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Impact of integrated nutrient management on the performance of *kharif* rice and its effect on succeeding crops for sustainable productivity

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ABSTRACT

Mono-cropping of riceby applying chemical fertilizers, time after time, has led to a decline or stagnation in yield due to multiple nutrient deficiencies, the degradation of soil physico-chemical properties,and an increase in insect pests and disease attacks. The core principle of integrated nutrient management (INM) is to maintain or adjust soil fertility at optimal levels and provide plant nutrients to sustain desired crop productivity. This is achieved by maximizing the benefits from all available sources of plant nutrients in acompatible and sustainable manner. Adding legumes to a rice-based cropping system is a traditional practice in rainfed conditions and is an ethical practice commonly followed by farmers.The residual effect of INMapplied to rice exhibits a beneficial impact on soil fertility and the yields of the following season's leguminous crops. This natural fertilizing effect is a significant advantage of including leguminous crops in crop rotationsand making judicial use of residual nutrients applied to the previous crop, contributing to enhanced productivity across the farming system.The ability of legumes to fix atmospheric nitrogen through root nodules makes it a viable option for developing more sustainable production systems by providing nitrogen to the componentsand subsequent crops. Moreover, legumes are an important source of protein and minerals in human diets and animal feed for small and marginal landholders.

Keywords: *integrated nutrient management, rice, leguminous crop,residual effect,rice-legume sequence, rice-groundnut sequence, system yield.*

1.Introduction

Rice (*Oryza sativa L.*) is the most significant and widely cultivated food grain globally, often referred to as "global grain" due to its essential role as a staple food around the world. Rice is a vital staple food, especially in Asia, where it forms the primary source of sustenance for billions of people. Rice has deeply ingrained itself into thetradition, culture, and daily life of human civilization, particularly in India. As time passed, rice spread to other parts of the world, and in recent times, it has become not just a major food crop but also an integral part of global agricultural economies. It thrives in warm, water-abundant environments, and advancements in farming techniques have boosted its yields, making it essential for ensuring the food security of the burgeoning global population.

Rice-based cropping systems are facing sustainability concerns due to the heavy reliance on chemical fertilizers and agrochemicals, which deplete soil fertility and pose long-term risks to soil health. The rising cost of these chemicals has further added to the issue. As a result, interest in organic alternatives has been revived. While chemical fertilizers are well-known for boosting yields, organic inputs are beneficial forgrain quality andthe sustainability of the environment. This goal is better achieved through a combination of chemical and organic inputs rather than relying solely on either of the single inputs. Thus, a balanced and rational use of fertilizers and organics can effectively enhance productivity and rice quality.

Combining mineral fertilizers with organic manure creates an environmentally sustainable, economically feasible, and socially acceptable production system. The inclusion of organic fertilizers such as vermicompost, green manures, oil cakes, farmyard manure, etc., enhance soil fertility in addition to resulting in higher crop yields,enhances organic waste decomposition, improves soil properties, buffer the soil p^H, promotes the growth of microorganisms that improve soil health and support plant development.Enhanced microbial activity not only accelerates nutrient transformation, making nutrients more available to plants, but also positively impacts crop growth by producing enzymes, increasing soil carbon content, and fostering a healthier soil ecosystem. The interest in the use of green manure as a part of the cropping system is improving soil health by ameliorating soil p^H, soil structure, water holding capacity, and nitrogen addition also helps in raising the organic matter content in the soil [7].Integrated nutrient management followed in *kharif*rice will have a residual nutrient surplus for growing a crop successfully in the *rabi* season under residual fertility conditions.

A meta-analysis performed by [18] showed that the inclusion of legumes enhanced the soil's organic carbon content. Due to the extended area under rice fallow,leguminous pulse crops are well suited to the system and are favored by farmers because of their low nutrient requirements, short growing period,andbeneficial effects on the soil environment. Besides being an important source of protein-rich food for humans and feed for animals,

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leguminous crops have the unique ability to form a symbiotic relationship with specific *rhizobium*bacteria, allowing the plant's nitrogen needs to be met via biological nitrogen fixation in root nodules. Moreover, the green biomass and residues of the crop can be incorporated into the soil to replenish nutrients that were exported to the crop and improve soil fertility. While there has been research on nutrient utilization in various cropping systems, additional work is needed to understand the residual effects of integrated nutrient management practices used in rice cultivation on the growth andproductivity of succeeding leguminouscrops. An attempt has been made in this research paper to review the impact of integrated nutrient management in rice and study its influence on the yield of succeeding legume cropsgrown under residual conditions and soil fertility status by maintaining sustainable soil productivity.

2. Concept of integrated nutrient management(INM)

For enhancing agricultural production, the prime input nutrient addition to the soilplays amajor role. The selection of nutrient source and time of application influences the recovery of added nutrients. Integrated nutrient supply not only improves the physical, chemical, and biological health of the soil and increases the availability of both applied and native soil nutrients but also helps in retarding degradation of soil, deterioration of water, and environmental quality by enhancing carbon sequestration and checking the losses of nutrient to water bodies and atmosphere [12]. One of the advantages of using organic sources is that they act as slow-release fertilizers and synchronize the demand for nutrients by the plants, both in time and space, with the supply of nutrients from the labile soil and applied nutrient pools.

This INM concept has developed the use of renewable sources of plant nutrients, taking into consideration the ecology, escalating cost of chemical fertilizers, loss of soil productivity, and yield instability [32]. It can reduce plant requirements for inorganic fertilizers, resulting in reduced use of purchased fertilizer nutrients, which aids in a significant saving of scarce cash resources for small farmers in developing countries.Integration of organic nutrient sources like FYM, vermicompost, crop residues, green manuring, etc., along with inorganic sources of nutrients, not only convert the soil rich in a large number of micro and macro elements but also helps considerably to improve the physicochemical properties of soil. INM enhances all aspects of nutrient cycling, including N, P, K, and other macro, secondary, and micronutrient inputs and outputs, with the objectives of orchestrating nutrient demand by the crop and its release in the environment. With the INM practices, different nutrient losses like leaching, runoff, volatilization, and immobilization are decreased.Which indirectly favors the high nutrient use efficiency. The fact that INM may both maintain soil resources and boost crop output is now more widely recognized [25].

INM integrates the objectives of production with ecology and environment, i.e., optimum crop nutrition, optimum functioning of the soil health, and minimum nutrient losses or other adverse effect on the environment. So, INMinvolves the use of organics, which is an integral part of a sustainable agricultural system as it includes a way of disposing of organic wastes safely and efficiently, turning them into high-quality compost. To maximize the potential of crop yields and maintain crop yields as well as the soil fertility levels, comprehensive nutrient management strategies are essential to adapt to cropping systems rather than individual crops [19].

The key components of the INM concept include increasing the farmers' awareness about the valuable use of INM practices, inviting them to forget the excessive use of chemical fertilizers, and encouraging them to focus on long-term plans for sustainable agriculture. The overall objective of INM is to achieve high crop productivity and resource use efficiency with the utilization of soil nutrients in an effective manner.The introduction of leguminous pulse crops in rotation is another option to enhance the availability of pulse and economize the use of costly fertilizers.

The basic concept of INM includes the following:

- Regulation of plant nutrient supply to the desired level for nurturing the required crop productivity.
- Appropriate arrangement of chemical fertilizers, organic manures, crop residues, and nitrogen-fixing crops for the system of land usage, ecological, social, and economic situations.
- An integrated nutrient management system enhances the soil physical circumstances in terms of soil structure, aggregate stability, soil moisture retention, and hydraulic conduction. Such enhancements in soil physical conditions support soil fertility and productivity.

3. Components of INM

Significant elements of INM can be grouped into three broad groups:

3.1 Organic Manures

Organic manure is the organic material obtained from animal, human, and plant residues, which comprises plant nutrients in intricate organic forms. The Primary organic sources are manures that are farm wastes, cattle shed wastes, night soil, vermicompost, slaughterhouse waste, fish meals, agro-industry by-products, etc. These manures also enable soil to hold more water and help improve soil drainage. They produce organic acids that help to dissolve soil nutrients and make them readily available for the plants.

3.2 Biofertilizers

Biofertilizer is defined as a product containing living microorganisms that, when applied to soil, seeds, or surfaces of the plant, colonize near the rhizosphere or interior tissues of plants and promote plant growth. Biofertilizers are typically bacteria or fungi capable of nitrogen fixation, phosphate solubilization, sulfur oxidization, plant hormone production, or decomposition of organic compounds [36]. The most common biofertilizers and biocontrol agents currently in use belong to a group known as plant growth-promoting rhizobacteria,PGPR [23][26]. PGPR colonizes the rhizosphere of many plant species, where they induce beneficial effects for the host, for example, increased plant growth and reduced susceptibility to diseases caused by plant pathogens, such as nematodes, fungi, bacteria, and viruses [17]. Benefits of PGPR can include increased seed germination rate, root growth, yield, leaf area, chlorophyll content, nutrient uptake, protein content, hydraulic activity, tolerance to abiotic stress, shoot and root weights, and delayed senescence[2]. The commonly used Nitrogen-fixing biofertilizers are Rhizobium, Azotobacter, Azospirillum, and Blue-green algae [35]. Whereas biofertilizers like *Pseudomonas striata, Bacillus polymixa, Aspergillus awamori,* and *Penicillium digitatum*arephosphorus-solubilizing biofertilizers (Sharma *et al*., 2013) [31].

3.3 Inorganic fertilizers

Industrially manufactured substances that contain essential plant nutrients in particular amounts and readily supply nutrients when applied to the plants or soil. The different inorganic fertilizers are Urea, single super phosphate, diammonium phosphate, ammonium sulphate, muriate of potash, calcium ammonium nitrate, etc.

4. Integrated nutrient management on the productivity of rice-legume cropping sequence and residual soil fertility status

Integrated nutrient management, among all strategies of sustainable crop production, plays a significant role through reduceduse of chemical fertilizers [32]. The removal of nutrients by crops from the soil exceeded their restoration through fertilizers rather than manures, causing unbalanced nutrients in the soil [14]. Organic manures, in combination with chemical fertilizers, improve the high yield of crops as compared to only fertilizers [28]. The addition of organic manure, lime, and bio-fertilizers enhanced soil organic carbon, moisture infiltration rate,and retention capacity [29]. Biofertilizers promote fertilizer nutrient use through biological nitrogen fixation systems, which further solubilize fewer mobile nutrients and lead to a stable and sustainable agriculture system [21] [22].

4.1 Effect of INM on rice and its effect on the yield of succeeding crops, lentil, gram, grass, pea and soil fertility status

The experiment conducted by [5] in the rainfed lateritic belt of West Bengal,observed higher values of yield and yield-attributing characters of rice with the application of 75%RDF (RDF-60:30:30 N, P_2O_5, K_2O kg ha^{-1}) and 3t ha^{-1} of FYM followed by application of 75% recommended dose of fertilizer (RDF) and 3.65t of well-decomposed rice straw ha^{-1}. Here, the substitution of 25% of RDF through chemical fertilizer with either 3t FYM ha-1 or 3.65 t well decomposed rice straw ha^{-1} increased rice grain yield by 15.38% and 13.38%, respectively,and straw yield by 7.24 and 5.64%, respectively over 100% RDF through chemical fertilizer. This might be because organic manures, besides supplying additional amount of nutrients, also brought about improvement in the physical properties of soil andimproved water and nutrient-holding capacity of the soil.A similar view was also expressed by [8].

The residual effect of treatments imposed on rice significantly affected the succeeding legume crops (lentil, gram, and grass pea). The yield attributes of pulses like maximum pods plant^{-1}, seeds pod^{-1}, 1000 seed weight were recorded with application of 75% RDF and 3t ha^{-1} of FYM applied to rice crop followed by application of 75% RDF and 3.65t of well-decomposed rice straw ha^{-1} and 100% RDF. Likewise, the residual nutrient of treatments 75% RDF and 3t ha^{-1} of FYM and 75% RDF and 3.65t of well-decomposed rice straw ha^{-1} gave seed yield of 874 kg ha^{-1} and 742 kg ha^{-1}, respectively in terms of grain equivalence of lentil, which was higher by 17.72 and 13.27%, respectively than 100% RDF. It was mainly because of organic manures have a long-lasting effect on soil productivity[37]. Among the different pulse crops compared, Bengalgram recorded the highest equivalent yield, followed by lentil and grass pea. This might be due to the fact that: gram showed more effectiveness towards the utilization of residual soil moisture compared to lentil and grass pea in medium-land situations[10].

Availability of total N status in the soil over initial value decreased considerably after transplanted rainy season rice in almost all the treatments except 75% RDF and 3t ha^{-1} of FYM and 75% RDF and 3.65t of well-decomposed rice straw ha^{-1}, where 25% of chemical inorganic fertilizers was replaced either by 3t of FYM ha^{-1} or 3.65t ofwell-decomposed rice straw ha^{-1}. At the end of the second year, higher available P status of the soil was recorded from the plots, which received 75% RDF and 3t ha^{-1} of FYM. Legumes in rotation increased the total N and P_2O_5status of the soil [4]. Likewise, the incorporation of inorganic fertilizers+FYM or well-decomposed rice straw in the rice-pulse cropping system resulted ina gradual increase of available K. Higher K build-up over the initial K status was noticed in the treatment 75% RDF and 3t ha^{-1} of FYM, which was closely followed by 75% RDF and 3.65t of well-decomposed rice straw ha^{-1}.

4.2 Effect of INM on rice and its effect on yield of succeeding pea crop and soil fertility status

A study was conducted by [27] at Kanpur to develop an INM module for a rice-pea cropping system for sustainable production. According to his study,rice grown after green manuring of *Sesbania*in-situalong with half of the quantity of recommended dose of NPK fertilizers(60, 13.2, and 24.9 N, P_2O_5, K_2O kg ha^{-1}) accompanied by microbial cultures(*Azospirillum*, PSB and BGA) yielded maximum, 4453kg ha^{-1}. The results indicated that 50% of RDF can be substituted with the use of green manuring (GM) along with bio-fertilizers. Early decomposition of succulent legumes such as *Sesbania* might have caused early release and availability of plant nutrients,which in turn might have resulted in a higher yield of rice.

Among three organic manures (FYM, vermicompost (VC) and green manuring crop, *Sesbania* incorporation) during *kharif*, FYM(20t ha^{-1}) along with one-fourth quantity of NPK in conjunction with bio-fertilizers recorded the highest grain yield of pea(2954 kg ha^{-1}). The residual effect of organic manures was found to be in the order FYM>VC>GM. Reduction in half quantity of RDF could be made with the application of green manuring along with bio-fertilizers(*Azospirillum*, PSB, and BGA) without any reduction in the yield of rice, whereas in pea three-fourth quantity may be saved with the application of FYM(20t ha^{-1}) or vermicompost(10t ha^{-1}) in conjunction with bio-fertilizers(*rhizobium* and PSB).

The organic carbon content of the surface soil increased with the application of manures along with fertilizers. The highest organic content was observed with the application of FYM, followed by vermicompost and green manuring crop incorporation. Theavailable P content of the surface soil increased appreciably with the application of manures along with other fertilizers as compared to the sole application of NPK fertilizers. The increased available P content of soil might be due to the release of CO_2 and organic acids during decomposition, which helps in the solubility of native soil P and, inturn enhances the availability of P. Available K content of surface soil increased considerably due to combined application of manures, bio-fertilizers, and inorganic fertilizers as compared to the sole application of inorganic fertilizers.

4.3 Effect of INM on rice and its effect on yield of the succeeding groundnut crop and soil fertility status

The resultsof research work conducted by [9]at Agronomy Main Research Farm, OUAT(2014-15)revealed that application of

75% RDN+25% N through FYM+$ZnSo_4$@ 25kg ha^{-1}recorded significantly higher plant height in all stages of rice. However, it was statistically at par with treatment 75%RDN+25% N through FYM+Zn EDTA spray(sprayed @ 0.2% at 15, 30 and 45 DAT). Maximum leaf area index(2.04) was recorded with 75% RDN+25% N through FYM+$ZnSo_4$, which was significantly higher as compared to other treatments, and lowest leaf area index (1.59)was observed under the RDN at all stages of observations. Similarly, significantly higher dry matter (1324 g m^{-2}) was recorded with application of 75% RDN+25% Nthrough FYM+$ZnSO_4$and the lowest dry matter (975.2 g m^{-2}) was recorded with RDN application. Better performance with 75% RDN+25% N through FYM+$ZnSo_4$with respect to growth characters could be explained by more excellent release and supply of nutrients in varied proportions and duration from the combined use of organic manures(FYM) and chemical fertilizer along with the application of $ZnSo_4$@ 25kg ha^{-1} as basal dose.

Application of 75% RDN+25% N through FYM+$ZnSo_4$ @ 25 kg ha^{-1} significantly exhibited its superiority to increase the number of productive tillers m^{-2}(307), panicle length(25.9 cm), number of filled grains $panicle^{-1}$(124). It was followed by the application of 75% RDN+25% N through FYM+Zn EDTA. Similarly, application of 75% RDN+25% N through FYM+$ZnSo_4$ @ 25 kg ha^{-1} recorded a higher grain yield (5146 kg ha^{-1}). However, there was no statistical difference between 75% RDN+25% N through FYM+$ZnSo_4$@ 25 kg $ha^{-1}$and 75% RDN+25% N through FYM+Zn EDTA (spray) for grain yield.The succeeding crop, groundnut crop height was higher with the residual impact of the application of 50% RDN, 50% N through FYM, and Sulphur application @ 30kg ha^{-1} to *kharif* rice, which was significantly higher over other treatments. This may be attributed to the beneficial effect of applyingsulphur along with FYM, and similar observations were also made by [3].

The groundnut plants recorded higher LAI due to the residual effect of 50% RDN+50% N through FYM+ $ZnSo_4$@ 25kg ha^{-1} than rest of the treatments and were statistically at par with 50% RDN+50% N through FYM+Sulphur at all stages of growth[30]. It isalso noticed progressing development of LAI with $ZnSo_4$ application. Higher dry matter per plant resulted in groundnuts plants due to residual effect of 50% RDN+50% N through FYM+$ZnSo_4$ at all stages of observations but was statistically similar with 50% RDN+50% N through FYM+Zn(spray) and 50% RDN+50% N through FYM+Sulphur. The higher dry matter may be attributedto better foliage, and leaf area which ultimately would have added to the DMP(g $plant^{-1}$). Similar observations were also recorded by [15][1]. The increase in CGR due to residual effect of 50% RDN+50% N through FYM+$ZnSo_4$ might be attributed to the stimulating effect of the application of $ZnSo_4$, which increased the number of leaves and more leaf area in groundnut. Other workers [34][6] observed similar results. The residual effect of 50% RDN+50% N through FYM+$ZnSo_4$@ 25kg ha^{-1} significantly exhibited its superiority due to increase in number of pod $plant^{-1}$(18.6), kernel per pod(2.2), 100-kernel weight(47.7g), pod yield(1780kg ha^{-1}), haulm yield(3050 kg ha^{-1}) and harvest index of 36.85%. The lowest (1227 kg ha^{-1}) pod yield of groundnut was recorded due to residual effect of RDN only which might be attributed due to insufficient supply of nutrient under residual condition.

4.4 Effect of INM on rice and its effect on yield of succeeding green gram crop and soil fertility status

Research work of[24]at Navsari Agricultural University, Gujarat revealed that growth attributing characters, grain yield (55.68 q ha^{-1}) and straw yield(75.87 q ha^{-1}) were significantly high by application of RDF to rice crop. Among the INM treatments applied, 75% RDN through chemical fertilizer + +25% RDN through vermicompost registered significantly higher growth parameters and rice yield. Sole application of RDF gave the highest NPK content in rice grain (1.325, 0.297, and 0.390%, respectively), straw (0.688, 0.087, and 1.455%, respectively), and also the total NPK uptake (125.82, 23.02 and 131.4 kg ha-1) of rice on the pooled mean basis of three years observation. However, it was found to be at par with NPK content in rice grain and N and P content in rice straw by the application of 75% RDN through chemical fertilizer (CF)+25% RDN through VC.

The succeeding crop, greengram was superimposed with three levels of fertilizers, and pooled data of three years showed that the application of RDF resulted in superior green gram growth parameters and seed yield per plant (5.58). The total seed and haulm yields (9.79 q ha^{-1} &24.28 q ha^{-1} respectively). The experiments also confirm that the highest harvest index(28.70) and rice equivalent yield (95.09 q ha^{-1}) was achieved with sole RDF treatment. However, this was at par with the application of 75% RDF through Commercial fertilizer + 25% through organic fertilizer (vermicompost) to rice crop.

With the exception of total P uptake by application of INM treatment 75% RDN through CF + 25% RDN through VC, which was followed by 75% RDN through CF + 25% RDN through bio compost, the NPK content in seed (3.448, 0.124, and 1.112%, respectively), haulm (0.902, 0.091, and 1.788, respectively), and total uptake (55.94, 3.42, and 54.36 kg ha-1, respectively) was found to be statistically equal to the NPK content in seed, haulm, and total uptake as a result of rice residual treatments to greengram.This could be because of the extra nutrients that organic manures provide, as well as the beneficial effects of organic matter decomposition that positively impact the soilphysical and chemical characteristics. [16] obtained a similar result in rice-based crop sequences under the Indo-Gangetic plains of India. Higher N fixation by the green gram crop was made possible by the integrated application of nutrients to the preceding crop, rice. Organic manures can supply a variety of macro and micronutrients. Because legumes can fix nitrogen, crop sequences that included them had more nitrogen available in the soil. Furthermore, it can be claimed that the nitrogen-rich biomass supplied bygreengrammay have sped up the free-living organisms' fixation of nitrogen [11].

A study conductedby[20] in two consecutive years (2017–2018 and 2018–2019)to evaluate the impacts of integrated nutrient management on the productivity of aromatic rice–greengram cropping system and nutrient balance of the post-harvest soil for agricultural sustainability under rainfed conditions with six main plots and three subplotsunder the coastal plain agro-climatic condition that taller plants (135.4 and 138.1 cm, respectively) were recorded with 50% RDF + 50% RDN through FYM closely followed by the treatment consisting of 75 % RDF + green manuring (127.9 and 131.4 cm, respectively) and 75% RDF + 25% RDN through FYM (122.8 and 124.0 cm, respectively) at harvest in the two years of experimentation. The treatment consisting of 50% RDF + 50% RDN (FYM) also noted the maximum tillers m^{-2} (359.3 and 372.6, respectively) at 90 DAT, closely followed by the application of 75% RDF + green manuring (341.9 and 351.0, respectively) at 90 DAT.

With integrated nutrition management approaches, short-grain aromatic rice's leaf area and leaf area duration varied greatly. The highest values were recorded at 50% RDF + 50% RDN

(FYM), which was comparable to 75% RDF + green manuring. In all treatments, aromatic rice's leaf area duration (LAD) rose from 30 to 60 DAT to 60 to 90 DAT.Higher LAD (105.0 and 115.3 days, respectively) at 30–60 and 60–90 DAT were obtained with 50% RDF + 50% RDN (FYM) closely followed by 75% RDF + green manuring (100.2 and 111.3 days in 2017 and 2018, respectively). The lowest values (78.3 and 81.9 days) were observed in 50% RDF + 25% RDN through FYM treatment.At harvest, significantly maximum dry matters (770.4 and 757.1 g m^{-2}, respectively) were obtained due to the application of 50% RDF + 50% RDN through FYM being at par with the application of 75% RDF +green manuring (743.9 and 757.7 g m^{-2}, respectively).Because the application of 50% RDF + 50% RDN through FYM was comparable to the application of 75% RDF + green manuring (743.9 and 757.7 g m-2, respectively), the maximum dry matters (770.4 and 757.1 g m-2, respectively) were achieved at harvest.

The significantly higher ear-bearing tillers m^{-2} (315.7 and 321.0, respectively) were registered with 50% RDF + 50% RDN through FYM over other treatments in 2017 and 2018, being at par with 75% RDF + green manuring (305.4 and 312.6, respectively) and 75% RDF + 25% RDN through FYM (295.8 and 302.6, respectively).The filled grainspanicle^{-1} in 50% RDF + 50% RDN through FYM remained statistically at par with the application of 75% RDF + green manuring (160.2 and 164.2, respectively). The treatment consisting of 50% RDF + 50% RDN through FYM significantly registered the highest length of panicle (27.6 and 27.9 cm, respectively) being at par with the treatment receiving 75% RDF + green manuring (27.0 and 26.9 cm, respectively), 75% RDF + 25% RDN through FYM (25.1 and 25.9 cm, respectively) and 50% RDF + green manuring (24.2 and 25.5 cm, respectively) in 2017 and 2018. The treatment receiving 50% RDF + 50% RDN through FYM recorded significantly higher test weight (18.2 and 18.6 g, respectively) at par with 75% RDF + green manuring. Moreover, the treatment receiving 50% RDF + 50% RDN through FYM recorded significantly highest grain yield (3837 and 3914 kg ha^{-1}, respectively) over other treatments being at par with 75% RDF + green manuring (3438 and 3539 kg ha^{-1}, respectively) in 2017 and 2018.Similarly, significantly higher straw yield (5278, 5342 kg ha^{-1}, respectively) in 2017 and 2018 was found by the treatment comprised of 50% RDF + 50% RDN (FYM) over other treatments being at par with 75% RDF+green manuring (4924 and 4931 kg ha^{-1}, respectively).Among different INM practices practiced,a significantly higher harvest index (42.1 and 42.2%, respectively) in 2017 and 2018 was recorded, with the treatment consisting of 50% RDF +50% RDN through FYM being at par with the treatment comprising 75% RDF + green manuring.

Concerning nutrient management practices followed in preceding aromatic rice, application of 50% RDF +50% RDN through FYM resulted in significantly higher plant height of green gram over other treatments at all growth stages, and at harvest highest plant height (37.3 cm) was recorded as being at par with 75% RDF + green manuring (36.4 cm).At harvest, significantly higher dry matter accumulation (15.9 and 16.3 g $plant^{-1}$, respectively) in 2017–2018 and 2018–2019 respectively, were observed by 50% RDF + 50% RDN followed by 75% RDF + green manuring (14.6 and 15.0 $gplant^{-1}$, respectively).Among different INM practices applied to preceding rice, application of 50% RDF + 50% RDN through FYM significantly produced the highest pods/plant (11.0 and 11.1, respectively), followed by the treatment receiving 75% RDF + green manuring (10.2 and 10.4, respectively) and 75% RDF + 25% RDN through FYM (8.3 and 8.7, respectively)in the two-year study.Although the recorded number of seeds per pod (10.8) was higher with the application of 50 % RDF and 50 %RDF through FYM, it was comparable to 75 % RDF + green manuring (10.7).Notably, residual application of 50% RDF + 50% RDN through FYM to rice produced the highest seed yield of greengram (798 and 815 kg ha-1, respectively) in 2017–2018 and 2018–2019 on separate study years, 75% RDF + green manuring (to rice) came in second. Similarly, the application of 50% RDF +50% RDN through FYM recorded higher stover yield (1993 and 1922 kg ha^{-1}, respectively) in 2017–18, and 2018–2019 respectively, followed bythe application of 75% RDF + green manuring and 75% RDF + 25% RDN through FYM.

Integrated nutrient management practices for the rice-greengram system positively influenced the net balance of nitrogen in the soil at the end of the cropping system. The highest N uptake in the cropping system was obtained from 50% RDF + 50% RDN through FYM treatment (332.0 kg ha^{-1}). Application of 75% RDF + green manuring to short grain aromatic rice crop and 75% RDF + R*hizobium* + PSB in greengram significantly increased available N (225.7 and 217.1 $kgha^{-1}$, respectively) in the soil at the end of the system in each year. The net gain in nitrogen status in soil was maximum by application of 75% RDF + green manuring (26.4 kg ha^{-1}) followed by 50% RDF + 50% RDN through FYM (21.9 kg ha^{-1}) and 75% RDF + 25% RDN through FYM (19.5 kg ha^{-1}). The treatment receiving 50% RDF + 50% RDN through FYM to rice and 75% RDF + *Rhizobium* + PSB to greengram produced significantly higher total phosphorus uptake (57.4 and 46.1 kg ha^{-1}, respectively). The application of 75% RDF + green manuring (8.9 kg ha-1) resulted in the greatest net improvement in soil phosphorus status, followed by 50% RDF + 50% RDN through FYM (7.2 kg ha-1) and 75% RDF + 25% RDN through FYM (4.2 kg ha-1). Application of 50% RDF + 50% RDN through FYM to rice and 75% RDF + *Rhizobium* + PSB to green gram obtained the highest total potassium uptake (436.0 and 373.4 kg ha^{-1}).The net gain in potassium status in soil was maximum by application of 75% RDF + green manuring (26.9 kg ha^{-1}) followed by 50% RDF + 50% RDN through FYM (22.9 kg ha^{-1}) and 75% RDF + 25% RDN through FYM (22.5 kg ha^{-1}).

5. Challenges of integrated nutrient management in rice-based systems

Integrated Nutrient Management (INM) promotes sustainable agriculture by combining organic and inorganic inputs to enhance soil fertility and crop productivity. However, its implementation faces several challenges:

- **Limited Availability of Organic Inputs:** Essential organic materials like compost and green manures are often scarce or of inconsistent quality, particularly in developing regions, hindering effective nutrient management.

- **Knowledge and Skill Gaps**: Effective INM requires a comprehensive understanding of soil health and nutrient integration. Many farmers lack access to training and extension services, leading to suboptimal practices.

- **Labor and Time Constraints:** The preparation and application of organic amendments are labor-intensive and time-consuming, posing challenges for smallholder farmers with limited resources.

- **Economic Considerations:** While INM can reduce long-term costs, the initial investment in organic inputs and potential short-term yield reductions may deter adoption, especially without immediate economic incentives.

- **Infrastructure and Policy Support**: Successful INM implementation requires supportive infrastructure and policy frameworks. Inadequate facilities and lack of government support can impede widespread adoption.

- **Environmental and Climatic Factors:** Variability in climate conditions affects the decomposition of organic materials and nutrient release patterns, disrupting synchronization between nutrient availability and crop demand.

- **Monitoring and Evaluation Challenges:** Assessing INM effectiveness necessitates regular soil testing and monitoring, which may not be accessible or affordable for all farmers, making informed adjustments difficult.

Addressing these challenges requires a multifaceted approach, including farmer education, infrastructure development, policy support, and research into region-specific INM practices. By overcoming these obstacles, INM can be more effectively integrated into agricultural systems, promoting sustainability and productivity.

6. Conclusion

The current study underscores the notable influence of different agricultural approaches, specifically chemical and organic fertilization, on soil physical, chemical, and biological attributes. Integrated nutrient management demonstrated the most significant potential for improving nutrient availability, and soil health, as evidenced by elevated levels of microbial biomass, organic carbon content, and enzymatic activities. While organic farming showed moderate positive effects, chemical farming, despite delivering short-term productivity gains, was associated with a gradual decline in soil quality. However, integrated nutrient management is a balanced practice that not only boosts soil fertility but also contributes to the long-term sustainability of agricultural systems.These findings emphasize the urgent need to shift toward more ecologically sound farming practices without reducing the food demand of the over-burgeoning population and maintaining the long-term sustainability of the soil. Integrated nutrient managementseems to be the solution, which is alsoan environmentally friendly option that fosters biodiversity and aids in carbon sequestration.

7. Future scope of study

The future scope of integrated nutrient management (INM) research is vast and promising. Future studies should focus on long-term field trials across diverse agroecological zones to assess the sustainability and adaptability of INM practices. Investigating the synergistic effects of combining organic and inorganic fertilizers on soil health parameters, such as microbial diversity and enzymatic activities, will provide deeper insights. Additionally, exploring the role of INM in carbon sequestration and greenhouse gas mitigation can contribute to climate-resilient agriculture. Advancements in precision agriculture technologies, like remote sensing and soil health monitoring tools, can enhance the efficiency of nutrient application. Furthermore, integrating socio-economic studies will help understand the adoption barriers and benefits of INM for smallholder farmers. Collaborative research involving agronomists, soil scientists, and policymakers is essential to develop region-specific INM guidelines that promote sustainable crop production while preserving environmental health.

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