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Meta-Analysis Approach to Measure the Effect of Integrated Nutrient Management on Crop Performance, Microbial Activity, and Carbon Stocks in Indian Soils

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Cereal crop production gains under conventional agricultural systems in India have been declining in recent years because of inadequate management practices, creating a considerable concern. These activities were shown to deplete soil organic matter stocks, resulting in a decrease in microbial activity and soil organic carbon (SOC) content. Moreover, even with minimal use of organic sources in cultivated land, soil carbon status deteriorated, particularly in subtropical climates. Integrated nutrient management (INM), a modified farming method, has the potential to effectively utilize organic and inorganic resources, to improve the quality of soils and crops, and making farming more economically viable and sustainable. The aim of this study was to use meta-analysis to quantify the effects of INM on crop production, soil carbon, and microbial activity in Indian soils. During the years 1989–2018, data from various research studies in India, mainly on nutrient management in rice and wheat crops, were collected. Meta-Win 2.1 software was used to analyze the results, and significance was determined at $p < 0.05$. The results showed that the yield of rice and wheat was 1.4 and 4.9% more in INM than that in 100% NPK (N: nitrogen, P: phosphorous, and K: potassium), and that respective yields were comparatively higher in loamy soils (2.8%) and clayey soils (1.0%). The INM treatment increased SOC and microbial biomass carbon (MBC), resulting in improved overall soil quality. The SOC stock was increased by 23.8% in rice, 15.1% in wheat, 25.3% in loamy soils, and 14.4% in clayey soils in INM over 100% NPK. Microbial quotient (MQ) data showed significant trends between different management systems in both soil types, for example, INM > 100% NPK > No NPK. Due to more soil cracking and reduced aggregate stability in the rice field (greater short-term soil structural changes), the SOC stock loss in rice was higher than that in wheat. The CO_2 equivalent emissions were 7.9 Mg ha^{-1} higher in no NPK (control) than in 100% NPK, and 16.4 Mg ha^{-1} higher in control than in INM. In other words, INM increased soil carbon sequestration by

2.3 Mg ha^{-1} as compared to using 100% NPK. Overall, the findings of this study show that INM could be a viable farming system mode in India for improving crop production, increasing soil carbon sequestration, and improving microbial activity while remaining economically and environmentally sustainable.

Keywords: Integrated nutrient management, Rice-wheat system, Soil texture, MBC, SOC, Microbial Quotient, CO_2 equivalent emission

INTRODUCTION

Soil organic matter (SOM) is an essential determinant of agricultural productivity, accounting for less than 5% of the overall soil weight (Banerjee et al., 2006), and it functions as a soil conditioner, source of nutrients, substrate for microbial activity, and protector of the environment (Schnitzer, 1991). Soil health status can be harmed from the continued adoption of intensive cultivation practices and the continued use of chemical fertilizers (Anwar et al., 2005; Kumar et al., 2017; Kumar et al., 2018; Sharma et al., 2019), often leading to declined soil organic carbon (SOC) (Singh et al., 1999) and unsustainable crop production systems. There is a growing scientific understanding that supports the use of organic fertilizer sources for soil sustainability and quality production, but the following issue remains, "Is this system sustainable for food security?" Furthermore, there is a scarcity of large quantities of high-quality organic materials for long-term use in cropping fields (Padbhushan et al., 2015; Padbhushan et al., 2016a, b; Kumar et al., 2018; Sharma et al., 2019).

The SOC has a significant effect on the physico-chemical and biological properties of soil (Kumar et al., 2018). Therefore, maintaining SOC in cropland is critical for improving agricultural productivity while also lowering carbon emissions (Rajan et al., 2012). Microbial biomass carbon (MBC), the mass of living components of soil organic matter, is both a source and sink of biologically mediated nutrients. Changes in MBC and microbial turnover from management practices including fertilizer application, tillage, and rotation can significantly impact on net N mineralization and microbial immobilization (Gupta et al., 2019). Since MBC is the dynamic component of SOC, it has been recommended as the most sensitive measure of a change in the SOC status (Powlson et al., 1987; Friedel et al., 1996; Padbhushan et al., 2016a, b). The MBC usually comprised 1–5% of the TOC and can detect a shift in the rate of organic matter turnover within 1–2 years (Gupta et al., 1994; Gonz alez-Quinones et al., 2011). The microbial quotient (MQ) is the ratio of MBC to SOC (%), and has been observed to adjust in a consistent manner as a result of good management practices, and it is a useful indicator to measure soil health (Sparling, 1997).

The processes by which SOC is lost or stabilized in the soil are affected by nutrient management activities, impacting carbon inputs and lability. In addition, wide carbon to nutrient (N, P, S) stoichiometric ratios of crop residues can also influence the efficiency of conversion of residue C through microbial turnover into SOM pool (Richardson et al., 2014). All these factors could influence the net result in changes in the soil organic carbon stock (SOC stock) in cropping soils (Ghimire et al., 2017). In various climatic conditions (temperate to tropical), SOC stock was lost by 60–75% from native lands (Lal et al., 2007; Ghimire et al., 2015) due to intensive cultivation and inadequate management practices.

The carbon dioxide (CO_2) equivalent emission is also one of the most critical soil measures for determining the nature of organic matter turnover and depletion of SOC stock (Padbhushan et al., 2020). By using proper management methods, SOC can be sequestered in the soil system (Ghimire et al., 2017; Sharma et al., 2019). Some of the best soil management practices for improving SOC and controlling losses from the soil to the environment are the addition of organic sources (e.g., manures), crop residue retention, and conservation tillage (Bronson et al., 1998; Lal et al., 2007; Ghimire et al., 2015; Rakshit et al., 2018; Kumar et al., 2019).

Integrated nutrient management (INM) has been demonstrated to enhance SOC when compared to other soil management approaches (Majumder et al., 2008; Bhardwaj et al., 2019). This practice aids in the effective use of chemical fertilizers in conjunction with renewable nutrient sources. Chemical fertilizers can meet the crop's immediate nutritional needs, while organic manures control nutrient absorption, boost soil quality, and have synergistic effects on crop growth (Yadav and Kumar, 2000; Bihari et al., 2018). Such integrated management practices are generally developed with an understanding of the interactions among crop, soil, and climate (Mahajan and Sharma, 2005; Mahajan et al., 2008). They generally include the application of organic manures, and crop residue retention that bridges the gap in C to nutrient stoichiometric ratios, and thereby improve the efficiency of conversion of crop residue C into SOC which generates a new and stabilized SOM. Moreover, INM practice generally combines the traditional and advanced practices of nutrient management into an ecologically sound and cost-effective farming system to nourish the crop for quality produce (Janssen, 1993; Wu and Ma, 2015). Overall, it can be one of the alternative approaches to promote soil sustainability as well as to ensure food security for overgrowing population.

Rice (*Oryza sativa*) and wheat (*Triticum aestivum*) are the main cereal crops in India, and they play an important role in ensuring food security and increasing income for rural populations. The rice–wheat system is widely used in the world, occupying 12.3 million hectares of the total land area and accounting for 77% of total food grain production (USDA, 2020–21). Our previous study on meta-analysis reported that the adoption of proper nutrient management practices can increase the crop productivity, profitability, and sustainability of rice and wheat crops in the Indian subcontinent (Sharma et al.,

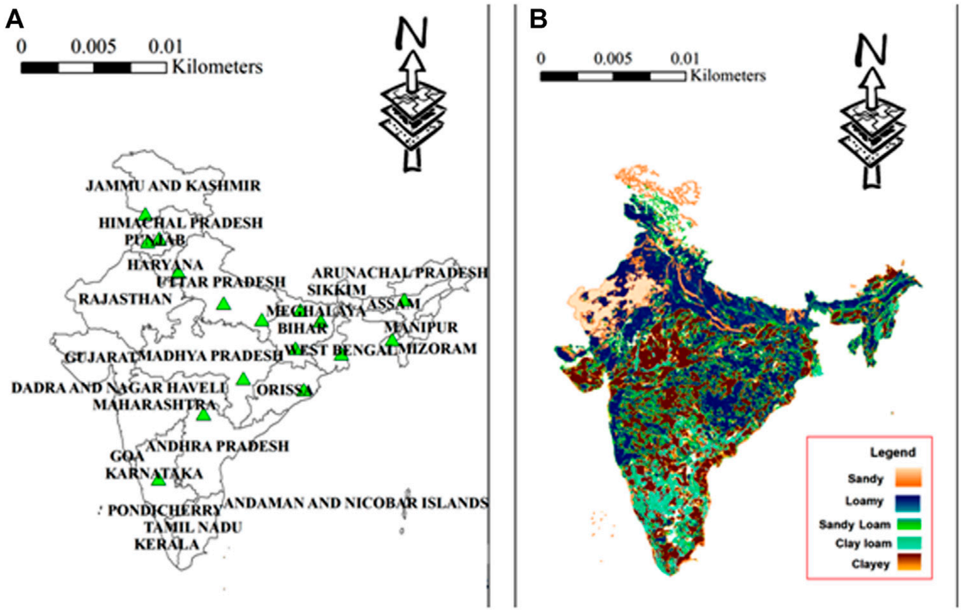

FIGURE 1 | (A) Location map showing major study sites of India; **(B)** different soil types predominant in India. Major study sites: Kanpur, Uttar Pradesh (sandy loam); Pusa, Bihar (silty clay); Sabour, Bhagalpur (sandy loam); Tripura, India (sandy clay loam); Sabour, Bhagalpur (clayey); Kathalagere, Bangalore (sandy clay); Ludhiana, Punjab (sandy loam); New Delhi, India (sandy loam); Pusa, Bihar (silt loam); Cuttack, Odisha (sandy clay loam); Khudwani, Kashmir (silty clay loam); Ranchi, Jharkhand (sandy clay loam); Tejpur, Assam (sandy loam); Ludhiana, Punjab (loamy sand); Dhiansar, Jammu (sandy loam); Raipur, Chhattisgarh (sandy clay loam); Varanasi, Uttar Pradesh (loamy); Kanpur, Uttar Pradesh (loamy); Sabour, Bhagalpur (sandy clay loam); and Kalayani, West Bengal (clayey).

TABLE 1 | Effect of integrated nutrient management (INM) on crop performance with respect to without NPK and 100% NPK in rice and wheat crops as influenced by soil texture: loamy and clayey in Indian soils.

Integrated nutrient management (INM) vs. without fertilization (Control)				
Class	Paired datasets (n)	% mean effect	% effect size interval	
			Minimum	Maximum
Rice	190	80.5*	72.0	95.2
Wheat	95	91.1*	86.1	111.2
Loamy	228	80.4*	80.3	99.8
Clayey	57	84.2*	72.1	112.1
Integrated nutrient management (INM) vs. recommended dose of fertilizers through chemicals only (NPK)				
Class	Paired datasets (n)	% mean effect	% effect size interval	
			Minimum	Maximum
Rice	186	1.4	0.3	2.9
Wheat	77	4.9*	1.4	6.1
Loamy	206	2.8*	1.2	3.9
Clayey	57	1.0	0.4	2.4

*(*indicates significant at p <0.05)*

2019). So, while the rice–wheat cropping system has long been recognized as an important contributor to food security, the challenges associated with its long-term viability are the cause for concern (Pittelkow et al., 2015). The system's long-term viability is threatened by decreasing SOM and nutrient status due to a lack of or injudicious use of organic sources, as well as an imbalanced and injudicious use of inorganic fertilizers (Sharma et al., 1994; Ladha et al., 2009; Erenstein et al., 2012; Gathala et al., 2014; Sharma et al., 2019). It was reported that using inorganic sources only retains SOC levels, while using both organic and inorganic sources in a rice–wheat cropping system increases SOC nutrient levels (Majumdar et al., 2008; Bhardwaj et al., 2019; Sharma et al., 2019).

In the recent years, meta-analysis has gained importance as a statistical approach to analyze the significant responses of treatments from diverse individual studies to evolve an overall general trend (Miguez and Bollero, 2005; Gardner and Drinkwater, 2009; Kallenbach and Grandy, 2011; Geisseler and Scow, 2014; McDaniel et al., 2014; Sharma et al., 2019). The impact of nutrient management activities on SOC has been well established globally through meta-analysis studies (West and Post, 2002; Anderson-Teixeira et al., 2009; Chivenge et al., 2011; Liu et al., 2014; Han et al., 2016; Qin et al., 2016; Haddaway et al., 2017). However, there has been little effort made to interrogate the quantitative evidence of effects of land use and nutrient management systems, in relation to Indian soils through meta-analysis, to derive the nature and magnitude of the effects on SOC stocks and drivers of its turnover. The main aim of this study was to measure the impact of INM on crop production, microbial activity, and carbon stocks under rice and wheat cropping in Indian soils through a meta-analysis approach. The specific objectives were to determine the effect of INM compared to other nutrient management practices in terms of the following: 1) rice and wheat crop performance, 2) MBC and SOC levels, 3) microbial quotient and SOC stocks, and 4) estimates of SOC loss and CO_2 equivalent emissions.

TABLE 2 | Physico-chemical and biological properties of studied sites in Indian soils.

Soil parameters	Unit of measurement		Without NPK	100% NPK	INM
Soil pH	No (soil: water- 1:2 or 1:2.5)	Minimum	6.00	5.70	6.05
		Maximum	8.66	8.72	8.72
		Average	7.70	7.78	7.78
Bulk density (BD)	Mg m^{-3}	Minimum	1.19	1.19	1.08
		Maximum	1.82	1.77	1.74
		Average	1.56	1.51	1.45
Soil organic carbon (SOC)	%	Minimum	0.26	0.40	0.49
		Maximum	0.98	1.04	1.57
		Average	0.55	0.66	0.80
Available nitrogen (av. N)	kg ha^{-1}	Minimum	106.50	172.35	160.10
		Maximum	242.40	288.60	330.62
		Average	145.75	228.64	209.15
Available phosphorus (av. P)	kg ha^{-1}	Minimum	7.25	10.75	8.63
		Maximum	20.30	40.54	50.70
		Average	16.04	21.17	22.90
Available potassium (av. K)	kg ha^{-1}	Minimum	84.74	82.88	119.68
		Maximum	318.00	325.00	328.00
		Average	150.32	178.68	184.86
Microbial biomass carbon (MBC)	mg kg^{-1}	Minimum	64	101	130
		Maximum	303	330	503
		Average	149	181	223
Soil organic carbon stocks (SOC stocks, soil depth: 0–15 cm)	Mg ha^{-1}	Minimum	4.6	7.1	7.9
		Maximum	26.8	27.6	41.0
		Average	12.8	15.0	17.3

MATERIALS AND METHODS

Data Collection, Compilation, and Soil Parameters Used in the Meta-Analysis Study

We searched the relevant online available literatures by using the terms “soil,” “rice and wheat crops,” “nutrient management,” “carbon,” “microbial biomass carbon ,” and “India.” The search was limited to literatures from Indian studies reported between 1989 and 2018. To understand the impact of INM on crop performance, microbial activity, and soil carbon stocks in rice and wheat crops grown in Indian soils, a total of 285 paired datasets from different published studies were sorted out according to a set of criteria for the meta-analysis study. All the data used in this analysis came from on-station trials performed in India at various sites (**Figure 1A**). The selected study sites are the most important in India since they reflect the primary agroclimatic zones and seasons in which rice and wheat crops are cultivated, as well as having common soil types. Moreover, India’s most common soil types, which include sandy, loamy, sandy loam, clay loam, clayey, and clayey loam soils, were also included in this study (**Figure 1B**).

Criteria Used for Data Collection

1) Selected crops for this study were available in a rice–wheat cropping system as these crops were grown as main cropping sequence in India.
2) The following treatments implemented for multiple seasons were used for this study as follows: without fertilization (control or no NPK); balanced chemical fertilizer only, that is, recommended nitrogen (N), phosphorus (P), and potassium (K) through inorganic fertilizers (NPK); and integrated nutrient management (INM, integration of organic manures like farmyard manure, vermicompost, green manures, biofertilizers, and other organic materials along with inorganic fertilizers).
3) Soil textures used in this study were categorized as loamy (moderately coarse to medium fine) and clayey (moderately fine to fine).
4) The broad climate categories of the major study areas were subtropical arid, moist to humid climatic conditions influenced by monsoonal seasonal variations. The areas were with three prominent seasons: summer, rainy, and winter, and were under irrigated conditions.
5) Selected parameters for this study were rice and wheat yield (kg ha^{-1}), soil pH, bulk density (BD, Mg m^{-3}), soil organic carbon (SOC, %), available N (kg ha^{-1}), available P (kg ha^{-1}), available K (kg ha^{-1}), and microbial biomass carbon MBC, (mg kg^{-1}).

Calculations for Soil Parameters Used in Meta-Analysis Study

Soil organic carbon stocks (SOC stocks, Mg ha^{-1}), microbial quotient (MQ, %), relative SOC stock loss (%), and carbon dioxide equivalent emission (CO_2 equivalent emission, Mg ha^{-1}) were derived from the primary data.

SOC stock was calculated by using **Equation 1** (Datta et al., 2015).

$$\text{SOC stock}\ \left(\text{Mg ha}^{-1}\right) = \text{SOC}\ \left(\text{g kg}^{-1}\right)\ \text{x BD}\left(\text{Mg m}^{-3}\right)\ \text{x soil depth}\ (\text{m})\ \text{x 10.} \tag{1}$$

The microbial quotient (MQ) was determined by using **Equation 2** (McGonigle and Turner, 2017).

$$MQ = \frac{MBC}{SOC} \text{ x } 100. \tag{2}$$

SOC stock loss related with nutrient management was determined by using **Equation 3** (Shanmugam et al., 2018; Padbhushan et al., 2020).

$$\text{Relative SOC stock loss } (\%) = \frac{(\text{SOC stock without fertilization} - \text{SOC stock 100\% NPK, INM})}{\text{SOC stock without fertilization}} \text{ x } 100. \tag{3}$$

The CO_2 equivalent emissions from SOC stock loss were estimated as the amount of carbon in the oxidized form using respective molecular weights by using **Equation 4** (Padbhushan et al., 2020).

$$\text{Carbon dioxide equivalent } = \text{carbon x } \frac{44}{12}. \tag{4}$$

The SOC stock loss values for respective treatments are used to measure the CO_2 equivalent emission in Mg ha^{-1}.

Data Analysis

MetaWin 2.1 software (www.metawinsoftware.com) was used to analyze the selected paired dataset as per the standard criteria. For rice and wheat crops, as well as loamy and clayey soil textures, both variables were independently subjected to meta-analysis. NPK and INM treatments were compared over control treatment from the different datasets and to determine the trends on the effect of INM on microbial activity and carbon stock. The meta-analysis was carried out in two parts, with the first examining the database collected from various studies and the second understanding the comparative changes between the different treatments. In the first stage, the effect size (ES) was computed for individual factor by **Equation 5** (Rosenberg et al., 2000) as follows:

$$ES = \ln V = \ln\left[\frac{Y_T}{Y_C}\right], \tag{5}$$

where V is the ratio between response variables Y_T and Y_c, Y_T is the mean of response variables (soil parameters) of the treatments (INM, 100% NPK), and Y_C is the mean of those variables without fertilization (control) as control. Datasets from various studies obtained from variable conditions act as multiplication replications, and common standard deviation was being used in the analysis through a number of observations applying a simple statistical approach. The obtained ES from the individual studies was pooled using a mixed-effect model to measure the cumulative ES and confidence intervals at 95 percent through bootstrapping with 4,999 iterations (Adams et al., 1997). The mixed-effect model is a random-effect meta-analytic model for categorical data (Rosenberg et al., 2000; Sharma et al., 2019), assuming random variation among studies within a group and fixed variation between groups.

Elucidation of Outcome

Findings were back-transformed and shown as mean effect change in percent caused by treatments in relation to those without fertilization either in the table or bar graph. The significant differences were measured only at $p < 0.05$. All the results from the meta-analysis are shown in either a table or bar graph to present the significant effect of compared nutrient managements.

RESULTS

Impact of INM on Crop Performance of Rice and Wheat Crops in India

The meta-analysis data showed that INM had positive effect on rice and wheat crops over control and recommended dose of fertilizers through chemicals only or 100% NPK (**Table 1**). The overall grain yield irrespective of soil types was significantly increased in INM than in control in rice and wheat crops by 80.5% (n = 190) and 91.1% (n = 95), respectively, whereas the yield for rice and wheat in INM was higher by 1.4% (n = 186) and 4.9% (n = 77), respectively, over 100% NPK (**Table 1**). Based on soil textural groups (loamy and clayey), INM also had a positive effect over other nutrient management options irrespective of crops. The grain yield of rice and wheat was significantly increased in INM than in control treatment by 80.4% (n = 228) and 84.2% (n = 57), whereas the yield for rice and wheat in INM was higher by 2.8% (n = 206) and 1.0% (n = 57), respectively, over 100% NPK (**Table 1**).

Soil Characteristics Under Different Nutrient Management Practices

Soil pH ranged from slightly acidic to alkaline with average values of 7.70, 7.78, and 7.78 in control, NPK, and INM treatments, respectively (**Table 2**). Soil BD was lower in INM treatment than in NPK and control (**Table 2**). The average values of BD in control, NPK, and INM were 1.56, 1.51, and 1.45 Mg m^{-3}, respectively (**Table 2**). The minimum BD was observed in INM (1.08 Mg m^{-3}), while the maximum BD was in control (1.82 Mg m^{-3}) (**Table 2**). The trend of SOC was found in the order of INM > NPK > control. The average SOC was 0.55, 0.66, and 0.80% in control, NPK, and INM, respectively (**Table 2**). A similar trend was also observed for Available N (av. N), Available P (av. P), and Available K (av. K). The average av. N, av. P, and av. K in control were 145.8, 16.0, and 150.3 kg ha^{-1}, respectively; for NPK, the values were 228.6, 21.2, and 178.7 kg ha^{-1}; and for INM, the values were 209.1, 22.9, and 184.9 kg ha^{-1}, respectively (**Table 2**). The average MBC was the highest in INM (223 mg kg^{-1}) followed by NPK (181 mg kg^{-1}) and the lowest in control (149 mg kg^{-1}) (**Table 2**). The SOC stocks were 4.6–26.6, 7.1–27.6, and 7.9–41.0 Mg ha^{-1} in control, NPK, and INM treatments, respectively (**Table 2**). The trend of SOC stocks was control < NPK < INM (**Table 2**).

Microbial Biomass Carbon (MBC), Soil Organic Carbon (SOC) Change, and Microbial Quotient (MQ) Variations in Different Nutrient Management Practices

The MBC and SOC showed significant positive effect for all comparisons (INM vs. control vs. NPK) in both crops (rice and

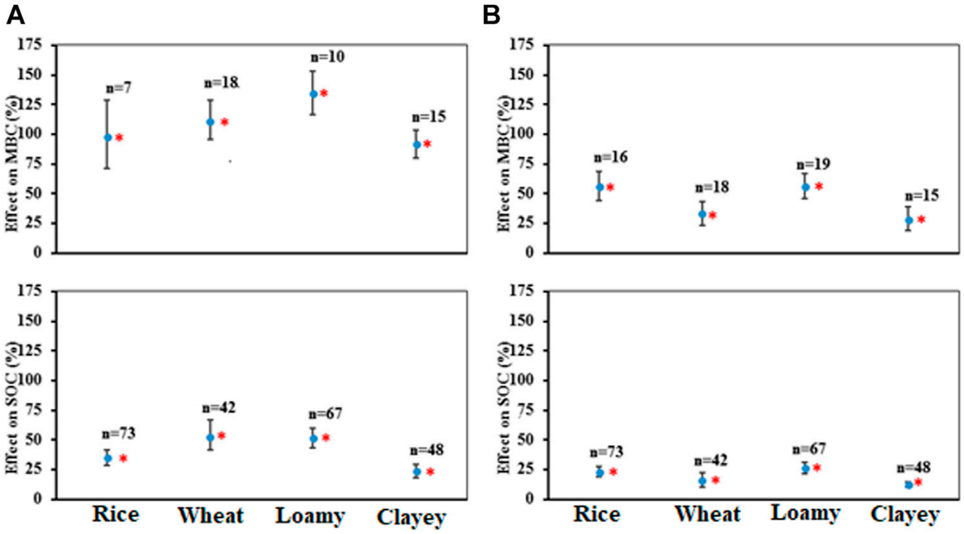

FIGURE 2 | Effect of integrated nutrient management (INM) on microbial biomass carbon (MBC) and soil organic carbon (SOC) with respect to **(A)** without fertilization/without NPK and **(B)** recommended dose of fertilizers through chemicals only (100% NPK) in rice and wheat crops as influenced by soil texture: loamy and clayey in Indian soils (*Indicates significant at $p < 0.05$).

TABLE 3 | Effect of integrated nutrient management (INM) on soil organic carbon (SOC) stocks and microbial quotient with respect to without NPK and 100% NPK in rice and wheat crops as influenced by soil texture: loamy and clayey in Indian soils.

Class	Nutrient management practices	INM vs no NPK	INM vs 100% NPK
		SOC stocks (Mg ha^{-1})	
Crops	Rice	36.5 (27.1–46.3)*	23.8 (17.0–30.6)*
	Wheat	51.2 (36.9–70.6)*	15.1 (5.7–24.3)*
Texture groups	Loamy	51.5 (40.9–63.3)*	25.3 (17.6–32.5)*
	Clayey	25.1 (16.5–34.6)*	14.4 (8.9–20.1)*
		Microbial quotient (%)	
Crops	Rice	46.6 (33.5–61.4)*	26.5 (21.5–32.3)*
	Wheat	38.8 (37.1–41.6)*	14.6 (12.3–17.3)*
Texture groups	Loamy	54.8 (50.9–58.4)*	23.47 (20.8–27.1)*
	Clayey	57.0 (52.59–61.45)*	14.4 (8.5–20.5)*

*Mean values are given with 95% CI in parentheses; *Indicates significant at* p *< 0.05.*

wheat) under soil textures (loamy and clayey) (**Figure 2**). The MBC was higher by 97.9% (*n* = 7) for rice and 111.1% (*n* = 18) for wheat in INM than control (**Figure 2**). The MBC was higher by 55.9% (*n* = 16) for rice and 32.9% (*n* = 18) for wheat crops in INM over NPK (**Figure 2**). When comparing the responses based on soil texture types, for example, loamy and clayey soils, the MBC was higher by 134.0% (*n* = 10) and 91.2% (*n* = 15), respectively, in INM than control, and 56.2% (*n* = 19) and 28.4% (*n* = 15), respectively, compared to NPK (**Figure 2**).

The SOC was higher by 34.9% (*n* = 73) for rice and 52.1% (*n* = 42) for wheat in INM than control, whereas it was higher by 23.2% (*n* = 73) for rice and 16.2% (*n* = 42) for wheat than NPK (**Figure 2**). Based on soil texture groups, SOC was higher by 51.2% (*n* = 67) and 23.4% (*n* = 48) for loamy and clayey soils, respectively, under INM than control, whereas it was higher by 26.5% (*n* = 67) and 12.3% than NPK (*n* = 48) (**Figure 2**).

The MQ, like MBC and SOC, showed significant positive effects across all comparisons and for both crops (rice and wheat) and soil textures (loamy and clayey) (**Table 3**). It was higher by 46.6 and 26.5% in INM than control and NPK, respectively, in rice crops (**Table 3**). In wheat crops, it was found to be 38.8% more in INM than control, whereas 14.4% more than NPK (**Table 3**). In loamy texture soil, 54.8% higher MQ was observed in INM than control, whereas 23.5% higher over NPK. In clayey soil, 57.0% higher MQ was found in INM than control and 14.4% higher over NPK. The general trend of MQ was as follows: INM > NPK > control (**Table 3**).

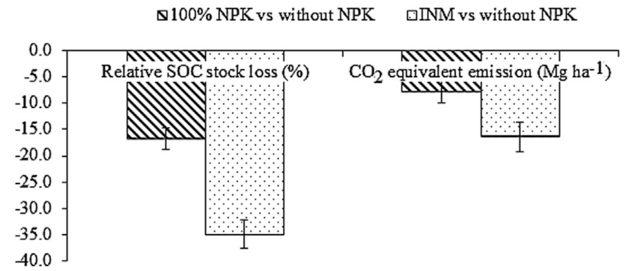

FIGURE 3 | Loss in relative soil organic carbon stocks (relative SOC stocks loss) and carbon dioxide (CO_2) equivalent emission in the treatment without NPK over the 100% NPK and integrated nutrient management (INM) (Note: Metadata has been represented as mean ± S.E).

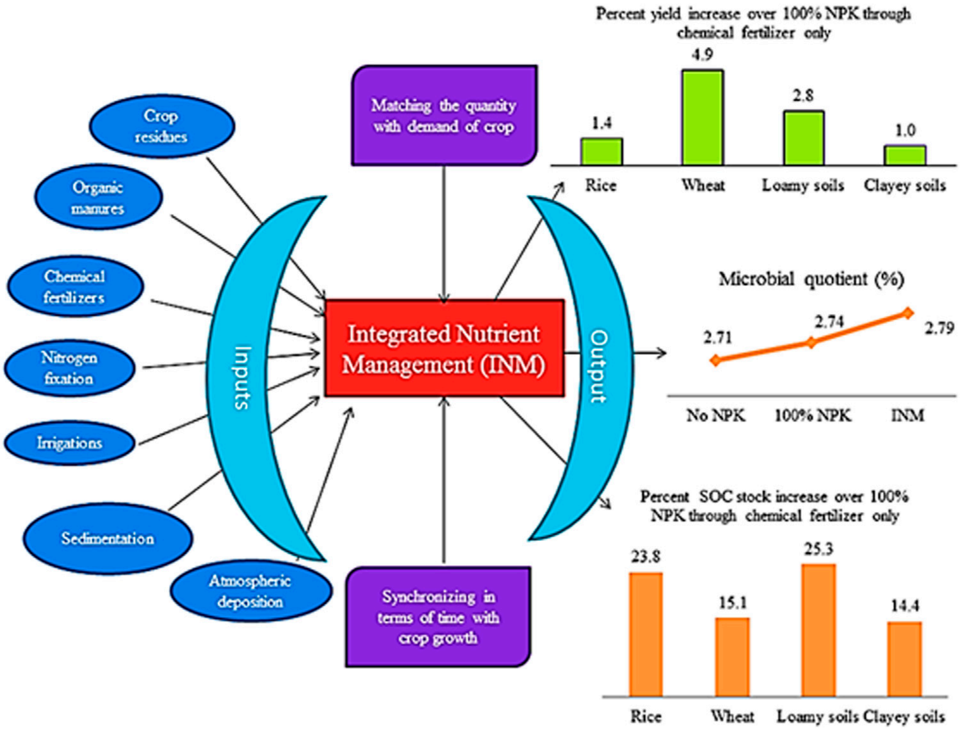

FIGURE 4 | Graphical illustration depicts the performance of INM over no NPK and NPK in crops (rice and wheat) and soil types (loamy and clayey).

SOC Stocks, SOC Stock Loss, and CO_2 Equivalent Emission in Different Nutrient Management Practices

Over the control, SOC stocks in rice crop were higher by 36.5% in INM, whereas it was higher by 23.8% than under NPK treatment. In wheat crop, SOC stocks were higher by 51.2% in INM than control, and it was higher by 15.1% than NPK. In loamy texture soil, SOC stocks were higher by 51.5% in INM than control and 25.3% over NPK and in clayey soil it was higher by 25.1% in INM than control and 14.6% than NPK. SOC stock was lowered by 16.7 and 34.9%, respectively, in control compared to NPK and INM treatments (**Figure 3**). CO_2 equivalent emission was estimated to be higher (7.9 Mg ha^{-1} over NPK and 16.4 Mg ha^{-1} over INM) in control than NPK and INM treatments (**Figure 3**).

DISCUSSION

Meta-analysis aided to extract general conclusions from a large amount of data to determine how soil properties respond to INM in comparison to other nutrient management practices, as well as crop type and soil texture can influence the results. This study presents a summary of results from experiments in India on crop performance, soil carbon, and microbial activity under various nutrient management practices in rice-wheat cropping systems (**Supplementary Table 1**).

Our findings revealed that crop production using INM practice has shown a positive impact on rice and wheat crops in Indian production systems. Results from this broad survey suggest that increased yield from a combination of organic and inorganic fertilizers in rice and wheat crops in India could be a viable and sustainable nutrient management option (**Figure 4**). Similarly, research from other countries also reported a positive impact of INM practices on crop production (Kramer et al., 2002; Mtambanengwe and Mapfumo, 2006; Kimani et al., 2007; Chivenge et al., 2011). The yield benefits are generally higher when organic and inorganic fertilizers were used together, due to the positive interactions between the two sources of nutrients, which increased nutrient supply and synchrony (Myers et al., 1994; Palm et al., 2001a, b; Vanlauwe et al., 2001a, b, c). The synchronization would have increased the efficiency with which the nutrients from the two sources were used, resulting in positive interaction effects on crop production compared to no application (control) or single application (NPK). Additionally, improved availability of major macronutrients, as well as micronutrients, would have contributed to the positive effects observed in the INM treatment (Palm et al., 1997; Zingore et al., 2007).

The present study also showed that INM application was more sustainable in loamy textured soils than in clayey soils based on yield response in rice and wheat crops. This could be because loamy soils generally have better drainage and aeration than those in clayey soils, thereby better soil porosity and increased plant-available water content, providing a favorable soil habitat for crop growth and development. Loamy soils also show higher yields partly due to less cracking, that is, better soil structure during the early stages of crop growth and development. Plant growth can be hampered by soil cracking, which is more common in clayey soils (Chakraborty et al., 2017).

Previous research in India has shown that adoption of INM practices significantly enhanced yields in rice and wheat crops compared to chemical fertilizers alone (Bhattacharyya et al., 2003; Sharma et al., 2019). For a similar yield level, the use of INM saved N by 25–50% under optimum economy return in wheat (Raguwanshi and Umat, 1994). The adoption of INM practices improved the soil nutrient status and bioavailability of several nutrients in the soil. Yadav (2001) found the enhanced soil available nutrient status by the use of INM over the other nutrient management practices. Sharma and Sharma (2002) found that application of INM increased av. N, av. P, and av. K by 6–24, 7–8, and 7–32 kg ha^{-1} in the soil, which corroborated with our study.

The use of organic materials such as manures, composts, green manures, and biogas slurry either alone or in combination with chemical fertilizers was shown to increase crop productivity in a number of crops, including rice and wheat (Janssen, 1993; Brar et al., 1999; Swarup and Yaduvanshi, 2000; Yadav and Kumar, 2000; Yaduvanshi, 2001; Paikaray et al., 2002; Prasad et al., 2002; Kumar et al., 2003; Kharub et al., 2004; Bhoite, 2005; Bajpai et al., 2006; Mishra et al., 2006; Singh et al., 2006; Surekha and Rao, 2009; Kumar and Singh, 2010; Zhang et al., 2012; Parkinson, 2013; Kumar et al., 2014; Kumari et al., 2017; Sah et al., 2018). This meta-analysis study indicates that improvements in crop productivity from the use of organic materials are widespread across different soils and many agroclimatic regions of India. Such improvements in crop productivity are generally seen compared to different types of chemical fertilizer use or no fertilizer application. Also, their use has shown to improve many soil's physical, chemical, and biological properties, thereby facilitating better nutrient availability and overall soil fertility. However, it is evident that the magnitude of effect can vary depending upon the soil type, environment, and cropping systems.

Studies from the long-term intensive rice–wheat cropping system had widely reported that without fertilization, or imbalanced and injudicious chemical fertilization, there was a measurable loss of organic C from soils, and hence, alternative agricultural management practices were required to control the SOC loss to the environment (Rasool et al., 2007; Lenka et al., 2014; Hossain et al., 2016). Our findings revealed that in both rice and wheat crops, SOC was accumulated by 16–23% on addition of organic materials in INM over the 100% NPK. Similar results were observed on the increased accumulation of SOC (18–62%) in a rice–wheat system from nutrient addition through organic sources (farm yard manure, straw and green manure) supplement with reduced NPK compared to 100% NPK (Gami et al., 2001; Majumder et al., 2008; Kukal et al., 2009).

Irrespective of crops and soil textures, our meta-analysis study also showed the sequestration of SOC in INM treatment compared to control and 100% NPK. Our meta-data revealed that loss of SOC stock was more in control followed by 100% NPK and INM treatments. The loss in SOC stock translated into CO_2 equivalent emissions and release into the atmosphere contributes to global warming (Lal et al., 2007). Several studies also reported that due to intensive cropping systems of rice and wheat caused a significant amount of SOC stock loss from agriculture soils (Dawe al., 2000; Regmi et al., 2002; Ladha et al., 2003; Lal et al., 2007; Hobbs et al., 2008; Ghimire et al., 2015).

The present study showed that loss of SOC stocks was observed more in rice than in wheat in Indian soil, especially with 100% NPK fertilizers compared to INM. In the puddled rice soils, severe soil cracking and reduced aggregate stability lowers the SOC content and its stock (Hobbs et al., 2008), which might be one of the reasons for the lower SOC content under paddy-cultivated Indian soil. It was also reported that the floodwater system influenced the SOC dynamic because of limited supply of oxygen affecting chemical processes (Bronson et al., 1997), causing changes in soil pH, redox potential, and reduction of nutrients (carbon, nitrogen, and sulfur) (Fageria et al., 2011). Higher redox potential could also cause significant loss in SOC as CO_2 emissions which add on global warming continuous from puddled fields (Masscheleyn et al., 1993).

The MBC content is considered as an eco-physiological index, which is an integrated measure of microbiological activity in soil. It is the living component of soil which is the active form of carbon pool. It links soil nutrients to energy (C) dynamics and has been identified as one of the sensitive indicators that respond to even short-term environmental and available nutrient variations in the soil from crop and soil management practices (Sparling, 1992; Haynes, 2008; Rajput et al., 2019). The decomposition and mineralization of organic substrates and the release of nutrients is regulated by microbial activity and turnover; the size and response of MBC to management practices can have a significant impact on nutrient availability and nutrient use efficiency by crops (Gupta et al., 2019). In this meta-analysis study, changes in MBC showed a similar trend to that of SOC but indicated greater responses than SOC. Soils under INM practices for both crops and soil textures generally showed higher MBC compared to without fertilization and 100% NPK treatments. Similarly, several studies reported that organic amendments would have a significant effect on the amount of MBC from the wide range of macro- and micro-nutrients added through the organic amendments (Hu et al., 2011; Chinnadurai et al., 2014; Tamilselvi et al., 2015; Liu et al., 2017; Rajput et al., 2019) but effectiveness of the organic sources depends on their quality. Green manure and the addition of crop residues had lower effectiveness than compost and biochar (Zavalloni et al., 2011; Liu et al., 2017).

The microbial quotient (MQ) denotes the importance of microbial biomass in increasing the SOC content in the soil (Sparling, 1992; Yang et al., 2010). The MQ is a soil indicator used for expressing changes in soil characteristics due to organic matter (Sparling, 1992). Novak et al. (2017) found the range of the MQ was 4.0–5.1% in Entisols and 1.0–1.9% in Inceptisols. A lower value of the MQ in Inceptisols was due to lower conversion of organic carbon into microbial biomass due to less microbial growth. In this study, the MQ was found positively affected by addition of organic matter in the INM compared to 100% NPK and without fertilization. The trend of the MQ in the decreasing order was INM followed by 100% NPK and without fertilization. MQ values were found to be more in rice than in wheat crop, and loamy soil than clayey soil, suggesting that habitat and crop type can influence microbial biomass levels within a system (Sparling, 1997). A higher MQ value suggests more availability of nutrients for microbial growth, and potential for the conversion of C inputs to microbial biomass for better soil quality and microbial functions (Richardson et al., 2014; Novak et al., 2017; Tresch et al., 2018). Availability of nutrients such as N, P, and S can limit microbial growth and consequently soil organic matter formation, especially in the nutrient-limited cropping soils in India. It is suggested that provision of adequate supply of nutrients can significantly increase the microbial humification efficiency, that is, the proportion of crop residue C converted into soil organic matter (Richardson et al., 2014). Therefore, organic amendments providing carbon and nutrients such as those seen under INM practices together would support higher levels of MBC, MQ, and microbial turnover resulting in greater efficiency of conversion of carbon into SOC and consequently increased SOC stocks.

CONCLUSION

Results from this meta-analysis study show that the INM treatment can increase rice and wheat yield, SOC content, and microbial biomass compared to the application of inorganic fertilizers alone, for example, 100% NPK chemical fertilizer treatment. This study also shows that crop yields, SOC, and MBC were higher in the loamy soils than in clayey soils in rice–wheat cropping systems. Additionally, the higher microbial quotient and concomitant increase of SOC in the INM treatment suggest that the nutrient addition most likely increased microbial humification efficiency and the observed increase in SOC stocks. Overall, findings from this study indicate the INM treatment as one of the better crop management strategies for Indian soils, in order to improve soil quality, soil biological health, and crop production, thereby improving food security for India's rapidly growing population.

AUTHOR CONTRIBUTIONS

SS framed the notion and was overall in charge of this manuscript preparation. RP, UK, and MK collected literature, analyzed data, and drafted the manuscript. DR helped in meta-analysis. RK did preparation of map. KA, VG, AK, BP, and AS edited the manuscript. All contributors discussed the outcomes and added to the final document. All authors have studied and approved the in print version of the paper.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2021.724702/full#supplementary-material.

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