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Can organic manures replace chemical fertilizers to enhance nitrogen and water use efficiencies of rice-wheat systems? A review

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Abstract
Applying alternative fertilization practices instead of conventional fertilizers might improve rice-wheat yield and nutrient use efficiency in rice wheat cropping systems. However, the current farming system is heavily reliant on chemical fertilizers, which negatively affect soil health, the environment, and crop productivity. Manures are significant organic source of plant nutrients. Farmer's awareness is increasing towards organic farming due to high cost of synthetic fertilizers and nutrient composition in Wheat grain all over the world. Improving crop production on a sustainable basis is a challenging issue in the present agricultural system. The replacement of chemical fertilizers with organic ones has received increasing attention in recent years. Compared with the chemical fertilizer treatments, equal amounts of substitutions with cow manure or chicken manure increased production, and a 25% nutrient substitution resulted in the best yield increase. The N accumulation and DM content both exhibited a slow-fast-slow growth trend throughout the various growth stages, and the average N uptake and DM accumulation in response to the treatments followed the order of chicken manure > cow manure > chemical fertilizer > straw return > CK. The N_{min} content in the profile not only increased as the N_{min} application rate increased but also showed greater increases at certain depths than at the surface, indicating that excessive N led to leaching. An appropriate proportion of organic substitution not only provides enough nutrients but also improves the soil environment and leads to increased yields.
Overall, the increase in grain yield from organic manures application (press mud, vermicompost and farmyard manure), alone and in combinations, was VC > VC + FYM > FYM > PM + VC > PM > PM + VC + FYM > PM + FYM with 68, 55, and 38% increase as compared to control. The highest improvement (14.1%) in grain protein contents was recorded from vermicompost as compared to control. Moreover, manure application (Fm and Fc + m) increased WUE of winter wheat by 5–9 % compared to chemical fertilization (Fc), due to the lower ET after anthesis. However, manure application decreased WUE of summer maize by 6–10 % than chemical fertilization, which caused by the higher ET before anthesis. Therefore, using organic manures instead of chemical fertilisers to improve soil quality, nitrogen and water use efficiency, and production in rice–wheat systems is a viable approach for sustainable agriculture.

Keywords: water use efficiency; biomass accumulation; soil water storage, rice–wheat systems

Introduction
Increases in grain yield over recent decades in India were largely dependent on heavy investments in fertilizer. India has been the world’s second biggest consumer of N fertilizer since 1985. However, too much chemical fertilizer results in soil degradation and low use efficiency of applied fertilizers (e.g., N) by crops, which leads to considerable losses of N and environmental pollution (Gastal and Lemaire, 2002) [11]. Compared to the separate application of chemical fertilizers, the application of manure is beneficial to the soil nutrient balance, soil structure and moisture-holding capacity, and facilitates environmental protection (Reganold, 1995; Conacher and Conacher, 1998) [33, 5]. Considerable research has focused on the effect of organic fertilizer applications on yield. Duan (2011) [10] showed that the application of manure along with mineral fertilizer over 15 years in China led to high yields. In addition, Diacono and Montemurro (2010) [8] showed that organic amendments consistently did not reduce crop yields, and Zhang *et al*. (2016) [42] showed that replacing 30% total N fertilizer (250 kg N ha^{-1}) with compost (the compost application rate was 3000 kg ha^{-1}, which was equal to 60 kg N ha^{-1}) is an effective method of increasing the cereal yield, N uptake and soil fertility, and reducing N loss. These findings demonstrate that optimum yields can be achieved by management

practices that involve alternative sources of N, and N availability can be successfully balanced with crop uptake (Kramer *et al*., 2002) [19]. India is the largest consumer of freshwater globally, 91% of which is withdrawn for food production (FAO, 2016). Groundwater depletion increased by 23% from 2000 to 2010 (Dalin *et al*., 2017) [7] and is a major concern for cereal production and self-sufficiency (Barik *et al*., 2017) [3]. Cereals play a dominant role in Indian diets and contribute to approximately 50% of the total water used in the agricultural production of food in India (Harris *et al*., 2017) [15]. The intensive irrigation for the rice-wheat cropping system has led to wheat and rice contributed 31% and 19% of the dietary blue WF respectively which aggravates the water scarcity, reduces the groundwater table, and threatens the sustainability of agriculture (Gleeson *et al*., 2012). Therefore, this calls for water-saving strategies to reduce water consumption and increase water use efficiency (WUE) to maintain the regional water balance and sustainable crop production. Achieving high productivity and high nitrogen use efficiency (NUE) simultaneously in agricultural production has become a major challenge with increasing food demand, natural resource depletion, and environmental deterioration. To improve yield and nutrient use efficiency, numerous short- and long-term studies have been conducted during the past decades, with most studies focusing on the effects of only one or two types of alternative fertilization options on crop yields or NUE at the field scale. However, organic fertilizer is quite low in nutrient content and its nutrient releasing ability is also low to meet crop requirements in a short time, hence the sole application of manure could not meet the usual intensity of agriculture production. Organic manure coupled with synthetic fertilizers has been confirmed to be a better approach to improve and sustain soil fertility and crop production than the sole application of mineral or organic manure (Kumar *et al*., 2017) [21]. Manure application is a practical solution to compensate for the negative effects of water stress by additional nutrient supplements. It also modifies soil physical properties, improves the root morphology, and stimulates plant growth (Zhang *et al*., 2016) [42]. Consequently, manure application under limited irrigation is supposed to increase WUE by raising crop production and taking full advantage of rainfall. In addition, effective integration of manure in the cropping system also reduces the environmental emissions from the animal production system and decreases the need for mineral fertilizers in the crop production system, which help to enhance nutrient use efficiency with lower environment impacts. Manure application improves soil characteristics, improves nutrient uptake (Li and Marschner, 2019) [22], and crop production by maintaining a sustainable environment (AlAmin *et al*., 2017) [1]. Globally, earthworm rearing is becoming an important business for the conversion of organic waste into useful nutrients (Hussain *et al*., 2018) [16]. Vermicompost has excellent potential for its application on field crops (Nurhidayati *et al*., 2018) [30]. Application of vermicompost stimulates soil microbial activity and their growth helps in mineralization of plant nutrients, and eventually improves soil fertility and quality in the crop production system (Balasubramanian *et al*., 2013) [2]. Application of vermicompost improves soil aeration, water holding capacity, and availability of plant nutrients (Gill *et al*., 2019) [13]. Vermicompost is a good choice as a substitute for chemical fertilizers in sustainable agriculture. Farmyard manure is an organic source of fertilizer containing dung and crop residues etc. Supply of manures like farmyard manure not only improved the organic matter content but also had higher porosity, aggregate stability, and hydraulic conductivity; however, over longer term; better soil productivity can be achieved by its large amount of application. The production of farmyard manure can easily be done at the farm level and thus exhibits good potential for its usage as an organic source rather than dependence on chemical fertilizers. Before industrialization, farmers used to depend on organic nutrient sources for crop productivity. Currently, farmers use chemical fertilizers because they are readily available to plant, higher nutrient use efficiency, and better control of nutrient supply in compliance with crop requirements. However, use in excessive quantity can cause nutrient loss, acidification or basification of soil, decrease in microbial population, and contamination of groundwater (Chen 2006) [4]. The use of organic sources can be very beneficial for sustainable crop production without deteriorating fertility of the soil and long-term output. The specific objective of the present review were to determine the most effective and economical combination of organic and inorganic N fertilizer to improve crop growth, N uptake and to determine the maximum proportion of conventional chemical nitrogen input that can be substituted with alternative fertilization options without causing a decrease in nutrient and water use efficiency. To propose alternative solutions to increase on-farm biomass production for use as organic inputs for maintaining or improving on-farm soil fertility and increasing crop yields.

Organic fertilizers undoubtedly can produce quality products

Organic fertilizers produce better quality products compared to conventional farming or chemical fertilizers Organic fertilisers are mineral sources that are found in nature and include a moderate amount of plant nutrients. They are capable of resolving issues caused by synthetic fertilisers. They reduce the need to apply synthetic fertilisers on a regular basis to maintain soil fertility. Mamaril *et al*. (2009) [27]. Crinnion, (2010) [6] also reported that organic varieties, while being higher in all these nutrients, are also significantly lower in nitrates and pesticide residues. There is also consistent evidence that, in general, organic plant-based foods contain a higher amount of beneficial, health-promoting secondary plant compounds than non-organic plant-based foods. Willer *et al*. (2008) [39] also reported that organically processed products do not contain hydrogenated fats and other additives whose negative health impacts are widely acknowledged. Organic foods are more potent suppressors of the mutagenic action of toxic compounds and inhibit the proliferation of certain cancer cell lines. Clear health benefits from consuming organic dairy products have also been demonstrated regarding allergic dermatitis (Crinnio, 2010) [6]. Parrott and Marsden, (2002) [31] reported an improvement in taste and nutritional content of products by the farmers converted into organic system. Due to high quality of organic products, farmers practicing organic farming can receive higher economic returns due to higher premiums of the products. Organic fertilisers are environmentally friendly since they are biodegradable, renewable, and sustainable. They maintain a steady supply of key nutrients and replenish the soil's vitamin and mineral content, which has been depleted. In today's market, there are numerous high-quality organic fertilisers. Minfert produces some of India's most effective organic fertilisers.

Bio-fertilizers can increase nutrient content of soil

Biofertilizers are preferred alternatives to chemical fertilizers for improving the overall health status of plants. Besides being environment friendly, biofertilizers showcase other important features, including their sustainability within agricultural soils. Biofertilizers are materials that contain beneficial microbes to increase the availability of soil nutrients and promote plant growth which is a prospect for sustainable agricultural development (Mącik *et al*., 2020) [25]. Soil organisms are essential components of the soil, contributing to soil productivity. There are aerobic and anaerobic N_2-fixing bacteria and some other bacteria and fungi which are effective in decomposing or mineralizing SOM. These microorganisms can be used to dispose farm wastes and to improve soil productivity. Bio fertilizers, which are applied to seeds, soils in seedbed, or to composting materials can increase the number of microorganisms and accelerate certain microbial processes such as atmospheric N_2 fixation, phosphate solubilisation, or cellulose degradation (Mamaril, 2004) [28]. Advocates of organic fertilizers claim that microbial fertilizers or bio fertilizers, containing organisms such as bacteria, fungi, algae, actinomycetes and so forth, contribute significant amount of nutrients to the crop and can be used to any crop or any type of ecosystems (Mamaril *et al*., 2009) [27]. The fact is that bio fertilizers do not directly contribute nutrients but merely make nutrients available from other sources like atmospheric N_2 or SOM (Mamaril, 2004) [28]. The incorporation of organic matter increases the microbiological activity and enhances the physical and chemical conditions of soil. However, in many cases, these materials contain low concentrations of N. Biological nitrogen fixation (BNF) is one of the most fundamental processes used to supply N to the soil, especially in combination with organic matter (Lima *et al*., 2010) [23]. Biofertilizers, which contain living microbes that when applied for plants, seeds, and soil, fill the rhizosphere and boost plant development by improving nutrient flow to the plant, have become popular in organic farming (Singh *et al*., 2020) [35]. These are used to speed up microbial processes that increase the accessibility of nutrients that can be easily taken by plants (Mazid and Khan, 2014) [29]. Microbial bio-fertilisers can be a useful choice for preserving productivity while using a more environmentally friendly and integrated nutrient management strategy. They've been developed to take use of naturally occurring nutrient mobility mechanisms, which boost soil fertility and crop yield (Singh *et al*., 2020) [35].

Effect of alternative fertilization options on nitrogen use efficiency

Ding *et al*. (2018) [9] revealed that the magnitude of increases in REN, AEN and PFPN 34.8%, 29.5% and 6.3%, respectively, for SRF and 23.5%, 10.2% and 5.4%, respectively, for SMF. The AEN and PFPN increases (18.4% and 4.7%) under SR were significant, whereas that of REN under SR was not. Regarding NUE, the application of SRF showed the best performance among the alternative fertilization options can increase both rice yield and nitrogen use efficiency, and that conventional chemical fertilizers can be partially replaced with alternative ones without negatively affecting rice productivity. Hameed *et al*. (2019) reported that the response of N curves varied between water regimes. The slope for agronomic efficiency (AE) was high at 0 N rate, and it tends to decrease as N rates increase. The lowest yield was obtained with a single split basal application of N, with high physiological efficiencies (PE), lowest fertiliser recoveries (RE), and lowest agronomic efficiency (AE). The best split found was (3:3:3:1) during the transplanting, tillering, panicle initiating, and booting stages. However, split N doses in the Alternate wetting and drying method (AWD) performed better than continuous flood (CF). AWD had high partial factor productivity and agronomic efficiency was high at CF. The high nitrogen uptake in AWD could be due to less nitrogen leaching, resulting in high N uptake and yield with high nitrogen efficiency when compared to CF. Re-watering can improve photosynthesis in later stages, increase carbon remobilization from vegetative tissues to grains, increase root biomass associated with high yields, and increase nitrogen uptake. Wang *et al*. (2021) [38] observed that with irrigation (W1) decreased annual WUE of wheat-maize system by 9% in the normal years, while it increased that by 8% in the dry years. Manure application (Fm and Fc + m) increased WUE of winter wheat by 5–9 % compared to chemical fertilization (Fc), due to the lower ET after anthesis. However, manure application decreased WUE of summer maize by 6–10 % than chemical fertilization, which caused by the higher ET before anthesis (Fig.1 a & 1b and Fig.2).

Soil water storage

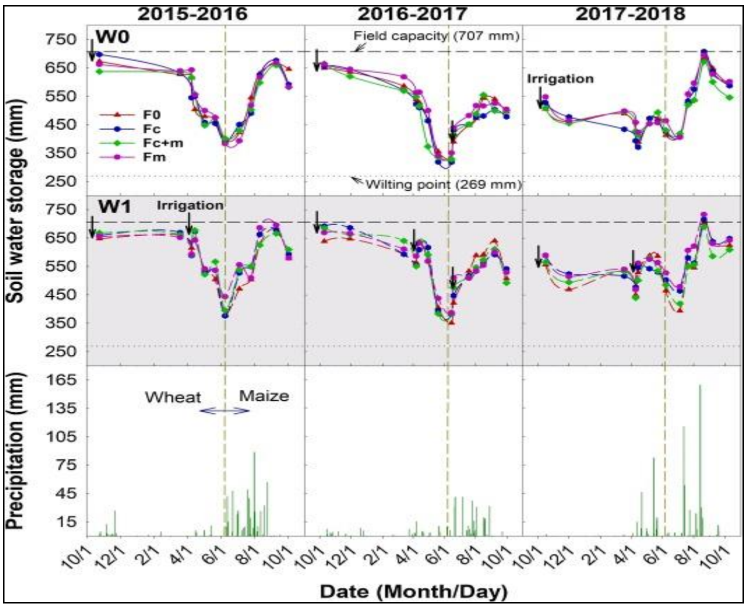

Fig 1a: The response of soil water storage within 200 cm depth to precipitation for winter wheat and summer maize under no fertilizer (F0), chemical fertilizer N (Fc), 50 % chemical fertilizer N + 50 % manure N (Fc + m), and manure N (Fm) with (W1) and without (W0) irrigation at the wheat jointing stage in three years

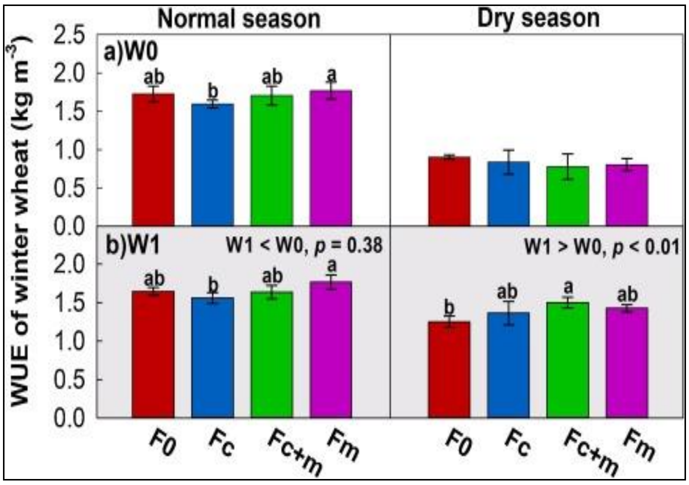

Fig 1b: The water use efficiency (WUE) of winter wheat under no fertilizer (F0), chemical fertilizer N (Fc), 50 % chemical fertilizer N + 50 % manure N (Fc + m), and manure N (Fm) with (W1) and without irrigation (W0)

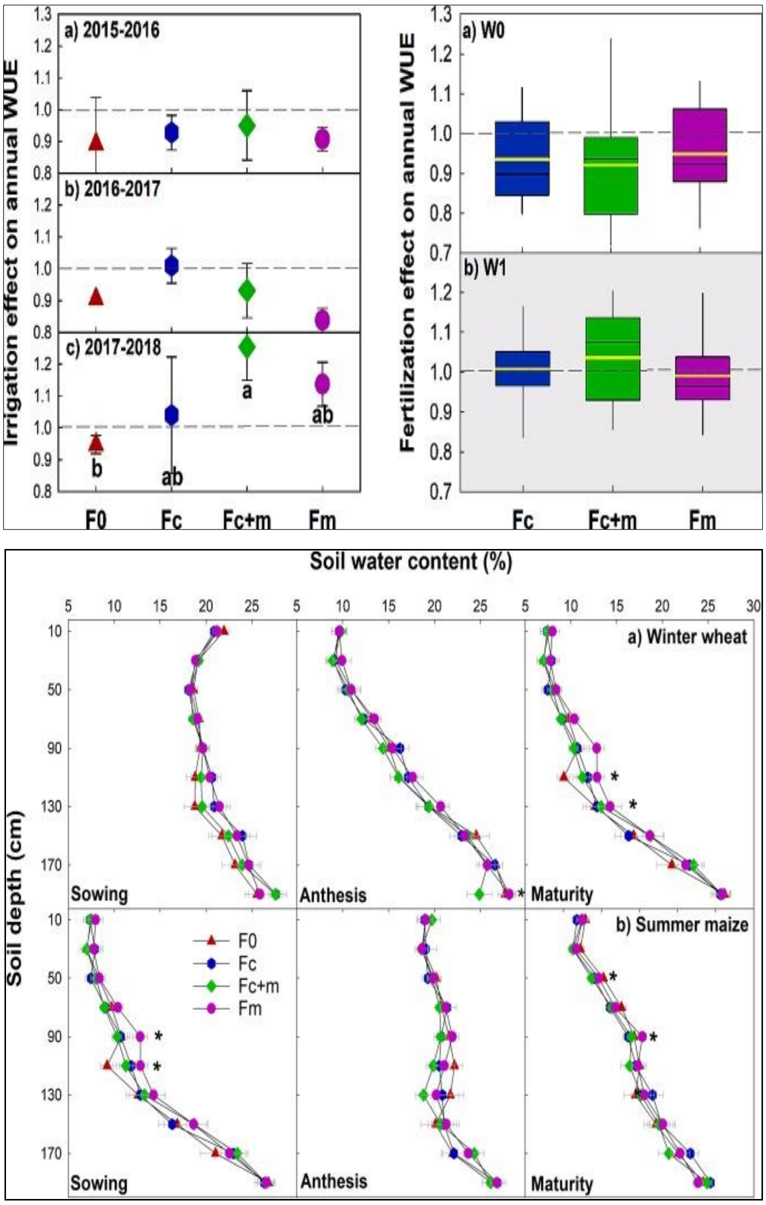

Fig 2: The irrigation and fertilization effects on annual water use efficiency (WUE)

Geng *et al*. (2019) [12] reported that the N_{min} content in the profile generally increased with the increase in MF application, and the soil N_{min} content in the fertilized treatments varied significantly across the two years. Overall, The MF treatment resulted in the highest N_{min} content, and the CK resulted in the lowest N_{min} content within the soil profile (Fig.3). The measurement of the N_{min} content along the soil profile down to 100 cm showed that the N_{min} contents in the

CK, S100, CM100, PM100 and S75 CM75, PM75 decreased as the profile depth increased; meanwhile, there was an additional accumulation in the soil (20–40 cm in 2015 and 40–60 cm in 2016) compared with that at the surface or other depths of N_{min} contents in the MF, S50, CM50, PM50, S25, CM25, and PM25; the N_{min} content at 20–40 cm depth was 35.5% higher than that at the surface in 2015; and the N_{min} content at the 20–40 cm depth was 40.4% higher than that at the surface in 2016. The additional accumulation in the soil indicated that excessive N_{min} fertilizer leads to leaching.

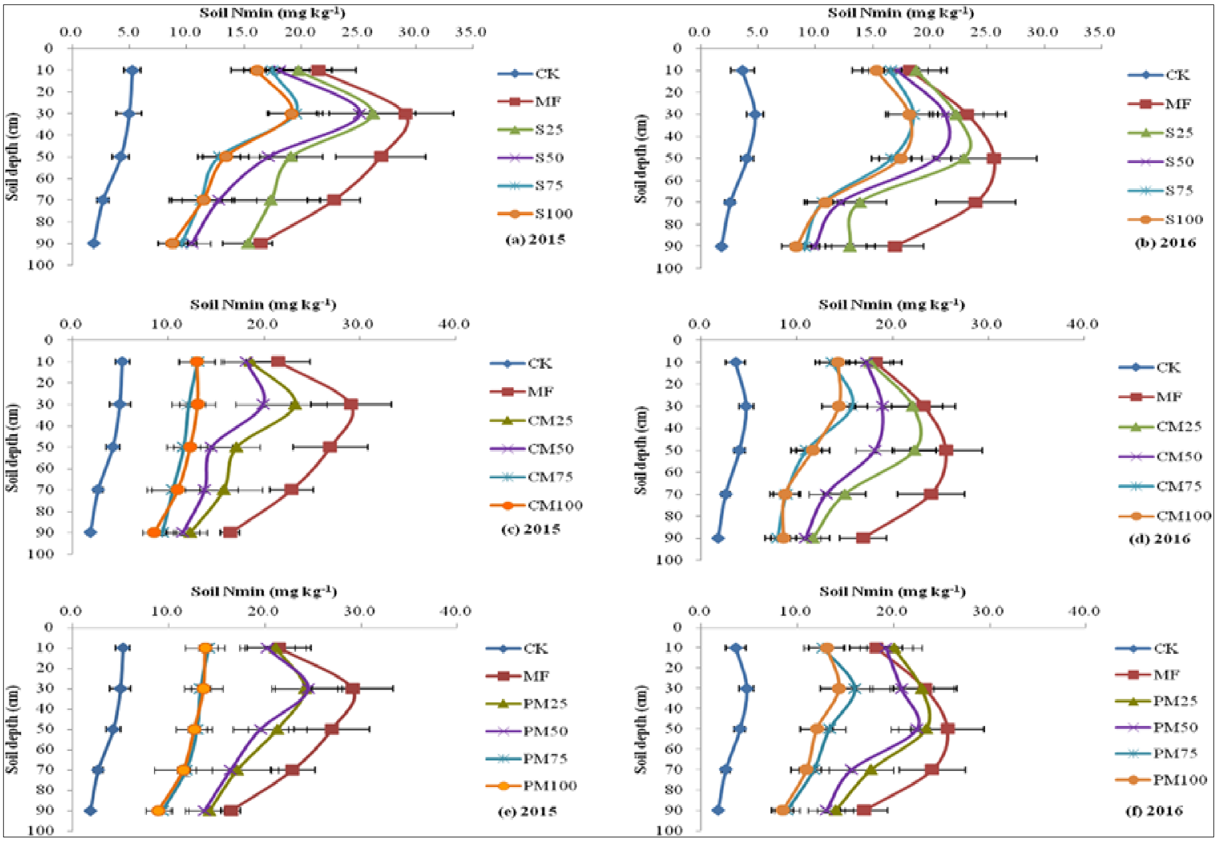

Fig 3: Mineral N concentration and distribution in the soil profile

Zhao *et al*. (2018) also found that organic amendments generally reduced the ET in the first 100 cm of the soil profile from sowing to harvesting over the two maize growing seasons. More specifically, MBF significantly decreased the SWSD in the 0-100 cm soil layer by 18.3 and 29.5 mm compared to CO in 2014 and 2015, respectively Fig. 4a. Meanwhile MWS and MFM also decreased the SWSD by 0.8 and 4.1 mm in 2014 and 24.6 and 15.3 mm in 2015 compared to CO, respectively. Notably the middle layer (20-60 cm) contributed to the major variations of the SWSD from the entire profile. There were clear variations in the SWSD across treatments at different growth stages (Fig.4b), which depended on the intensity and distribution of rainfall and evaporation. At the early growth stages, the maize plants were small and water depletion mainly resulted from soil evaporation. However, crop transpiration was the major pathway for water depletion due to the fast development of maize canopy. This was especially true in MWS which resulted in a significantly higher SWSD due to the best maize growth at 40-80 DAS over the two year period. Moreover, it was clearly implied that the positive effects of organic amendments on SWSD mainly occurred in the early/middle – late growth stages of the dry spell.

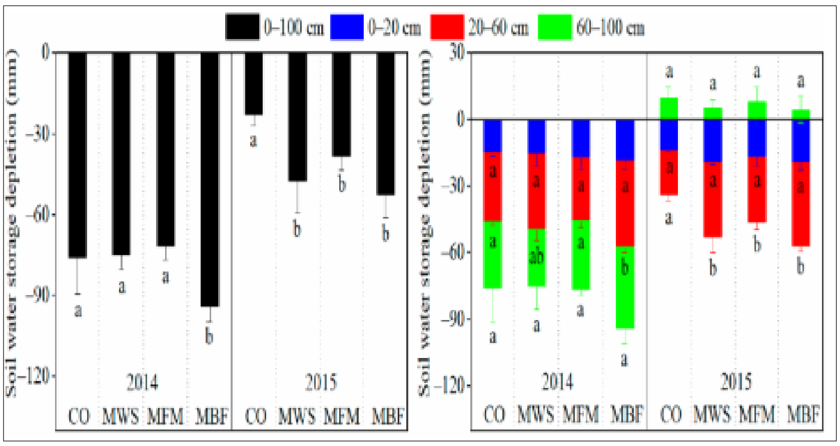

Fig 4a: Total water storage depletion (SWSD) under indicated treatments from different soil layers in the 2014 and 2015 growing seasons

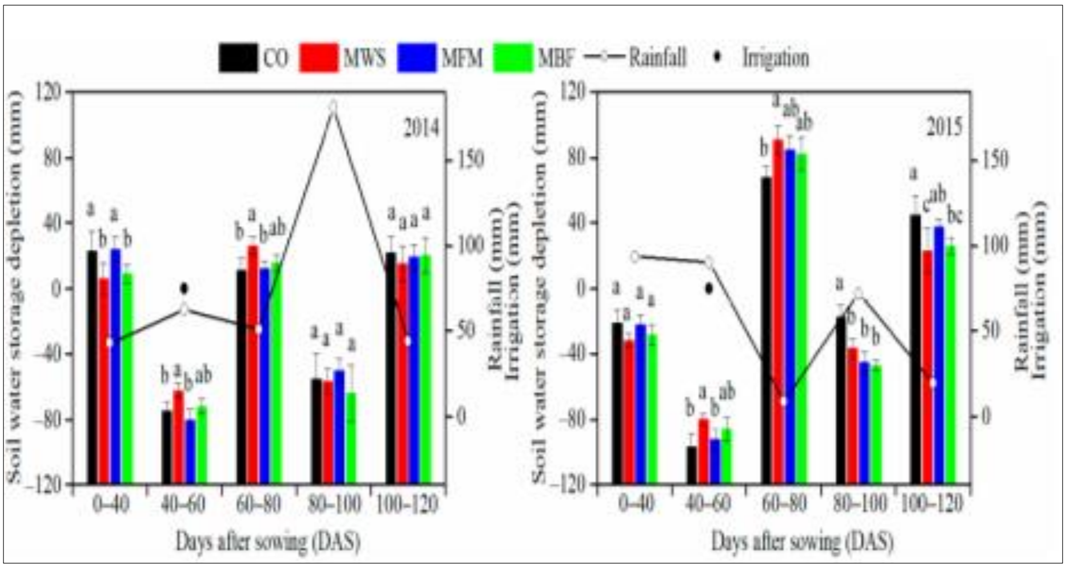

Fig 4b: The soil water storage depletion (SWSD) in the 0-100 cm layers indicated treatments during different growth stages

Ding *et al*. (2018) [9] reported that a significantly positive yield response of early, middle, and late rice to straw return relative to straw removal, with percentage changes of 8.4%, 5.1%, and 4.8%, respectively (Fig.5a). The effect size for early rice was significantly higher than that for middle rice. There was no significant yield response of single rice to straw return compared to straw removal, and this trend was also observed in response to the application of organic fertilizers. In paddy fields, a green manure (GM) crop is generally grown prior to rice planting, and the straw is generally incorporated into the soil after harvest of the GM crop. Therefore, GM is rarely returned to late or single rice under current agronomic practices. The retention of GM with early and middle rice resulted in a significant yield increase of 6.4% and 6.8%, respectively, relative to no GM retention (Fig. 5a). Consequently, the overall effect of GM retention on rice was significantly positive, with a mean yield increase of 6.7%. The magnitude of yield increase with GM addition declined with increasing inorganic N.

The application of secondary/micronutrient fertilizers (SMF) significantly increased rice yield by 4.6% relative to the control (fertilized without secondary or micronutrients) across all comparisons (Fig. 5b). Among the four rice types, single rice showed a significantly higher response to the application of SMF, with a yield increase of 7.3% compared with the three other rice types. However, the magnitude of the yield response to SMF was highly dependent on the types of SMF. For example, the application of boron

(B) produced the highest significant yield increase, i.e., an average of 8.1%, while the application of sulfur (S) resulted in the lowest (and insignificant) increase (1.9%) (Fig.5b). The yield response to other nutrients followed the order: silicon (Si)>zinc (Zn)>calcium (Ca)> magnesium (Mg). Moreover, significant increases in REN, AEN and PFPN under SRF and SMF relative to that attained under conventional fertilization. The magnitude of increases in REN, AEN and PFPN 34.8%, 29.5% and 6.3%, respectively, for SRF and 23.5%, 10.2% and 5.4%, respectively, for SMF. The AEN and PFPN increases (18.4% and 4.7%) under SR were significant.

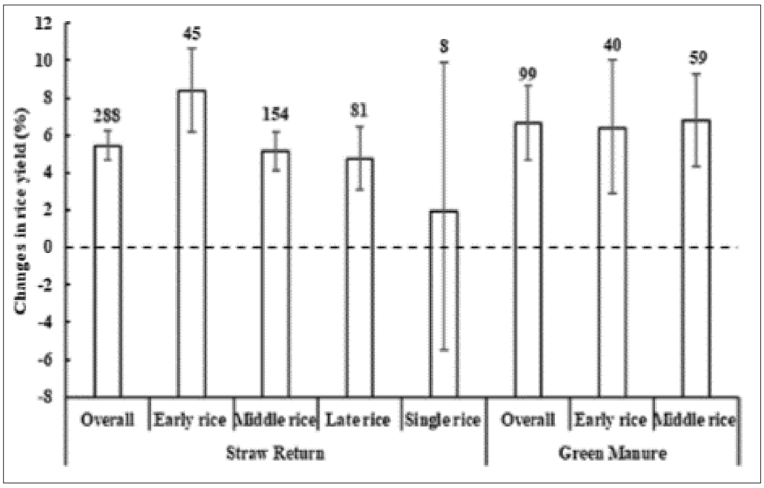

Fig 5a: Influence of straw return and green manure on percentage changes in rice yield across different rice types

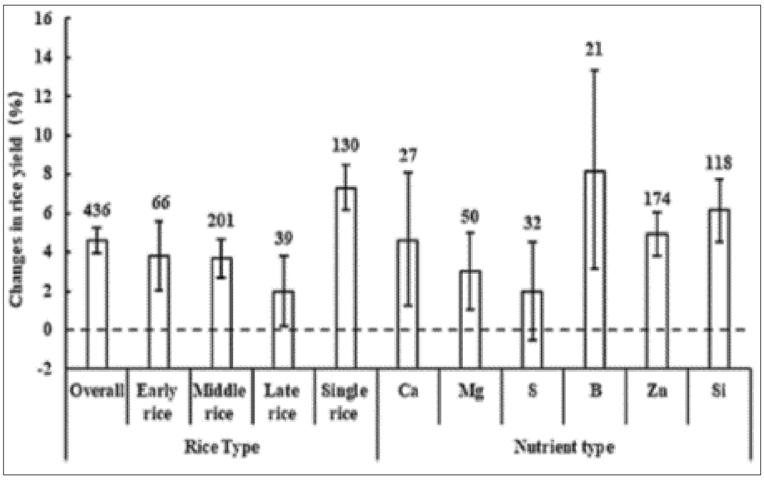

Fig 5b: Influence of secondary/micronutrient fertilizer on percentage changes in yield across different rice types and nutrient types

Iqbal *et al*. (2019) revealed that sole urea application (T_2) resulted in a higher biomass (18.14 g $hill^{-1}$ and NA 0.38 g $hill^{-1}$) at the tillering stage across the seasons, while at heading and maturity, there was maximum biomass accumulation (43.32 and 66.22 g $hill^{-1}$) and NA (0.43 and 0.67.56 g $hill^{-1}$), respectively, in T_6 across the seasons. In-addition, T_2 and T_4 were statistically comparable with T_6. The lowest biomass and NA were observed in control, followed by T_5 and T_3, during both seasons. Co-applied organic and inorganic fertilizer had significantly increased nitrogen use efficiency (NUE) compared with sole inorganic fertilizer application. Among the treatments, T_6 showed higher NUE by 43.5%, followed by T_4 at 42.8%, across the seasons (Fig. 6). Similarly T_3 and T_5 also increased NUE and lower NUE was noted in sole urea fertilizer treatment.

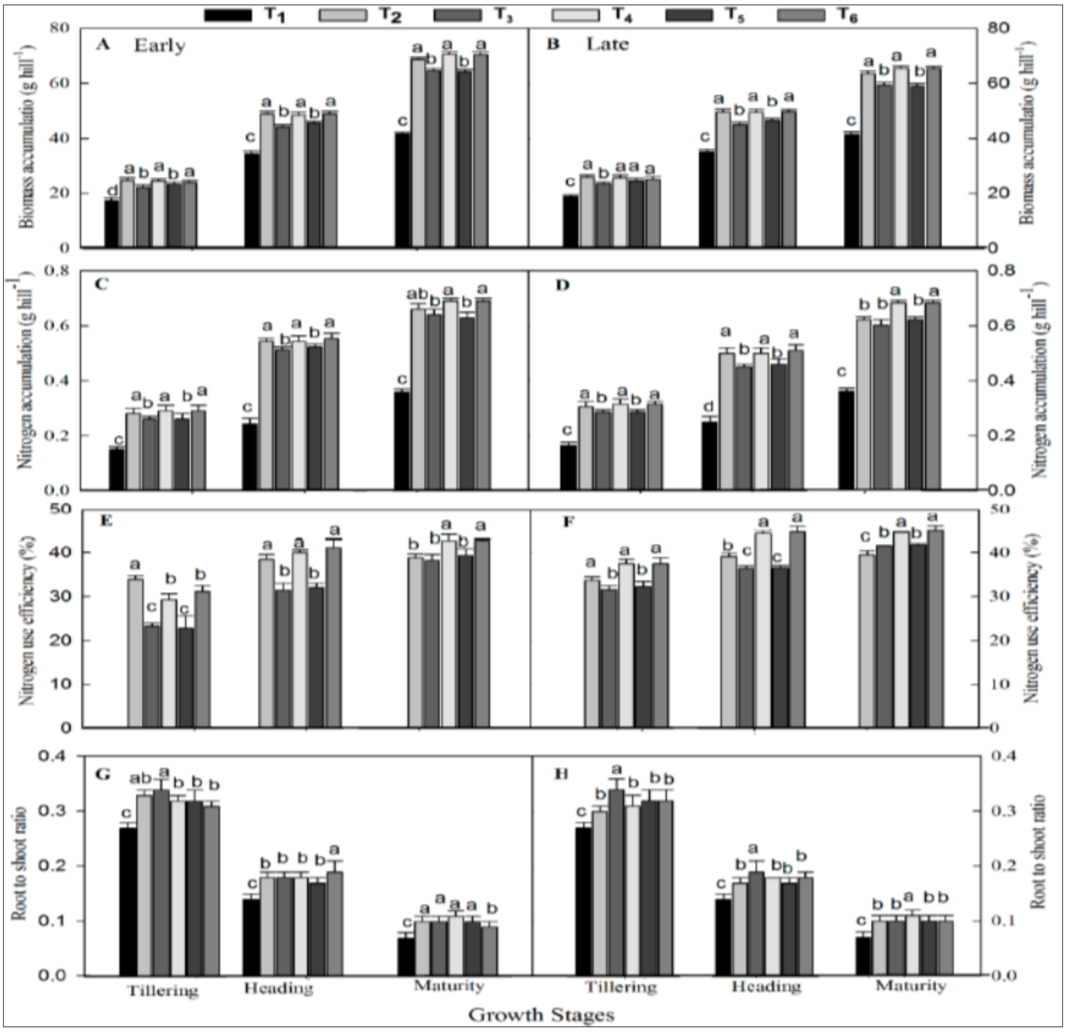

Fig 6: Changes in biomass accumulation during at early (**A**) and late season (**B**), N accumulation during early (**C**) and late season (**D**), nitrogen use efficiency during early (**E**) and late season (**F**), and root-to-shoot ratio during early (**G**) and late season (**H**) of rice at the tillering, heading, and maturity stages under organic manure and inorganic fertilizer application. Note—T_1: no N fertilizer, T_2: 100% CF, T_3: 60% CM + 40% CF, T_4: 30% CM + 70% CF, T_5: 60% PM + 40% CF, T_6: 30% PM + 70% CF.

Nitrogen Balance and Apparent Nutrient Recoveries

Nitrogen input–output balance is very important for biomass and yield accumulation process of a crop as well as for the uptake of other plant essential nutrients. We simply examined the N input–output balance by subtraction of plant N accumulation form total N application. Yadav *et al*. (2009) [41] reported that Continuous rice-wheat cropping system had variable efforts on soil fertility depending on soil types, nutrient application and productivity levels. The improvement in mean grain yield of wheat (4.0 t ha^{-1}) and straw (6.3 t ha^{-1}) was recorded due to use of organic manure (FYM + Sesbania) to proceeding rice as compared to control (Singh *et al*., 2001) [34]. Application of vermi-compost at 3t ha^{-1} +RDF significantly recorded maximum plant height, at harvest, DM and LAI at 30,60 and 90 DAS total and effective tillers per plant, grain/ear,1000 grain weight, grain and straw yield in wheat crop. Combined application of 100% NPK+FYM 15 tha^{-1} increased significantly in grain and straw yield of wheat and bio-fertilizer, which sustained better growth produced better yield attributes and ultimately higher grainyield of wheat. Application of FYM (12 tha^{-1}) with 75% NPK improves the fertility status and also recorded higher grain and straw yield of wheat than 100% NPK (Ram *et al*., 2006) [32]. Application of 100% NPK +FYM (10 t ha^{-1}) recorded significant increase in biological parameters *viz*. soil microbial biomass carbon (SMBC), soil microbial biomass nitrogen (SMBN) and dehydrogenase activities (DHA) to the extent of 8.8, 9.8 and 9.0% compared to 150% NPK through chemical fertilizers without organics (Katkar *et al*., 2011) [18]. Application of NPK and FYM amended soil has higher microbial biomass in wheat (Majundar *et al*., 2008) [24]. Application of 100% NPK + 50% N through FYM showed beneficial effect on plant height and dry matter accumulation at harvest in wheat (Kumar *et al*., 2005) [20].

Timsina *et al*. (2006) [36] reported that monitoring plant concentrations, uptake, and balance of N assist in our understanding of plant and soil N status and in devising N-fertilizer strategies for both individual crops and a cropping system. There were significant linear relationships between total system productivity (TSP) and annual N application and between TSP and annual system-level N uptake. Considering no N loss through the system, N fertilizer resulted in a positive N balance that ranged between 24–190 kg ha^{-1} compared with a negative balance of between 40–49 kg ha^{-1} without it. However, if a 30% N loss was assumed, N balances were reduced to between −37–62 kg ha^{-1} for N-containing treatments, and to between −64–55 kg ha^{-1} for the control treatments respectively.

Xue *et al*. (2014) [40] observed that wet decomposition in rice season averaged 25.83 kg N ha^{-1}, synonymous to about 56 kg urea, and therefore, contributed to about 10% of the total of N input. Together with the fertilizer N input, the average total N input was about 191–309 kg ha^{-1} in rice season and 185–245 kg ha^{-1} in wheat season. Crop harvest was the main output of N, and ranged from 157.1 to 355.8 kg ha^{-1}, accounting for 70–83% of the total N output. The annual N export through runoff and leaching ranged from 29.71 to 43.26 kg ha^{-1} in the first rice–wheat rotation year, accounted for about 8–9 % of the total N fertilizer input; whereas, in the second crop year, the annual N export decreased to 3.32 to 8.67 kg ha^{-1}, due to low precipitation. Ammonia volatilization loss in wheat season was set as 1% of the N fertilizer input. Positive N balance was only observed in FN treatment, and N surplus was 44.3 kg ha^{-1} (Fig. 7).

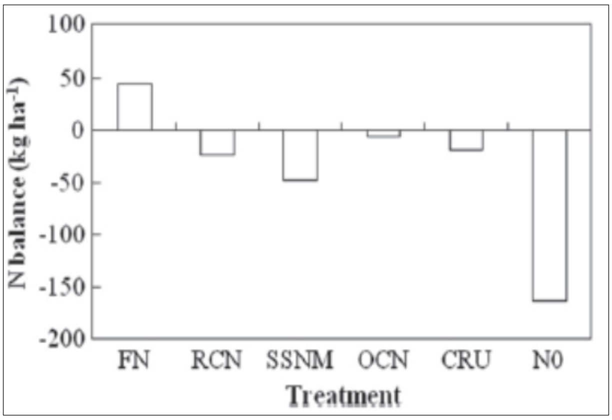

Fig 7: Partial N balance of different treatment (N balance = (irrigation N+ deposition N+ fertilizer N) − (crop N uptake – runoff – leaching –NH_3 volatilization)).

Conclusions

This review paper concluded that the alternative fertilization options can increase rice yield and NUE relative to conventional chemical fertilizer. The magnitudes of the yield responses to each alternative fertilization option depended on the rice type and fertilizer source. The application of slow-release fertilizers or organic fertilizers could substitute for considerable amounts of conventional chemical N fertilizers without negative effects on rice productivity. Yield responses to organic fertilizer, straw return and green manure were affected by the amount of inorganic N input. Our findings highlight the potential of these alternative fertilization options to improve both rice productivity and NUE.

To sustain the productivity of rice–wheat system it is imperative to integrate 50%NPK along with 50% N through FYM, GM, and WCS to rice and wheat with recommended level of fertilizers or apply 50% more N to rice and 25% more N to wheat. The increase in DTPA-extractable Zn, Cu, Fe, and Mn may be attributed to the chelating action of organic compounds added to the soil in the form of FYM, WCS, and GM. The organic compounds released during decomposition of FYM, WCS, and GM enhanced the availability of micronutrients by preventing fixation, oxidation, precipitation, and leaching. Among the different organic sources of N applied to rice, FYM and GM played significant role in enhancing the levels of chemical and biological parameters. Thus, replacing chemical fertilisers with organic manures is a promising option for improving soil quality, nitrogen and water use efficiency, and productivity of rice–wheat systems for sustainable agriculture.

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