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Optimum wheat productivity under integrated plant nutrient management is associated with improved root system and high nutrient efficiency

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Abstract

Depleting soil fertility and low fertilizer efficiency in alkaline calcareous soils are serious issues worldwide creating an immediate threat to environment and food security. Integrated nutrient management (INM) can be a promising eco-friendly strategy for improving crop performance and resource efficiency to resolve these concerns. A field study was conducted to investigate the integrated effect of organic sources [farm yard manure (FYM) @ 10 tons ha^{-1} and press mud (PM) @ 5 tons ha^{-1}] along with various NPK rates [100, 75, 50% recommended dose of fertilizer (RDF)] on root system, nutrient efficiency, and yield of wheat cultivar Kiran-95. Longest roots were measured in FYM + RDF$_{50}$ while highest surface area and number of root tips were recorded in PM + RDF$_{50}$ than RDF alone. However, maximum root volume and average root diameter was observed in PM + RDF$_{100}$ and PM + RDF$_{75}$, respectively compared with RDF only. PM + RDF$_{100}$ considerably enhanced grain yield and related traits i.e., spike length, tillers count m^{-2} and 100-grain weight as compared to RDF only. Integration of PM and 100% RDF showed higher NPK uptake, than RDF alone. Recovery efficiency (RE) of NPK was calculated higher at lower fertilizer rates and vice versa. The sole application of RDF$_{100}$ showed least RE of NPK whilst PM + RDF$_{50}$ revealed higher RE of NPK. The results suggested that INM could be a sustainable approach to enhance wheat productivity and nutrient efficiency in alkaline calcareous soils. In addition, PM along with RDF$_{100}$ NPK fertilizers proved superior in improving root traits and nutrient accumulation thereby increasing wheat grain yield.

Keywords: Farm yard manure, nutrient substitution, press mud, root traits, wheat.

Introduction

Soil is a non-renewable natural resource, facing serious hazards of degradation due to unsustainable land uses and management practices worldwide. The loss in soil fertility due to continuous nutrient mining by crops without adequate replenishment is creating an immediate threat to environment and food security (Ahmad et al., 2007). Wheat (*Triticum aestivum* L.) is a leading food grain crop of Pakistan, contributing about 1.7% of the country's GDP and 8.7% of value addition in agriculture. During 2020-21, area under wheat crop was 9.178 million hectare with annual production of 27.293 million tons while average yield stood at 2.97 tons per hectare (GOP, 2021). This current yield per hectare of wheat is very low than the potential yield. There are multiple soil related constraints behind low yield including low organic matter, high pH, calcareousness, nutrient depletion and less use of organic nutrient sources (Akhtar et al., 2007). Low soil organic matter (< 1%) and associated nutrient supply is among the leading yield limiting factors in intensive cereal based cropping systems of arid and semi-arid regions worldwide (Mulvaney et al., 2009). Moreover, indiscriminate use of chemical fertilizers deteriorates soil structure, pollutes ground water and increases nitrate

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concentration (Zhang et al., 2010). Although, the use of mineral fertilizers cannot be over-looked but due to their rising costs and environmental concerns, there is a need to supplement them with available organic resources (Phullan et al., 2017). Additionally, soil fertility status can be restored, maintained and/or improved with the integrative use of organic and mineral nutritional sources (Akhtar et al., 2007).

Prior to green revolution, farmers usually replenished their soils for plant nutrients by adding different organic wastes. Synthetic fertilizers enabled farmers to get higher yields only with these fertilizers, thereby reducing the use of organic materials drastically (Ahmad et al., 2007). Use of mineral fertilizers alone in intensive cropping systems creates infertility and unfavorable soil physical, chemical and biological conditions for optimum plant growth (Speir et al., 2004). The high costs of chemical fertilizers and soil degradation concerns have forced people to reconsider the organic sources in agriculture again. The gradually deteriorating soil health can be mitigated by use of organic sources (Jilani et al., 2007). Inclusion of these materials has been advocated to improve soil organic matter, soil structure, water infiltration, water holding capacity, aeration and soil granulation (Ibrahim et al., 2012). Optimum use of organic materials also encourages biological activities in soil. Combined application of organic and chemical fertilizers influence positively on microbial biomass and hence soil health (Dutta et al., 2003). However, type and quality of organic materials and application method are crucial for influencing soil characteristics and nutrient recycling (Ahmad et al., 2007; Chaudhry et al., 2013). According to Pang and Letey (2000), different organic sources have different decay rates, so the rate of nutrient mineralization for various sources is not matched with the rate of nutrient uptake by different crops.

During the past few decades, cultivation of high yielding genotypes in intensive agriculture and imbalanced use of chemical fertilizers has negatively influenced soil fertility in many sub-optimal agro-ecosystems around the globe (Speir et al., 2004). Integrated nutrient management (INM) is of utmost significance for improving soil fertility, biological properties, soil carbon pools and sustaining crop productivity of intensive cropping systems (Brady and Weil, 2008; Kumari et al., 2011). The prime objective of this concept is to increase crop yield, reduce cost of production and improve soil health (Singh et al., 2008). Different components of this approach includes: recycling of crop residues, use of organic manures, inclusion of soil fertility restoring crop, cultivation of efficient genotypes, utilization of biological agents, and balanced use of fertilizers (Wu and Ma, 2015). Adoption of INM concept is imperative to enhance input use efficiency, soil health and crop production in order to ensure global food security. This is the best approach for better utilization of organic nutrient sources to produce crops with less expenditure (Swarup, 2010). It optimizes all aspects of nutrient cycling intended to synchronize nutrient demand by the plants and its release into the soil (Zhang et al., 2012). It also minimizes land degradation and enhances farm productivity by improving soil physical, chemical, biological and hydrological properties (Saikia et al., 2015)..

Cattle's farm yard manure (FYM) and press mud (PM) from sugar industry are indigenous nutrient sources for crop production. The FYM is a cheap and easily available organic source which supplies macro and micronutrients, besides improving soil health (Sabah et al., 2014). The PM is a solid by-product of sugar industry which is about 3% from total quantity of cane crushed and is a rich source of organic carbon, NPK and micronutrients (Rakkiyappan et al., 2001). In Pakistan, it has been estimated that about 1.5 million tons of nutrients are available from FYM, while sugar industry is producing about 1.2 million tons of PM every year (Soomro et al., 2013). Several researchers have reported that long-term and balanced application of chemical fertilizers and organic sources can improve soil health, crop productivity, and nutrient use efficiency than any of these applied alone (Shah et al., 2009; Antil et al., 2011; Sabah et al., 2014; Ganaie et al., 2015). The present field study was therefore, planned to investigate the integrative response of FYM and PM along with various rates of NPK fertilizer on root system architecture, nutrient use efficiency and grain yield of wheat crop in alkaline calcareous soil.

Material and Methods

Site description

Experiment was conducted during Rabi, 2018-19 at the research area (Latitude 25º 24' 47" North and Longitude 68º 31' 07" East) of Nuclear Institute of Agriculture (NIA), Tandojam – Pakistan. The climate of the study area is arid with average annual precipitation of 136 mm. During the study period, the average daily maximum and minimum temperatures were 28.5 and 11.8 ºC respectively, while average sunshine was 8.3 hours day^{-1}, average relative humidity was 56.1% and average evaporation was 4.4 mm day^{-1}. The maximum total rainfall (28.0 mm) was recorded in the month of January, 2019 (Figure 1). The soil of the experimental site was silt loam in texture, slightly alkaline in soil reaction, deficient in organic matter, total nitrogen and available phosphorus, while adequate in available potassium. Detailed soil physico-chemical properties of the experimental site (down to 0 - 6"and 7 - 12" depth) are given in Table 1.

Table 1. Physico-chemical properties of experimental site (down to 0 - 6" and 7 - 12" depths) and nutrient composition of organic amendments (FYM and PM) used in the study

Parameters	Units	Soil		Organic amendments	
		0 – 6″	7 – 12″	FYM	PM
Sand	%	8.10	10.60	-	-
Silt	%	73.58	71.70	-	-
Clay	%	18.32	17.70	-	-
Textural class	-	Silt loam	Silt loam	-	-
pH_s	-	7.90	7.80	-	-
EC_e	dS m^{-1}	4.18	2.14	-	-
Organic matter	%	0.80	0.72	-	-
$CaCO_3$ contents	%	5.92	5.95	-	-
Sodium (Na)	mg g^{-1}	35.65	23.00	-	-
Chlorides (Cl)	mg g^{-1}	0.14	0.27	-	-
Nitrogen (N)	mg g^{-1}	0.53	0.36	7.00	12.0
Phosphorus (P)	mg g^{-1}	0.0031	0.0011	2.30	1.50
Potassium (K)	mg g^{-1}	0.158	0.124	26.0	62.0

FYM = farm yard manure; PM = press mud; pH_s = pH of soil saturated paste; EC_e = electric conductivity of saturated paste extract

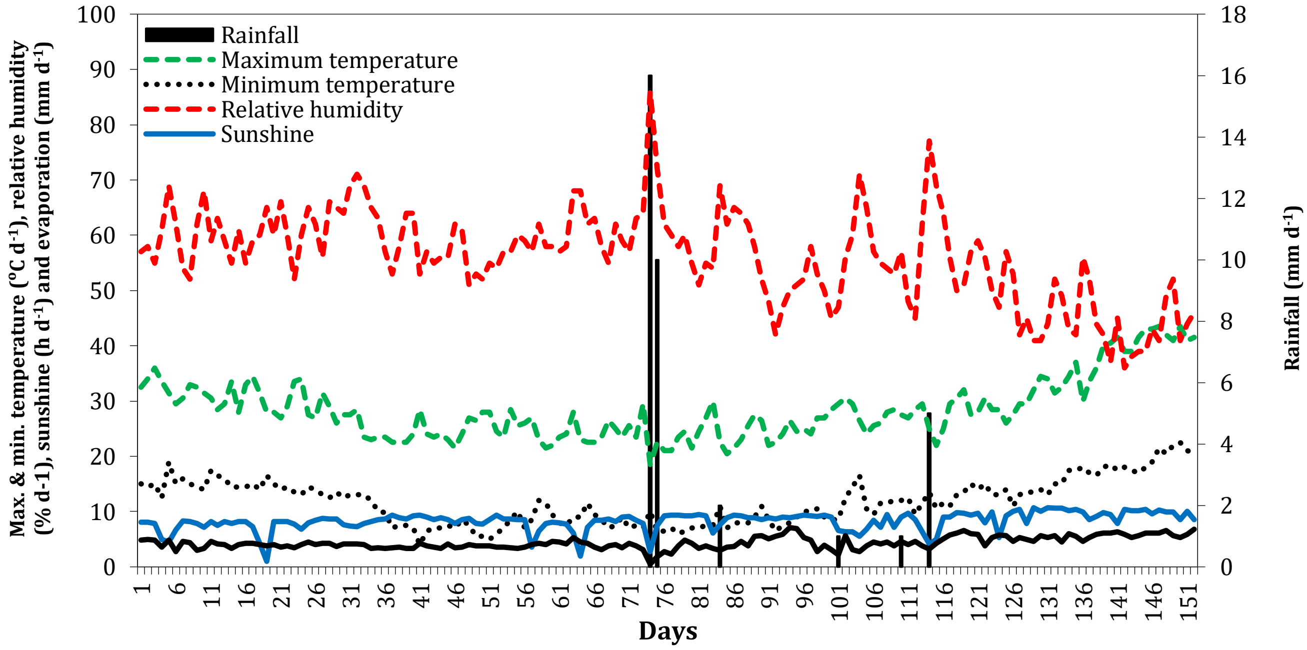

Figure 1. Daily maximum and minimum temperatures (ºC day^{-1}), relative humidity (% day^{-1}), sunshine (hours day^{-1}), evaporation (mm day^{-1}), and rainfall (mm day^{-1}) during the whole growing period of wheat crop

Experimental details

A field experiment was conducted to investigate the integrated effect of organic amendments i.e., farm yard manure (FYM) and press mud (PM) along with different rates of NPK fertilizer i.e., 100, 75, and 50% recommended dose of fertilizer (RDF) on yield, nutrient use efficiency and root morphology of wheat crop. The FYM and PM were applied at the rate of 10 and 5 tons ha^{-1} respectively, while RDF was used at the rate of 120-90-60 kg N-P-K ha^{-1}. A randomized complete block design was employed with three replications and ten treatments (control, RDF, FYM, FYM + RDF_{100}, FYM + RDF_{75}, FYM + RDF_{50}, PM, PM + RDF_{100}, PM + RDF_{75}, and PM + RDF_{50}). Detail of treatments used in experiment is described in Table 2. Seed of wheat cultivar 'Kiran-95' was obtained from Plant Breeding and Genetics Division of NIA, Tandojam – Pakistan. Sowing of wheat crop was done in individual plots of size 5 m × 5 m using single row hand drill by keeping inter-row spacing of 30 cm and seed rate of 125 kg ha^{-1}. Required amount of phosphorus and potassium according to treatment plan was applied at sowing, while nitrogen was applied in three equivalent splits i.e., at sowing, tillering, and booting stage. All other agronomic and crop protection measures i.e., irrigation, weeding, etc. were adapted uniformly to all plots. At maturity, the crop was harvested, threshed mechanically and data regarding yield and associated traits were recorded.

Soil analysis

For determining soil physico-chemical properties of experimental soil, five samples were randomly collected prior to crop sowing. A composite sample was air-dried and grounded to pass through a 2 mm sieve. Soil texture was determined using hydrometer method by performing mechanical analysis of soil separates (sand, silt, and clay) in which soil is dispersed with sodium hexametaphosphate solution (Bouyoucos, 1962). Soil reaction (pH) and electrical conductivity (EC) were determined using soil saturated paste following Anderson and Ingram (1993). Organic matter was quantified by chromic acid digestion according to Walkley-Black method (Nelson and Sommers, 1982). Calcium carbonate, sodium and chloride contents in soil were estimated according to Estefan et al. (2013). Kjeldahl nitrogen was determined following Jackson (1962). While Phosphorus and potassium were estimated using ammonium bicarbonate-diethylene triamine penta-acetic acid (AB-DTPA) as extracting solution (Soltanpour and Workman, 1979).

Table 2. Detail of treatments used in individual plot (n = 3)

	Treatments	Abbreviation	N	P_2O_5	K_2O
T_1	Control	Control	-	-	-
T_2	RDF (100%)	RDF_{100}	120	90	60
T_3	FYM (10 t ha^{-1})	FYM	-	-	-
T_4	FYM (10 t ha^{-1}) + RDF (100%)	FYM + RDF_{100}	120	90	60
T_5	FYM (10 t ha^{-1}) + RDF (75%)	FYM + RDF_{75}	90	67.5	45
T_6	FYM (10 t ha^{-1}) + RDF (50%)	FYM + RDF_{50}	60	45	30
T_7	PM (5 t ha^{-1})	PM	-	-	-
T_8	PM (5 t ha^{-1}) + RDF (100%)	PM + RDF_{100}	120	90	60
T_9	PM (5 t ha^{-1}) + RDF (75%)	PM + RDF_{75}	90	67.5	45
T_{10}	PM (5 t ha^{-1}) + RDF (50%)	PM + RDF_{50}	60	45	30

RDF = recommended dose of fertilizer; FYM = farm yard manure; PM = press mud ; Fertilizer (N, P, K) levels are based on kg ha^{-1}

Characterization of root system architecture

At anthesis, three plants were selected from individual treatment in order to characterize root system architecture. The selected plants were carefully removed from field with soil to ensure maximum protection of the plant root systems. Shoots were separated from roots at the crown level and the soil was gently washed away by slow agitation in a water tank. After washing the adhering soil, root system was gently blotted with absorbent paper. They were then scanned to determine following root parameters i.e., root length, surface area, number of root tips, average root diameter and root volume using root scanner (Epson Professional Scanner), and the images were analyzed using WinRHIZO™ Pro software (Regent Instruments Inc., Canada).

Plant analysis

Plant samples (grain and straw) were dried in a forced air-driven oven at 70 °C for 72 hours. Dry samples were grinded to pass through a 0.42 mm screen using a Wiley's mill. Plant samples were analyzed for total N concentration following modified Kjeldahl method using a fully automated distillation unit (2200 Kjeltec, FOSS, UK). Samples (0.3 g each) were wet digested using 10 mL of di-acid digestion mixture [(HNO_3:$HClO_4$ (5:1, *v/v*)]. Total P concentration in samples was estimated according to procedure as described by Estefan et al. (2013) at 470 nm wavelength using a double beam spectrophotometer (U-2900UV/VIS, Hitachi, Japan). While total K concentration was determined using flame photometer (Corning 400, UK).

Calculation methods

Nutrient uptake (NU), and nutrient efficiency relations i.e., recovery efficiency (RE), agronomic efficiency (AE) were calculated following Pan et al. (2017).

$$\mathrm{NU\ (kg\ ha^{-1})} = \frac{\mathrm{N\ concentration\ (\%)} \times \mathrm{Grain\ or\ straw\ yield\ (kg\ ha^{-1})}}{100}$$

$$\mathrm{RE\ (\%)} = \frac{(\mathrm{TNU_F} - \mathrm{TNU_{CK}})}{\mathrm{F_N}} \times 100 = \frac{\Delta \mathrm{TNU}}{\mathrm{F_N}} \times 100$$

$$\mathrm{AE\ (kg\ kg^{-1})} = \frac{(\mathrm{GY_F} - \mathrm{GY_{CK}})}{\mathrm{F_N}} = \frac{\Delta \mathrm{GY}}{\mathrm{F_N}}$$

Where TNU_F and TNU_{CK} shows total nutrient uptake (kg ha^{-1}) from fertilized and control plots, respectively; GY_F and GY_{CK} is grain yield (kg ha^{-1}) of fertilized and control plots, respectively; and F_N is the amount of nutrient applied (kg ha^{-1}).

Statistical analysis

The generated data was subjected to statistical analysis using computer based software STATISTIX 8.1 (Analytical Software, Inc., Tallahassee, FL, USA) to evaluate the response of integrated plant nutrient management on root system, yield and nutrient efficiency of wheat crop. All data reported in this manuscript are the means of three replicates and presented with standard errors. Treatment means showing significant differences among each other were identified through least significant difference test at 5% probability level. While graphical presentation of the data was performed using Microsoft Excel (Redmond, WA, USA).

Results

Variation in root system architecture of wheat under INM

The data pertaining to various root traits i.e., root length (RL), surface area (SA), number of root tips (NRT), average root diameter (ARD), and root volume(RV) of wheat plants are depicted in Figure 2. Results indicated that integration of chemical fertilizers with organic sources i.e., farm yard manure (FYM) and/or press mud (PM) significantly improved the studied root traits. The magnitude of RL varied from 190.7 cm in control to 494.3 cm in FYM + RDF_{50} treatment. However the treatments FYM + RDF_{50} and PM + RDF_{50} showed statistically identical results for RL. Overall, 14% higher RL was recorded with the integration of PM as compared to FYM. Root SA increased at lower rates of NPK fertilizer, irrespective of amendments. Highest root SA (96.9 cm^2) was measured in treatment PM + RDF_{50} followed by FYM + RDF_{50} (90.2 cm^2) while minimum was recorded in control (27.8 cm^2). The NRT per plant varied with changing NPK rates along with organic interventions. The NRT increased from 598 in control treatment to 928 in PM + RDF_{50} followed by PM + RDF_{75} (900) and FYM + RDF_{50} (879). Wheat plants showed differential response for ARD to applied fertilizer with or without PM and/or FYM. The control treatment exhibited least ARD (0.50 mm), which escalated to 0.54 and 0.66 mm in response to FYM and PM, respectively. Averaged across amendments, PM resulted in 8% higher ARD than FYM. The maximum RV (1.35 cm^3) was noticed in PM + RDF_{100} showing statistical similarity with FYM + RDF_{100} (1.32 cm^3). However, least RV (0.43 cm^3) was recorded in control plots.

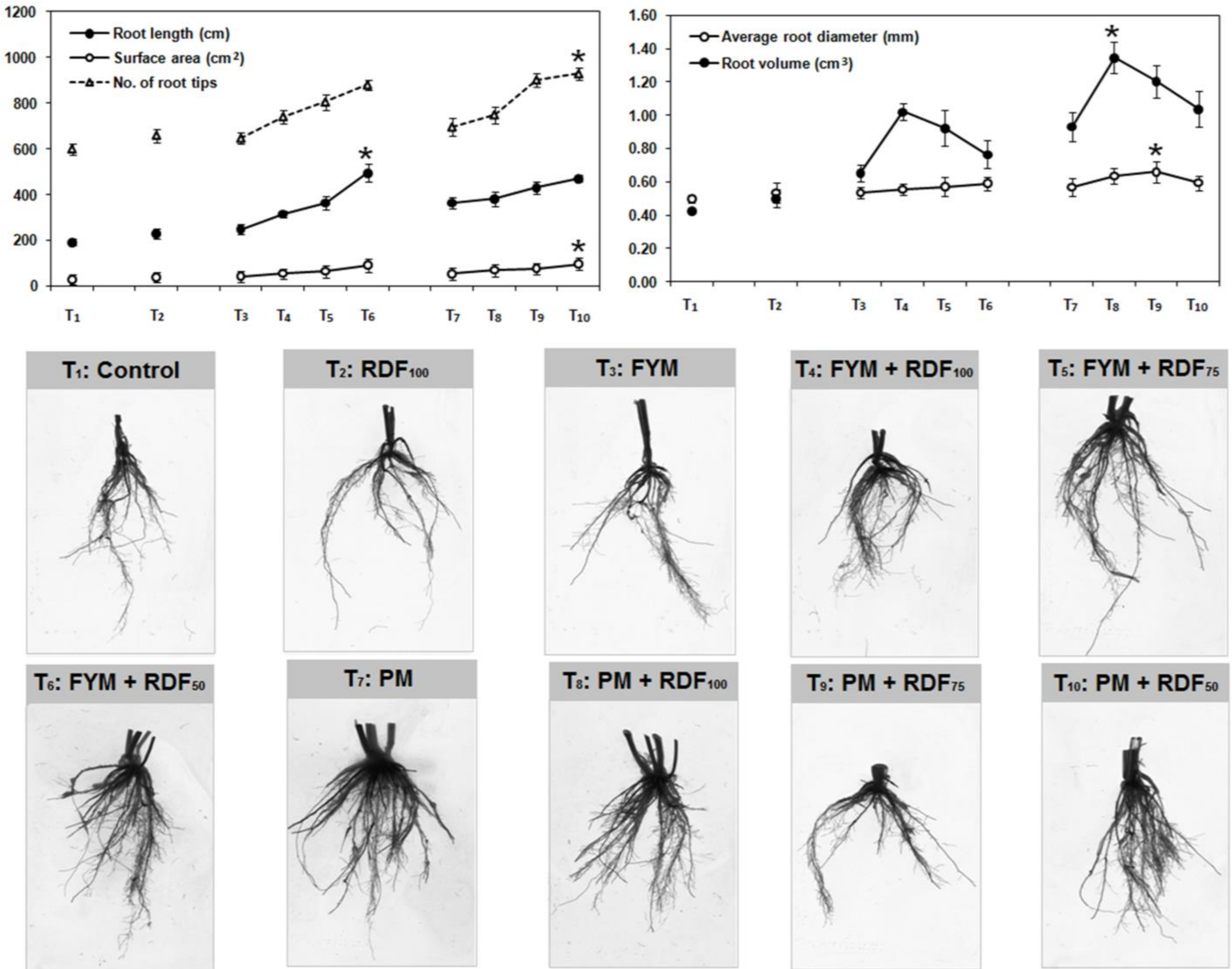

Figure 2. Variation in different components of root system architecture (i.e. root length, surface area, No. of root tips, average root diameter, and root volume) of wheat in response to integrated plant nutrient management. Treatment details are given in Table 2. Each plotted point is the mean ± SE of three replicates. Significant highest value for each root trait is indicated by * (LSD test, $P \leq 0.05$)

Yield and associated traits of wheat in response to INM

Yield and associated traits of wheat crop varied significantly ($P \leq 0.05$) in response to integrated management of inorganic and organic intrusions. The data regarding yield associated traits i.e., plant height, number of tillers m^{-2}, spike length, and 100-grain weight are presented in table 3. Results revealed that different treatments contributed effectively in enhancing yield of wheat crop. Moreover, integrated effect of PM was more pronounced than FYM with respect to traits relevant to yield. Integration of organic amendments and chemical fertilizers increased plant height of wheat plants as compared to sole addition of chemical fertilizers. Control plots showed least plant height (85.7 cm) while the treatment PM + RDF_{100} produced highest plant height (100.3 cm).Variations among different treatments for number of tillers m^{-2} were found significantly. The data indicated that treatment PM + RDF_{100} produced highest number of tillers m^{-2} (576) followed by FYM + RDF_{100} (543) while minimum number of tillers m^{-2} were recorded in control (253). Treatments PM + RDF_{75} and FYM + RDF_{75} remained at par to each other (493 vs. 485). Spike length increased but remained at par with corresponding increase in fertilizer rates with either organic source. Control plots revealed spike length of 8.1 cm which enhanced to 10.3 cm with the RDF_{100} while maximum spike length (10.7 cm) was recorded in PM + RDF_{100} treatment. Likewise minimum 100-grain weight (2.61 g) was observed in control treatment that was increased to maximum (4.77 g) in PM + RDF_{100} treatment. While treatments FYM + RDF_{100} and PM + RDF_{75} remained non-significant with each other (4.44 vs. 4.55 g).

Table 3. Yield and associated traits of wheat crop in response to integrated plant nutrient management

Treatments	Plant height (cm)	No. of tillers m^{-2}	Spike length (cm)	100-grain weight (g)	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})
Control	85.7 c	253 f	8.1 d	2.61 f	2.7 e	4.9 f
RDF_{100}	97.9 a	433 c-e	10.3 ab	4.04 d	4.9 b	7.1 ab
FYM	91.4 b	375 e	9.1 c	3.47 e	3.2 d	5.7 d-f
FYM + RDF_{100}	98.1 a	543 ab	10.4 ab	4.44 bc	5.3 a	7.4 a
FYM + RDF_{75}	97.1 a	485 b-d	10.4 ab	4.33 c	4.7 b	6.4 b-d
FYM + RDF_{50}	96.6 a	440 c-e	10.2 ab	4.27 c	4.0 c	6.0 c-e
PM	92.0 b	402 de	9.8 bc	3.63 e	3.3 d	5.3 ef
PM + RDF_{100}	100.3 a	576 a	10.7 a	4.77 a	5.6 a	7.8 a
PM + RDF_{75}	99.7 a	493 a-c	10.5 ab	4.55 b	4.8 b	6.7 bc
PM + RDF_{50}	97.3 a	460 b-e	10.1 ab	4.32 c	4.3 c	6.1 cd
LSD 0.05	3.87	88.5	0.86	0.21	0.34	0.78

Treatment details are given in Table 2. Treatment means not sharing similar letter(s) in the same column differ significantly from each other (LSD test, $P \leq 0.05$). Values are means of three replications (n = 3)

Wheat yield increased significantly in response to organic sources alone and/or in conjunction with chemical fertilizers (Table 3). In this regard, yield response of PM was observed higher when combined with chemical fertilizers thereby proving superior to all other treatments. Maximum grain yield (5.6 t ha^{-1}) was recorded in PM + RDF_{100} treatment that showed statistical similarity to treatment FYM + RDF_{100} (5.3 t ha^{-1}). Control produced grain yield of 2.7 t ha^{-1} which escalated to 4.9 t ha^{-1} with the addition of RDF_{100}. The treatments PM + RDF_{75} and FYM + RDF_{75} remained non-significant to each other (4.8 vs. 4.7 t ha^{-1}). Similarly, highest straw yield (7.8 t ha^{-1}) was produced from treatment PM + RDF_{100} followed by FYM + RDF_{100} (7.4 t ha^{-1}), and RDF_{100} (7.1 t ha^{-1}), while minimum straw yield was recorded in control treatment (4.9 t ha^{-1}).

Differential nutrient uptake by wheat under INM

Data regarding nutrient (i.e. nitrogen, phosphorus and potassium) uptake by wheat crop under the integration of organic sources and chemical fertilizers is given in Table 4. Wheat crop exhibited variable response for nutrient uptake by grains and straw when grown with different treatments of organic and inorganic sources. Nutrient uptake improved significantly with the integrated use as compared to sole application of these materials. But the integrated effect of PM was more pronounced than FYM. Minimum grain N uptake (50.3 kg ha^{-1}) was estimated in control treatment that was escalated to maximum (101.9 kg ha^{-1}) in PM + RDF_{100} followed by FYM + RDF_{100} (98.5 kg ha^{-1}). While treatments PM + RDF_{75} and FYM + RDF_{75} proved statistically non-significant with each other (94.0 vs. 91.5 kg ha^{-1}). Control plots revealed straw N uptake 10.7 kg ha^{-1} which enhanced to 15.5 kg ha^{-1} with RDF_{100} while reached to maximum (21.9 kg ha^{-1}) in PM + RDF_{100} treatment. Similarly, total N uptake (grain + straw) varied considerably among different treatments and indicated highest (123.8 kg ha^{-1}) in PM + RDF_{100} followed by FYM + RDF_{100} (118.0 kg ha^{-1}) while minimum was recorded in control plots (61.1 kg ha^{-1}). Treatments PM + RDF_{75} and FYM + RDF_{75} (111.7 vs. 107.7 kg ha^{-1}), and PM + RDF_{50} and FYM + RDF_{50} (99.4 vs. 97.4 kg ha^{-1}) remained at par to each other.

Table 4. Nutrient uptake (i.e. grain, straw, and total) by wheat in response to integrated plant nutrient management

Treatments	Nitrogen uptake ($kg\ ha^{-1}$)			Phosphorus uptake ($kg\ ha^{-1}$)			Potassium uptake ($kg\ ha^{-1}$)		
	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total
Control	50.3 f	10.7 f	61.1 f	6.6 e	3.1 e	9.7 g	28.3 d	22.5 c	50.8 g
RDF_{100}	92.6 bc	15.5 cd	108.1 c	16.4 bc	7.7 c	24.1 c-e	50.0 ab	33.7 b	83.7 cd
FYM	61.8 e	11.8 ef	73.6 e	9.2 d	4.0 e	13.1 f	33.0 d	23.0 c	56.0 fg
FYM + RDF_{100}	98.5 ab	19.5 ab	118.0 ab	20.0 a	9.6 ab	29.5 ab	55.2 ab	38.1 ab	93.3 ab
FYM + RDF_{75}	91.5 c	16.1 cd	107.7 c	17.7 bc	7.9 c	25.6 cd	49.5 ab	36.7 ab	86.3 c
FYM + RDF_{50}	83.4 d	14.0 de	97.4 d	15.8 c	6.2 d	22.0 e	42.5 c	32.9 b	75.4 e
PM	62.2 e	13.1 d-f	75.3 e	10.6 d	4.2 e	14.8 f	34.1 d	23.5 c	57.6 f
PM + RDF_{100}	101.9 a	21.9 a	123.8 a	20.3 a	10.5 a	30.8 a	55.8 a	40.1 a	96.0 a
PM + RDF_{75}	94.0 bc	17.6 bc	111.7 bc	18.2 ab	9.1 bc	27.3 bc	49.3 b	39.6 a	88.9 bc
PM + RDF_{50}	83.6 d	15.8 cd	99.4 d	17.0 bc	6.1 d	23.1 de	42.8 c	34.9 ab	77.7 de
LSD 0.05	6.06	3.14	7.88	1.03	1.42	3.34	6.34	5.60	6.22

Treatment details are given in Table 2. Treatment means not sharing similar letter(s) in the same column differ significantly from each other (LSD test, $P \leq 0.05$). Values are means of three replications (n = 3)

Combined application of organic and chemical fertilizers significantly enhanced P uptake by wheat crop than the sole addition of chemical fertilizers. The control treatment showed minimum grain P uptake (6.6 $kg\ ha^{-1}$) while treatment PM + RDF_{100} accumulated maximum grain P (20.3 $kg\ ha^{-1}$). The grain P uptake in FYM + RDF_{75} (17.7 $kg\ ha^{-1}$) and PM + RDF_{75} (18.2 $kg\ ha^{-1}$) remained statistically identical to the treatment RDF_{100} (16.4 $kg\ ha^{-1}$). The highest straw P uptake was estimated in PM + RDF_{100} treatment (10.5 $kg\ ha^{-1}$) which remained statistically at par to FYM + RDF_{100} (9.6kg ha^{-1}). The total P uptake by the above-ground plant parts (grain + straw) was recorded minimum in control plots (9.7 $kg\ ha^{-1}$) while the treatment PM + RDF_{100} showed maximum value of total P uptake (30.8 $kg\ ha^{-1}$) followed by the treatment FYM + RDF_{100} (29.5 $kg\ ha^{-1}$) and RDF_{100} (24.1 $kg\ ha^{-1}$). Treatments PM + RDF_{75} and FYM + RDF_{75} remained at par to each other (27.3 vs. 25.6 $kg\ ha^{-1}$). Similarly, treatments PM + RDF_{50} and FYM + RDF_{50} were also assessed statistically non-significant with each other (23.1 vs. 22.0 $kg\ ha^{-1}$).

Different treatments comprised of inorganic and organic sources influenced significantly on K uptake by wheat crop. The grain K uptake ranged from 28.3 $kg\ ha^{-1}$ in the control treatment to 55.8 $kg\ ha^{-1}$in PM + RDF_{100} followed by the treatment FYM + RDF_{100} (55.2 $kg\ ha^{-1}$) and RDF_{100} (50.0 $kg\ ha^{-1}$). Straw K uptake increased with the additional chemical fertilizers, irrespective of organic amendments. Highest straw K uptake (40.1 $kg\ ha^{-1}$) was estimated in PM + RDF_{100}which remained at par to treatments PM + RDF_{75} (39.6 $kg\ ha^{-1}$), FYM + RDF_{100} (38.1 $kg\ ha^{-1}$), and FYM + RDF_{75} (36.7 $kg\ ha^{-1}$). While minimum straw K uptake was recorded in control treatment (22.5 $kg\ ha^{-1}$). Total K uptake (grain + straw) different significantly among various treatments and estimated maximum (96.0 $kg\ ha^{-1}$) in PM + RDF_{100} treatment followed by FYM + RDF_{100} (93.3 $kg\ ha^{-1}$) while minimum was recorded in control plots (50.8 $kg\ ha^{-1}$). Treatments PM + RDF_{75}, FYM + RDF_{75} and RDF_{100} indicating values for total K uptake of 88.9, 86.3 and 83.7 remained statistically identical with each other.

Variation in nutrient efficiency relations of wheat under INM

The data regarding nutrient efficiency relations i.e. recovery efficiency, and agronomic efficiency in wheat in response to integrated nutrient management is depicted in Table 5. Recovery efficiencies of NPK were observed higher at lower rates and vice versa. The magnitude of N recovery efficiency varied from 39.2% (RDF_{100}) to 63.8% (PM + RDF_{50}) followed by FYM + RDF_{50} (60.6%). All other treatment remained non-significant for N recovery efficiency. The minimum P recovery efficiency (16.1%) was calculated with RDF_{100} which escalated to 29.8% with PM + RDF_{50} followed by FYM + RDF_{50} (27.4%). While treatments PM + RDF_{75} and FYM + RDF_{75} (26.1 vs. 23.6%), and PM + RDF_{100} and FYM + RDF_{100} (23.5 vs. 22.1%) proved statistically non-significant with each other. The treatment RDF_{100} revealed K recovery efficiency of 54.8% which enhanced to 82.1% with FYM + RDF_{50} while reached to maximum (89.5%) in PM + RDF_{50} treatment.

The agronomic efficiency of nutrients was also recorded higher at lower levels of fertilizers, irrespective of organic sources. The maximum N agronomic efficiency (27.1 $kg\ kg^{-1}$) was recorded in treatment PM + RDF_{50} followed by PM + RDF_{100} (24.3 $kg\ kg^{-1}$), while RDF_{100} showed minimum value for N agronomic efficiency (18.5 $kg\ kg^{-1}$). The treatment PM + RDF_{50} and PM + RDF_{100} exhibited higher P agronomic efficiency by showing values of 36.1 and 32.4 $kg\ kg^{-1}$ respectively. However, the lowest P agronomic efficiency (24.7 $kg\ kg^{-1}$) was observed in plots with RDF_{100} only. The treatment PM + RDF_{75} showed statistically identical results for agronomic efficiency of P with the treatments FYM + RDF_{100}, FYM + RDF_{75}, and FYM + RDF_{50}. The treatment RDF_{100} showed lowest value of K agronomic efficiency (37.0 $kg\ kg^{-1}$), while the highest K agronomic efficiency was estimated in PM + RDF_{50} (54.2 $kg\ kg^{-1}$) which remained statistically at par to PM + RDF_{100} (48.6 $kg\ kg^{-1}$).

Discussion

Plant roots are the main structures for water and nutrient acquisition from soil. Identification and manipulation of favorable plant root traits is a fundamentally important strategy to improve crop productivity on soils with poor fertility status (Meister et al., 2014; Li et al., 2016). Results of current study revealed that root system architecture (RSA) of wheat was influenced significantly under the integrated use of FYM and/or PM along with mineral fertilizers. Increase in root length, root surface area, and number of root tips at lower NPK rates, irrespective of organic sources, is the manifestation of the fact that plants invest more into belowground plant parts in order to explore more soil volume under limited nutrient availability for fulfilling their nutrient requirements (York et al., 2018). Among organic amendments, integrative response of PM was more pronounced in improving root traits as compared to FYM. The improved physical properties in response to INM system might have provided a more desirable soil environment for the better root development. Wheat plants have monocot/fibrous root system having total root length, root volume, root surface area, root diameter and number of roots as major traits (York et al., 2018). Nutrient availability poses profound impact on RSA by manipulating the root length, root diameter, root angle, number of roots and root hairs (Gruber et al., 2013). Wutthida and Karel (2015) studied the effect of nutrient deficiency on RSA of wheat and found that total seminal root, lateral root length and root-shoot ratio increased under N deficiency, while P deficiency revealed higher total root area and average root diameter; nonetheless K deficiency influenced slightly on the RSA of wheat.

Improvement in crop yield is the ultimate target of any nutrient management strategy. Addition of organic amendments on long-term basis along with inorganic fertilizers may enhance soil fertility by increasing organic C, macro and micronutrient contents (Antil et al., 2011). Our results clearly indicated that various treatments contributed effectively to increase wheat yield. Yield response of PM along with chemical fertilizers proved superior to all other treatments. The application of PM + RDF_{100} showed maximum increase in yield and associated traits (Table 3). The benefit of organic sources was quite evident as they ensured a steady nutrient supply, important for better plant growth. Higher availability of plant nutrients released from FYM and/or PM might have contributed in improving yield and related traits. Moreover, contribution of humic substances from these sources along with chemical fertilizers exert positive impact on crop performance by enhancing water and nutrient absorption from soil thereby resulting in yield improvement (Ganaie et al., 2015). Bhandari et al. (2002) found identical results for rice yield with the *Sesbania* green manure plus 50% recommended NPK dose and 100% NPK alone. Wheat yield significantly enhanced with the use of chemical fertilizers along with compost, FYM and *Sesbania* green manure when compared to control (Sabah et al., 2014). Likewise, integration of FYM (15 t ha^{-1}) and chemical fertilizers (250-120-125 kg NPK ha^{-1}) showed the maximum grain yield of 8.47 t ha^{-1} in maize crop (Randhawa et al., 2012). Soomro et al. (2013) reported 25% saving of chemical fertilizers in sugarcane crop under the INM with FYM and/or PM applied at the rate of 20 t ha^{-1}.

Sharma and Sharma (2002) investigated the effect of INM on the sustainability of rice-wheat cropping system and observed higher N uptake of rice-wheat system by 38-45 kg ha^{-1}, P uptake by 7-10 kg ha^{-1}, and K uptake by 25-42 kg ha^{-1} in response to FYM + NPK fertilizer. In current study, nutrient uptake significantly improved with the conjunctive use of inorganic and organic nutrient sources as compared to sole application of these materials. But the integrated effect of PM was superior to FYM (Table 4). Mitra et al. (2010) described that higher nutrient uptake under INM might be due to the release of native nutrients, synthesis of complex intermediate organic molecules during decomposition, their mobilization with different nutrients, and accumulation in various plant tissues. More nutrient uptake under INM can be attributed to additional supply of nutrients through these organic sources. Moreover, the synergistic effect of organic matter addition on the availability of native and applied nutrients could be the reason behind higher nutrient uptake and crop yield. Singh et al. (2006) and Phullan et al. (2017) reported high uptake of macronutrients (N, P and K) in response to addition of FYM and green manure. According to Shah et al. (2009), combined application of organic (poultry manure, filter cake, and FYM) and inorganic sources in the ratio of 25:75 can increase grain yield and N uptake of wheat. Joint application of organic and chemical fertilizers has positive effect on N, P and K contents in sugarcane leaf tissues (Bokhtiar and Sakurai, 2005). Singh et al. (2008) stated that high P availability with the FYM and/or PM along with inorganic P might be due to the addition of P through organic sources in excess of the crop removal. Organic acids produced from decomposition of organic resources facilitate the release of K from the K-bearing minerals, and thus enhance the K uptake by wheat (Ganaie et al., 2015).

In present study, nutrient (NPK) efficiency relations i.e., recovery efficiency and agronomic efficiency were recorded higher at lower fertilizer rates and vice versa. Least recovery efficiency of NPK were calculated with

RDF_{100} while highest were recorded in PM + RDF_{50}. Application of pressmud along with RDF_{50} and RDF_{100} produced higher agronomic efficiency of applied nutrients while RDF_{100} of NPK exhibited lowest values (Table 5). Recovery efficiency of any nutrient can be described as the amount of a particular nutrient absorbed by the plant per unit of nutrient applied, while agronomic efficiency refers to the grain yield produced per unit of nutrient applied (Fageria et al., 2010). The enhanced nutrient use efficiency under INM treatments might be attributed to the impact of organic sources on soil quality by favoring the vital soil physical, chemical, and biological processes that must occur in order to support plant growth (Bronick and Lal, 2005). Yaduvanshi (2003) reported that conjunctive use of mineral fertilizers and FYM increase nutrient efficiency in wheat (2.2%) and rice (30.6%). Similarly, Shah et al. (2009) found that organic and mineral nutrient sources in 25:75 are the best combination to achieve high nutrient use efficiency and sustainable yield of wheat crop. Abbas et al. (2016) reported that nutrient efficiency can be enhanced using suitable combination of organic and mineral sources and tightening the ratio of nutrients signifying that a rational merger of elements is crucial to improve their efficiency.

Table 5. Recovery and agronomic efficiencies of nitrogen, phosphorus, and potassium in wheat crop under integrated plant nutrient management

Treatments	Recovery efficiency (%)			Agronomic efficiency (%)		
	Nitrogen	Phosphorus	Potassium	Nitrogen	Phosphorus	Potassium
Control	-	-	-	-	-	-
RDF_{100}	39.2 d	16.1 c	54.8 e	18.5 c	24.7 c	37.0 c
FYM	-	-	-	-	-	-
FYM + RDF_{100}	47.4 cd	22.1 b	70.8 bc	22.2 bc	29.6 bc	44.4 bc
FYM + RDF_{75}	51.8 bc	23.6 b	78.7 ab	22.1 bc	29.5 bc	44.2 bc
FYM + RDF_{50}	60.6 ab	27.4 ab	82.1 ab	21.8 bc	29.1 bc	43.6 bc
PM	-	-	-	-	-	-
PM + RDF_{100}	52.3 bc	23.5 b	75.2 b	24.3 ab	32.4 ab	48.6 b
PM + RDF_{75}	56.2 a-c	26.1 ab	84.7 ab	23.8 ab	31.8 ab	47.7 ab
PM + RDF_{50}	63.8 a	29.8 a	89.5 a	27.1 a	36.1 a	54.2 a
LSD 0.05	10.49	5.47	17.52	4.45	5.94	8.91

Treatment details are given in Table 2. Treatment means not sharing similar letter(s) in the same column differ significantly from each other (LSD test, $P \leq 0.05$). Values are means of three replications (n = 3)

Conclusion

The results of current study suggested that integration of organic and mineral nutritional sources could be a sustainable strategy to maximize wheat productivity and nutrient efficiency on low-fertile alkaline calcareous soils. Although both organic sources (PM and FYM) improved root system, grain yield and nutrient uptake in wheat, but the integrative response of PM was most evident than FYM. Integrated use of PM along with RDF_{100} proved superior to all other treatments, indicating the highest grain yield and NPK uptake. Moreover, treatments PM + RDF_{75} and FYM + RDF_{75} showed statistically identical yield with RDF_{100}, suggesting that 25% mineral fertilizers can be saved through this integration approach. However, further evaluation of this approach on different soil types is needed to devise concrete recommendations for adoption on a wider scale.

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