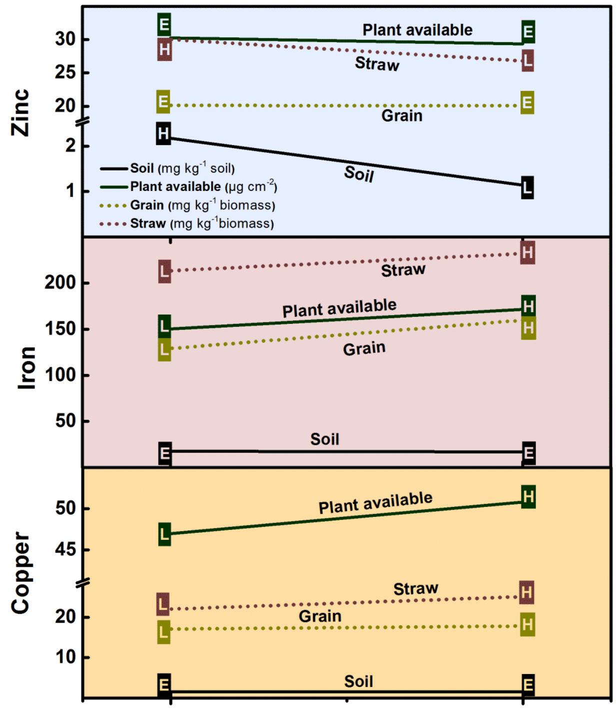

Fig. 7: Comparisons between 100% inorganic fertilizer application (F) and integrated nutrient management (INM) for soil (DTPA extractable), plant available (Ion exchange resin strip sorbed), grain (total), and straw (total) zinc (Zn), iron (Fe) and copper (Cu). H=higher, L=lower, and E=equal. F=100% inorganic macronutrient (N, P, K) fertilizers + 100% Zn fertilizers, INM= 55% inorganic macronutrient (N, P, K) fertilizers + organic inputs (treatment specific as explained in the legend of Fig. 1 to 5).

availability compared to LE, GM, WS, RS, F, respectively, during both the years.

Overall comparisons between 100% inorganic fertilizers and integrated nutrient management indicated that there were considerable effects of the integration of organics (Fig. 7). The $ZnSO_4$ application resulted in a buildup of Zn in the soil, while the plant availability did not change. While some effects on availability in straw could be seen, there were no changes in Zn in grains. For other micronutrients, Fe and Cu, where no fertilizer forms were added to the soil, organics integrated management had higher availability in soil solution, straw, and grains, while soil stocks did not differ significantly.

4. Discussion

The availability of three major micronutrients Zn, Fe, and Cu as influenced by management was evaluated in this study. The full-season averaged plant-available Zn, Fe, and Cu in soil solution was 15, 84, and 25µg cm^{-2} which roughly translates to the same amount in kg ha^{-1} for representative soil layer (0-15 cm). The daily-availability trends pointed towards a strong influence of moisture and water regime during the crop growth period on micronutrient availability. In general, moisture conditions nearing field capacity (moderate soil moisture condition) enhanced nutrient availability. In rice crop, the moisture conditions over 3 months of the active growth period (July-September) varied from flooded (initial one month), saturated (second month), and moist (last month) followed by almost dry conditions nearing harvest (about two weeks in October). In the case of the wheat crop, relatively drier conditions prevailed except intermittent flood irrigations (at 1-2 month interval) and rain events which brought the soil conditions to almost field capacity after a very short period (maximum one day) of saturated conditions. The daily variations in micronutrient levels could be related to these variations in soil water regime due to consequent changes in aerobic and anaerobic conditions that have a strong influence over nutrient availability (Bhardwaj *et al.*, 2019).

During rice cropping, we observed maximum availability of Zn, Fe, and Cu near harvesting time than in the starting months when flooded conditions existed. In wheat crop too, low concentrations of Zn, Fe, and Cu in soil solution coincided with either immediately after rainfall events or flood irrigation events. Translocation of nutrients from the soil to plant takes place by mass flow of the nutrients, absorption by roots through water flow driven by root pressure, and plant transpiration (White, 2012). The supply of nutrients to a crop is, therefore, determined not only by the rate of mobilization of nutrients at the surface of soil particles (diffusion rate of the ion through the soil matrix) but also by the water content of the soil (Kirkby and Romheld, 2004). During flooded and saturated conditions, as in the case of rice, the availability of nutrients like Fe could increase due to conversion from ferric to ferrous forms (Bhardwaj *et al.*, 2019; Ishimaru *et al.*, 2006). Yet, under such conditions, the losses due to leaching are also high. Further, the plant-available concentrations in soil solution may dip due to dilution effects. This could be the strong reason why ion exchange resin (IER) based determinations of plant-available concentrations revealed higher amounts during moderate (nearing field capacity) moisture conditions. Mineralization rates are also higher under aerobic conditions than those under anaerobic conditions (Murthy *et al.*, 1991). That is why more nutrient availability was observed during the wheat growing-seasons than that of during the rice growth (Fig. 5).

In general, the nutrient availability was higher in the management integrated with organics. It is worthwhile to again mention here that the managements with organic inputs had no addition of inorganic micronutrient fertilizers, though '*integrated*' word was preferred since 55% of macronutrient (N, P, K) fertilizers were added. Even F (100% inorganic fertilizers) management had only Zn fertilizer application (@7 kg ha^{-1}), and no Fe and Cu fertilizers were applied. Also in the case of LE, GM, WS, and RS, there were no external inputs of micronutrients, and only *in-situ* recycling of micronutrients from soil pools through amendments was the source. Only in case of FYM (farmyard manure addition) and F (for Zn), there were external inputs into the system. Therefore, except FYM, the higher availability of micronutrient Zn, Fe, Cu in the organic amended management must have been driven by the conversion of native soil pools (especially amorphous sesquioxide bound and crystalline sesquioxide bound) to available forms. The tapping of recalcitrant forms by plants grown *in-situ* (*Vigna* in LE treatment, *Sesbania* as green manure in GM, wheat in WS, and rice in RS) and their release upon decomposition of amendments enhanced micronutrient availability for plant uptake, it means (Fig. 4). It has been noted earlier that Zn supply improves in soil due to consistent slow release from the decomposition of organic matter as well as due to chelating effects (Gupta *et al.*, 2000). For example, Cu released from organic matter (or from the soil) would form complexes with organic matter, thereby preventing it from being adsorbed onto the soil solid surfaces or getting precipitated (Boudesoque *et al.*, 2007; Degryse *et al.*, 2009). Thus, it would have higher availability in soil solution. Similarly, Fe makes complexes with siderophores, like mugineic acid, which are easily absorbed by roots through mugineic acid-Fe transporters (Curie *et al.*, 2001). The build-up of soil organic matter has been noted to have a significant effect on the availability of Zn as well (Li *et al.*, 2007).

Besides soil organic matter mediated availability, changes in soil pH due to organic matter decomposition reactions could also play a significant role. Since the soils were alkaline in reaction (surface soil pH~8.4) a slight decrease in pH could increase micronutrient availability significantly. Micronutrients, particularly Zn, Fe, and Cu are more efficiently available to plants at lower pH. A slight increase in pH can reduce their availability significantly, mostly due to precipitation of salts (Sharma *et al.*, 2009). The decomposition of organic matter releases organic acids and carbon dioxide into the soil solution which causes more or less decreases in soil pH, as was noted in these experiments after organic material additions at rice transplanting. There were fluctuations in soil pH during the full cropping cycle but notable was the drop in pH of organic amended management after the incorporation of organic materials into the soil (Fig. 4). Production of organic acids helps in decreasing soil pH due to H^+ dissociation, and the magnitude of decrease depends on the dissociation degree and initial pH (Rukshana *et al.*, 2011). Alternate flooding and upland conditions in rice-wheat cropping bring different chemical environment during growing periods as degradation of organic materials and subsequent release of micronutrients vary according to the prevailing conditions. Under submerged conditions in rice, a series of electro and biochemical as well as microbiological changes occur in the soil, but during wheat growth, these changes are upturned owing to the upland (drier) and aerobic conditions (Bhardwaj *et al.*, 2019; Manchanda *et al.*, 2003). Therefore the availability is not only governed by the total soil pool but also by the conditions favoring their release from these pools. Besides, aliphatic and aromatic hydroxyl acids released during decomposition result in complexing free and available aluminum ions which decrease soil pH (Hati *et al.*, 2008). The positive effects of organic materials addition as in organic-integrated management in this study can also be physical. Organic matter addition has been noted to improve soil structure, and consequently better root proliferation and biomass, resulting in a higher total root surface for the uptake of micronutrients (Mandal *et al.*, 2003).

The deposition of Zn and Fe was more in wheat grain than in the rice grain, perhaps due to different mechanisms of Zn accumulation in these plants but the growth span may also have an influence. Rice is a three-month crop while wheat has an opportunity for extracting micronutrients from soil for more than 5 months. Unlike nutrient availability in soil solution which is governed by edaphic conditions like soil moisture and organic matter decomposition, the process of translocation of micronutrients varies among plants, being under genetic control as well. Moreover, it is also agreed by some researchers that the absorption and utilization of micronutrients from soil depend on the plant's physiological mechanisms (Ghandilyan *et al.*, 2006). Zn deficiency in flooded soils, as in the case of rice, is because of a decrease in the redox potential (Bhardwaj *et al.*, 2019). As a result, a lesser amount of Zn may be taken up by the rice plants in the early growth stages, and therefore deficiency symptoms also appear during early growth stages. Also, there were higher concentrations of all the three micronutrients in straw than grains. Although in the case of Zn, under moisture-sufficient conditions active root uptake is in continuity, and Zn remobilization from source tissues to grains is an important source of grain Zn; the deficient conditions could alter these mechanisms (Jiang *et al.*, 2007; Wu *et al.*, 2010; Kutman *et al.*, 2012). In contrast, Zn in wheat is freely transported through the phloem system, and it is an important process for Zn distribution in the wheat plant (Haslett *et al.*, 2001). This could be an important reason for similar levels of Zn in the grain and straw of wheat. Yin *et al.*, 2016, also noted that Zn concentration in rice crops is not significantly affected by Zn fertilization (soil or foliar) and a major part of Zn which is taken up is allocated to straw than grain (Yin *et al.*, 2016). The remobilization greatly varies depending on each element (Garnett and Graham, 2005). Even though plant shoots contain a high concentration of Fe, it is not always in available form. Similarly, Cu, like other micronutrients, was more dominant in straw than in the grain and soil. Being redox-active metal, it is not readily movable among different plant tissues. Though it can move from older to younger leaves, it is considered that plant Cu uptake is dominantly influenced by its availability in the soil (Tang *et al.*, 1999).

Overall, the integration of organics in soil nutrient management, in form of legume biomass incorporation, farmyard manure addition, and rice-wheat crop residue retention resulted in a systematic increase in plant availability in soil solution, and translocation to straw and grain. Plants scavenge micronutrients from the soil and a part of these scavenged micronutrients are recycled through organic inputs/ amendments. The availability of these recycled micronutrients for crop uptake is much higher than under inorganic fertilizer applications, particularly under alkaline pH conditions, where the precipitation of fertilizer salts (e.g. sulfates) takes place (Gupta *et al.*, 1987). Most of the micronutrient fertilizers are applied as sulfate salts (e.g. $ZnSO_4$, Fe_2SO_4, etc.) because of their high solubility and cost effectiveness (Cakmak, 2009). Precipitation of micronutrient fertilizer salts makes nutrient unavailable to plant though the concentration in soil may still be sufficient or even excess due to continuous application. This has been noticed in the soils of the Indo-Gangetic region which have mostly alkaline pH (>7.5). Our observations point towards the buildup of micronutrients in soils that were supplemented with inorganic fertilizers yet the availability to the crop plants is low. In this study, soil stocks of Zn were high in F (100% Zn fertilizer application) though the concentrations in grain and straw were not proportional to the soil stocks. Since we cannot recommend farmers to apply all seven essential micronutrients (Zn, Fe, Cu, Mn, B, Mn, Mo, Cl) fertilizers due to the resultant high cost of production, a system which gives a better opportunity for micronutrient enrichment of our foods should be preferable. Thus integration of organics in soil nutrient management programs, especially in alkaline soil conditions, can be a significant first step towards micronutrient nutritional quality of rice-wheat crops and may contribute to addressing micronutrient deficiency.

5. Conclusion

These studies indicated that integration of organics in nutrient management systems for rice-wheat cropping improved the availability of micronutrients -Zn, Fe, Cu in the soil for plant uptake, and also their translocation to grain and straw. Thus, integration of organics in nutrient management of rice-wheat cropping would be a significant first step towards improving micronutrient nutritional quality of rice-wheat crops and may contribute to addressing micronutrient deficiency since rice and wheat serve most of the world as staple foods and their straw serves as feed for animals in many parts of the world. Zn fertilizer ($ZnSO_4$) application resulted in Zn build-up in soils of alkaline reactions but not much effective to increase Zn content in rice-wheat, therefore it may be a pollutant in long run. Even without any micronutrient fertilizer application, organically integrated managements have better translocation of micronutrient Fe and Cu to crop grains and straw from the soil. Integrated nutrient management with the use of organics to cut down inorganic fertilizer use resulted in better daily micronutrient availability in soil solution for plant uptake.

Soil moisture conditions nearing field capacity (wheat)/ saturation (rice) favored higher availability of Zn, Fe, and Cu in soil solution, and provided a higher opportunity for their plant uptake. Micronutrient availability in rice-wheat systems is controlled by the quality of residues being added. Leguminous residues tended to make available more Zn, Fe, and Cu in soil solution for plant uptake compared to recalcitrant organic matter like rice and wheat stubble. Legume residue incorporation (green manuring with legumes; legume crop in rotation and its biomass incorporation) enhanced micronutrient harvest via increased availability in soil solution. It is concluded that integration of legume based organics in nutrient management is more effective in improving micronutrient availability and micronutrient harvest over the only inorganic fertilization use for improving micronutrient nutrition under rice-wheat cropping system in North-West Indo-Gangetic Plain.

Data Availability

The data supporting the findings in the manuscript is available from the corresponding author on a reasonable request.

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Authors' contributions

A.K.B generated the idea, designed the study, carried out the experiment works, analyzed data, and prepared the manuscript. R.K. and D.R. collected and analyzed the data and helped in manuscript writing. P.J., K.M., and A.S. collected supporting data, helped in the compilation, statistical analysis, graphical representation, and manuscript writing. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests, financial or non-financial. The funding agency had no role in designing the study, data collection, and analysis, or in manuscript preparation.

Ethical Approval

The article doesn't contain any study involving ethical approval.

Use of Generative AI or AI-assisted technologies

Authors declare that generative AI or AI-assisted technologies have not been used in the preparation of this manuscript

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