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Review Paper

Influence of integrated nutrient management on sustaining legume crop productivity and reducing environmental impact: A review

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ABSTRACT

Considering the emerging risks to India's production and the resources therein, there stands a need to recast the country's agriculture practices as functions of resilient integrated nutrients management recommendations, focused on risk reduction, improving factor productivity, and farm profitability without compromising food safety and environmental sustainability. Integrated nutrient management practices hold great potential which take into account economic, social and environment sustainability. In view of new challenges to production and resources likely to continue, redesign of the country's agricultural practices becomes imperative for resilience-integrated crop management recommendations that reduce risks, enhance factor productivity, and increase farm profitability without compromising food safety or environmental sustainability. Apart from use in the food and fodder, they improve soil fertility through the addition of organic matter, fix nitrogen and give structure to soils. Legumes are economically profitable, due to its low fertiliser and other input requirement, improves environmental quality by sequestering carbon and removing other pollutants. Some members of the legume family have been shown to have the ability to detoxify both organic contaminants and heavy metals.

Key words: INM, Legume crop, Intercropping, Nutrient assessment, Sustainable agriculture

INTRODUCTION

Legumes consist of over 20,000 species and form the third largest family. They are, in terms of food value, the most important sources of food consumed after cereals since they contribute to food security worldwide. Legumes are consumed in complement with cereals as a source of nutritional protein and contribute greatly to the total intake of protein (Schmidt and Oliveira 2023). The legumes are fascinating plants because they fix atmospheric nitrogen to ammonia through their interaction with specific soil-borne bacteria, the rhizobia, consequently ameliorating soil fertility. Such symbiotic interactions also help them to thrive in harsh and fragile environments and provide nutrients to other crops, such as cereals leading to sustainable food production (Mabrouk *et al*. 2018). Solutions to food and nutrition insecurity among different populations legumes one the most leading crop. Legumes and legume-based crops are encouraged among smallholder farmers in most developing countries. Smallholder farmers in most parts have practiced intercropping for a long in Asia, Africa, and Latin America and it is becoming wide due to the capacity of the system to produce high yields. with minimal inputs and its ability to save space (Yu *et al*. 2015). For instance, farmers in areas that often experience drought have always grown pigeon peas as an intercrop with cereals due to their drought tolerance (Semahegn 2022). However, due to a shortage of land, most small-scale farmers grow legumes as intercrops with staple cereals mainly maize. Farmers have been benefiting from the symbiotic biological commensalism between It can be legumes and cereal crops as intercrops (Singh *et al*. 2024). Legume varieties, species, and soil fertility determine their nutritional and chemical contents, which in turn determine their roles in the food, feed, and fuel industries. This section examines the three areas and how grain legumes contribute to each (El-Esawi 2019).

According to Food and Agriculture Organization (FAO), integrated crop management has been adopted recently in agriculture and is of much significance and relevance than the individual approach of crop, soil, water, nutrients, weeds, diseases, pests and energy management (Varatharajan *et al*. 2019). It integrates suitable agronomic management practices for raising a good crop including tillage and crop establishment methods, integrated nutrient management, integrated weed management IWM, integrated water management (IWM), integrated disease management (IDM) and integrated pest management (IPM) and integrated energy management (Venkatesh *et al*. 2023). Legume crops such as hairy vetch and crimson clover, can contribute significantly to the nitrogen requirements of subsequent crops through biological nitrogen fixation. In addition to providing nitrogen, legume cover crops can suppress weeds, provide suitable habitat for beneficial insects, and act as non-host crops in rotation (Adhikari *et al*. 2017). However, in area where excess nitrogen is already a problem, the use of ground cover may provide a sink to tie up some of this excess nitrogen and hold it until the next growing season.

Sustainability through pulses: A nutritional and environmental solution

Nutrient assessment of pulse crop

Pulse/legumes crops such as lentils, beans, peas, and chickpeas, have important part in both human and animal food because they possess high nutritional value, containing a fair quantity of proteins, carbohydrates, fibre, and micronutrients (Jawalekar *et al*. 2020). Legume crops meet a high need for nutrition for the increasing population but more in developing countries in the absence of easily accessible or, at times, expensive animal-based proteins (Singhal *et al*. 2016). The quality of protein assessed by its amino acid profile, particularly the presence of essential amino acids like lysine, which is often limited in cereals crops (Yadav *et al*. 2019). The United Nations declared 2016 as the "International Year of Pulses," with goals for attaining a significant rise in global production and consumption by 10% in 2020, coupled with raising awareness about accruing benefits from consuming them (Yadav *et al*. 2019). Even so, the production and productivity of global pulses have not shown a satisfactory enhancement during the last six decades due to their cultivation mainly in hostile environments and relative neglect by farmers and policy makers (Kumar *et al*. 2023). To meet the growing demand for pulses, it is estimated that global production needs to increase from 70 million tonne in 2015 to 372 million tons by 2030, 440 tons by 2050 and more than 500 million tons by 2100 (Lal 2017).

Character of pulses crop in soil health

According to Prashar and Shah (2016), one of the most efficient ways for rejuvenation of soil health without any sort of disturbance of this biota is its association with legumes. legume crops are soil conditioners and increase the physical qualities of the soil, offering a substrate for the organic matter of soil and the biological activity (Lal 2015). Leguminous cover crops do not allow erosion or nutrient leaching from the soil, and green manure crops improve the physical properties of the soil. According Cossel *et al*. (2019), legume crops have increased consideration for their potential to improve soil fertility for better sustainability in agriculture. Various organic compounds, such as amino acids, carbohydrates, vitamins, mucilage, and organic acids, are incorporated into the soil during legume decomposition and during crop growth, these compounds improve soil aggregation and binding, hence hydraulic conductivity, water holding capacity (WHC), water infiltration, and total pore space (Shukla *et al*. 2011). Legume crops are added in green manuring into the soil, to keep the C/N ratios in balanced equilibrium (Lithourlidis *et al*. 2011). According to Jensen *et al*. (2012), legume-based cropping systems highly improve soil fertility characteristics in terms of soil organic carbon (SOC) and the availability of nutrients, due to their inherent nature of nitrogen fixation. It has been reported in the meta-analysis that legumes store 30% more SOC than other species. According to Rutkowska and Pikula (2013), crop rotation with legumes/cover crops is the main component in stabilizing the SOC (soil organic carbon) pool in loamy and sandy-textured soils. Stagnari *et al*. (2017), reported that the type of soil affects the structure of the microbial community of the soil, nutrient dynamics of the rhizosphere, and plant growth. However, in a natural ecosystem, the legumes are reported to fix 25-75 pounds of nitrogen per acre per year, while in a cropping system, several hundred pounds are fixed. According to Frankow-Lindberg and Dahlin (2013), perennial or forage legumes such as alfalfa, sweet clover, the true clovers and vetches can fix between 250-500 lb of nitrogen per acre.

Concept of INM

In its most basic definition, integrated nutrient management (INM) is the practice of integrating both conventional and modern approaches to nutrient management into a sustainable and profitable agricultural system that makes prudent and efficient use of all potential sources of biological, inorganic,

organic components and substances (Singh *et al*. 2020). The goal of optimizing nutrient cycle is to synchronize the crop's nutrient need with its release into the environment. This includes optimizing inputs and outputs of N, P, K, and other macro- and micronutrients. According to Zhang *et al*. (2012), INM methods aim to minimize losses through leaching, runoff, volatilization, emissions, and immobilization while achieving high nutrient-use efficiency. According to Mohammadi and Sohrabi (2012), the goal is to improve the soil's physical, chemical, biological, and hydrological properties in order to maximize farm productivity and minimize land degradation. More people are starting to realize that integrated natural management (INM) can improve crop yields while subtly reducing soil erosion (Patel and Singh 2022). To enhance plant nutrients and conserve water, its methods incorporate farmyard manures, farm wastes, soil amendments, crop residues, green manures, cover crops, intercropping, crop rotations, fallows, conservation tillage, irrigation, and drainage (Singh *et al*. 2020).

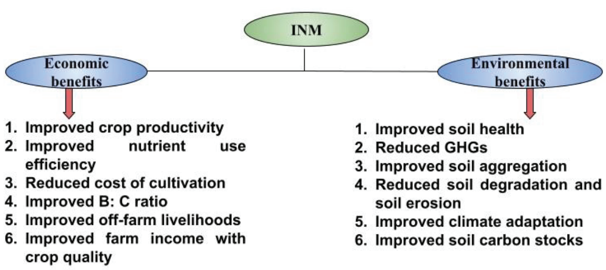

Fig. 1. Concept of Integrated Nutrient Management

Among the innovative methods incorporated into this approach are the use of urea coatings or inhibitors to reduce nutrient losses and maximize plant absorption, as well as the deep application of fertilizers (Zhang *et al*. 2012). As an alternative to profiting only from increased productivity, these methods push farmers to think more strategically about the future and the effects on the environment. The goal is to improve the soil's physical, chemical, biological, and hydrological properties in order to maximize farm productivity and minimize land degradation. More people are starting to realize that integrated nutrient management (INM) can improve crop yields while subtly reducing soil erosion. To enhance plant nutrients and conserve water, its methods incorporate farmyard manures, farm wastes, soil amendments, crop residues, green manures, cover crops, intercropping, crop rotations, fallows, conservation tillage, irrigation, and drainage (Singh *et al*. 2020). Among the innovative methods incorporated into this approach are the use of urea coatings or inhibitors to reduce nutrient losses and maximize plant absorption, as well as the deep application of fertilizers (Zhang *et al*. 2012). As an alternative to profiting only from increased productivity, these methods push farmers to think more strategically about the future and the effects on the environment.

The most important strategy of an INM

Find out whether agricultural plants have nutritional deficiencies or if soil nutrients are available. Soil nutrient availability is often assessed through laboratory measurements and sampling, however there are two main techniques to find nutrient shortages. The first is that visual cues, when combined with plant symptom analysis, can diagnose specific nutritional shortages. Furthermore, in cases where no outward signs of disease are present, a reference sample from a healthy plant can be used to compare laboratory results with those from post-harvest soil and tissue samples.

It also provides for the in-depth assessment of strengths and weaknesses in the present soil fertility management relative to nutrient diagnostics, including issues to do with over- or under-application of nitrogen fertilizers.

Find farming practices and implements which guarantee a constant supply of critical nutrients under various climatic and soil conditions presented fig 1. Soil nutrient budget for an area and time period can be arrived at by subtracting inputs and subtractions of nutrients. It will be possible to choose suitable INM technologies after these considerations have been clarified.

Analyze how well INM techniques work and how long they last. Technologies that are suitable for the local environment and the active participation of farmers in testing and analysis are essential components of INM approaches.

Importance of Integrated nutrient management

The world's population is increasing at a high rate and will double in three to five decades; therefore, providing food to such a large population without an increase in production is next to impossible (Page *et al.* 2020). In the not-so-distant future, environmental issues will surely ensue because of the fast increase in the usage of chemical fertilizers and stimulants to feed such a massively increasing human population. For this

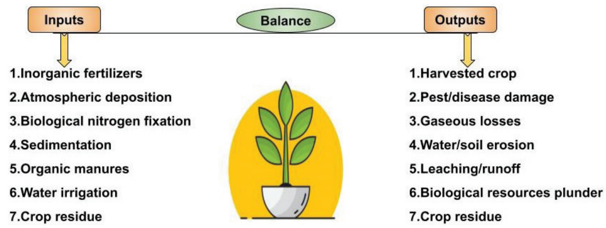

Fig. 2. Nutrient budget between inputs and outputs and working principle of INM

reason, ensuring continued soil viability requires a system of sustainable agriculture. The challenges mentioned can be solved in the long run, through sustainable maintenance of soil health and fertility, utilizing the integrated nutrient management system (Tahat *et al*. 2020). The term INM is used to signify the integration of synthetic fertilizers with naturally occurring resources such as agricultural and urban waste, composts, green manures, biofertilizers, and livestock manures (Antil 2012). Both organic and inorganic materials get combined to give an excellent return on crops and profits with fertility conservation of the soil (Kanna *et al*. 2013). Major advantage of the use of organic and inorganic Nutrient source; in combination; in integrated. Nutrient management has proved to be optimized to the use of every single component individually (Palaniappan and Annadurai 2018). The basic objective of integrated nutrient management is to have a homogeneous and highly effective mixture that shall allow better management and judicious application of fertilizers and maintain nutrients taken up by plants for increased productivity and yield, with minimum harm to soil nutrients and the environment. Integrated nutrient management, having diverse strategies, and using a balanced blend of organic, inorganic, and bioorganic microbes, is one such viable option. It can make the absorption of micronutrient and macronutrient molecules better. More relevantly, it can also obviate the problems associated with nutrient deficiency and meet crop nutrient food requirements without any effect on the environment or the things that they created by Salim and Owied (2017). Soil fertility management has generally been satisfying worldwide. There are new challenges in terms of preserving the improved condition of the soil. On the reverse, the quality of the soil degrades due to the wide application of chemicals. Furthermore, precipitous decline in the quality and fertility of soil has resulted in consequences such as less production of food and more costs that are associated with preserving the fertility of the soil. Considering these situations, we have a long-term solution to the problem of deteriorations of soils using sustainable technologies and ideas. There are various recommendations for the likely ideas and concepts put forward. Integrated nutrient management is a sustainable approach to soil fertility conservation and improvement. Soil health and fertility can only be maintained through sustainable agriculture with INM (Strauss *et al*. 2023).

Integrated nutrient management in legumes

An adequate supply of plant nutrients is thus required for better food-grain production that, in turn, supports lively hooks. In general, pulse crop is known to extract 30-50 kg of nitrogen, 2–7 kg of phosphorus, 12–30 kg of potassium, 3–10 kg of calcium, 1–5 kg of magnesium, 1–3 kg of Sulphur, 200–500 g of manganese, 5 g of bicarbonate, 1g of copper and 0.5 g of molybdenum from soil. In general, for example, producing one ton of biomass, pulse crops remove about 30-50 kg N, 2-7 kg P_2O_5, 12-30 kg K_2O, 3-10 kg Ca, 1-5 kg Mg, 1-3 kg S, 200-500 g Mn, 5g B, 1g Cu and 0.5g Mo from soil (Singh and Chhetri 2021, Laxmi *et al*. 2020). The overall health of the soil depreciates during uneven application of the fertilizers, and productivity is lost due to exhaustion of useful nutrients for growth, as proved by Bhandari *et al*. (2002). Generally, there are sufficient nutrient managements advice on agricultural crops for the whole world, but most the farmers do not apply fertilizers at recommended rates on account of higher costs and non-affordability (Kumar *et al*. 2014). Therefore, INM could be useful in supplementing crop nutrition with the careful use of organics, crop residues, bio-fertilizers, legume inclusion, etc., in conjunction with inorganic fertilizers. The INM techniques are also supported by the ICM principles, which aim to increase and maintain crop yields with minimal negative impacts on soil, the environment, and human health (Choudhary *et al*. 2015).

According to (Choudhary *et al*. 2020, Suri *et al*. 2013, Suri and Choudhary 2014), legume-based cropping systems play a crucial role in sustaining agricultural productivity and maintaining soil fertility. When comparing no-tillage with conventional tillage in three long-term rotations (15-26 years) with intercropped cover-crop legumes. Boddey *et al*. (2010) found that SOC increased from 5000 to 8000 kg/ha. Similarly, organic manures significantly boost soil microbial activity, soil structure, water holding capacity, and soil organic carbon (SOC). Chemical-cum-biofertilizer fertilizers play an important role in improving the health of the soil and thus in increasing the yields of crops. Rhizobium is a genus of bacteria which helps the legumes fix nitrogen asymbiotically (Patel and Gangwar 2023). That is why Rhizobium should be a staple of legume INM. The nutrient requirements of legumes, in addition to PSB and AM fungi, can be met through the use of phosphorus fertilizer. Nutrient acquisition and soil fertility with maximum pulse yield has been reported to result from tripartite AMF-Glycine-Rhizobium symbiosis by Kumar *et al*. (2014) and Bai *et al*. (2016). By applying the site-specific INM practices, it can be used to conserve soil health, livelihoods, and productivity related to farming while reducing hazards to the farm and the environment.

Legume-integrated energy management

Energy efficiency in agriculture has shockingly gone unnoticed among the hubbub surrounding the energy crisis. Measurement and monitoring of energy usage is important for achieving higher efficiency and economizing on crops. Legumes are an excellent source of protein due to their high content of protein apart from other useful ingredients like vitamins and minerals. Grown on low energy input environments previous decades (Kumar *et al.* 2019). As such, it involves additional attention to on how energy is used on such crops. We managed to achieve that by thorough investigations on energy use on all agricultural inputs, conducting field and farm machinery operations through application of a judicious use of energy resources (Rohullah 2016). Total energy can be evaluated to allow feasible designs for a cropping operation environmentally friendly building. Productivity on maximum yield of various crops is achieved through energy consumption (Taki and Yıldızhan 2018). In most circumstances, production cost increases as a result of tillage practices, by taking this into consideration, conserving crop production under conservation agriculture (CA) diminishes fossil fuel demand to some extent. This has been reported by many researchers; among them, the recent studies are by Choudhary *et al*. (2017). Besides being beneficial, the CA is economical and energy-efficient compared to CT (conservation tillage) under environmental sustainability. This has been well documented by Varatharajan *et al*. (2019). By implementing integrated crop management (ICM) strategies, one can enhance energy-use efficiency (EUE) by decreasing inputs such tillage operations and the consumption of herbicides, pesticides, and fertilizers (Varatharajan *et al*. 2019). The legume-based crop rotations with reduced tillage enhanced energy-efficiency in crop production systems. Savings in energy for ploughing and seed bed preparation perhaps. Rohullah (2016) reported ZT (zero tillage) reduced energy use with both flat-bed and raised-bed based ICM (Integrated crop management) modules. At the same time, the large amount of crop residues retained in soybean production meant that more energy had to be expended for residue handling. CA (Conservation Agriculture)-based ICM (Integrated crop management) modules, in contrast to their CT-based ICM equivalents, generated a higher amount of energy and specific energy output under either FB (flat-bed) or RB (raised bad) systems. Ultimately, ZT pigeon pea reduced the farm energy input, improving the energy output and efficiency while reducing expenses. CA and other agronomic interventions will, in the long run, reduce input energy and, due to production being reduced by improved EUE, also the output energy (Varatharajan *et al*. 2019). Compared to CT, CA systems significantly reduce the load on non-renewable energy input sources, which are reduced during the implementation of ICM modules that require an integrated input and resource strategy, drawing less from off-farm inputs since integrated energy management lies at the core of the ICM approach. This will lead to higher energy outputs with significantly lower inputs. Essentially, ICM is the process of reconciling application of today's technologies with best farming practices for the aim of striving for minimal energy and resource waste in agriculture (Hamzei and Seyyedi 2016).

Integrated crop management in legumes

Long-term planning from what I can gather from reading through the literature on integrated crop management (ICM), the great bulk of research appears focused upon the study of legumes or some other field crops with only one, two, or three components of ICM. Moreover, while the ICM is of much more importance and relevance according to FAO than the individual approaches of management for soil, water, nutrients, crops, pests, and energy, it has been applied in agriculture just recently (Selim 2020). On the other hand, there has been a considerable amount of effort that researchers have put in to enhance soil health and raise agricultural productivity with the help of ICRM (integrated crop residue management) (Wani *et al*. 2017). According to Tomar *et al*. (2019), in an investigation, it was assessed that ICM practices such as tillage, crop residue management, fertilizer management, weed management, and efficient use of farm machinery improved the crop productivity, profitability, and resource use efficiency in a rice-wheat system in Indo-gangetic plain region. Moreover, Patel *et al*. (2008) have claimed that ICM methods were superior to SRI and traditional methods of rice cultivation. Application of the ICM principles in agriculture through informed agricultural practices is not only an urgent need, especially in sensitive areas at present but also because of the degraded soil-water-continuum of the plant. Field crops have unfortunately received scant regard for the development of ICM methods and much less attention for legume production systems. Accordingly, a holistic package of integrated crop management (ICM) technologies for these legumes should be developed according to cropping systems. Further, there was no systematic study on the impact of different ICM modules like tillage, nutrients, weeds, water, and integrated pest management on crop yield, profit, input use efficiency, soil health, and saving of energy, labor, and water. Thus, if one needs to move forward in this high-potential research field, one should develop site- and resource-specific modules of ICM that contain suggestions acceptable to society, feasible in practice, and robust for the environment in the different agro-ecologies and cropping systems (Wani *et al*. 2017).

Legume effect in rainfed situations

Crop sequence

There is a nitrogen shortage in most of the deserts. Screening legumes for their potential to increase productivity is essential in dry, semiarid regions where the high cost of nitrogen fertilizer discourages its application (Soumare *et al*. 2022). Sorghum (*Sorghum bicolour*) is being cultivated on an increasing number of marginal and sub-marginal lands in dry land areas due to the pressures caused by the growing population. Sowing sorghum in Hyderabad's shallow red soils after cowpea, green gram, and groundnut boosted output. The N dose for sorghum was 60 kg N ha^{-1} when cowpea grain was the preceding crop, but only 20 kg N/ha when groundnut and green gram were the preceding crops (Naaiik *et al*. 2019). Another study indicated that in the allow-sorghum, cowpea-sorghum, and green manure (cowpea) sorghum systems, applying nitrogen to sorghum at rates higher than 15 kg/ha did not significantly improve grain output. The increased concentration of NO_3-N in the prior system's fodder and cowpea plots may account for this.

Nearly all dry land and marginal/submarginal areas predominantly depend on pearl millet (*Pennisetum americanum* L.) cropping, 97% area under it. Extensive research on intercropping systems within the plant species complex during the years has focused on castor, cowpea, groundnut, green gram, black gram, and dhaincha intercropped with pearl millets (Barod *et al*. 2017). In regions with an excess of rainfall, more than 600 mm and a lack of irrigation, it is cultivated in alternation with wheat, mustard, barley, gram, safflower, and gram rabi crops. Residual effects of grain legumes such as cowpeas or ground nuts during the season. According to Isah *et al*. (2020), approximate applying 60 kg N/ha on the following pearl millet. Much higher levels of nitrogen and phosphorus balances were obtained when sun hemp combined with dhaincha (green manure) took place of black gram, green gram, cowpea, or cluster bean (Perin *et al*. 2006).

Alley cropping system

In alley cropping, the arable crops are cultivated on land in alleys formed with trees or shrubs. This farming method was introduced in order to quickly improve soil fertility and raise productivity. Green leaf manures are added during an alley cropping when trees are being pruned in place to replace poor soil nutrients (Yustika & Muchtar 2016). Use of green leaf manures is environmentally friendly, with several advantages associated with it, such as improvement of soil health, increase in yields and returns, and increased effectiveness of applied nitrogen fertilizer. The adoption of such practices is important in improving dry land agricultural yields and profits in a sustainable manner (Eid and Negm 2018). In addition to reducing the requirement for nitrogen fertilizer, it provides one means of obtaining low input yields over time. The significantly higher fodder and fuel output of Leucaena more than made up for the decrease in crop yield (Sahare *et al*. 2018).

Lay farming system

Lay farming involves alternating between fields that are cultivated annually and fields that are used for artificial pastures for a period of two years or more (Martin *et al*. 2020). Naaiik *et al.* (2019) reported on shallow red soils in Hyderabad shown that systems where Stylosanthes was planted for two years resulted in noticeably better sorghum grain yields than systems where sorghum was mono crop. As a leguminous crop, Stylosanthes contributed to soil fertility, which was evident in improved plant development and increased production when followed by sorghum.

Intercrops

The many benefits of intercropping including the ability to maximize profits while minimizing risks, conserve soil, maintain soil fertility, manage weeds, and improve nutrition make it a popular choice among small-scale farmers (Suarez *et al*. 2022). On dryland, it is common to intercrop legumes with cereals. Research collaboration has resulted in identifying feasible intercropping patterns for different agro climatic regions across the country. These are just a few examples such as intercrop sorghum with green gram, soybean, cowpea, black gram and maize intercropped with ground nut, pigeon pea, or Pearl millet intercropped with pigeon pea etc. where nearly the full yield of the grain component may be obtained in addition to a bonus yield of approximately 60% of the legume crop. It is under cultivation as grain, feed, or green manure that legumes are included in the intercropping system (Nave and Corbin 2018).

Improving the general productivity of a system, the intercropped legumes significantly reduce resource consumption, particularly nitrogen. The level of nitrogen application that is supplemented by the addition of legumes to the intercropping system. Probably, one of the most important questions to be addressed when managing nitrogen in intercropping systems is how much nitrogen from legumes becomes available to the other crops. Not with standing, crop components differ in the requirements for nutrients (Giri and Satheesh Naik 2024). While cereals show a low P requirement but high requirements for N, the legumes require a high P in combination with an efficient system for symbiotic N fixation (Nget *et al*. 2022). That is why fertilizer application is considered complex. The N economy of intercropped legumes has not been properly assessed in many intercropping systems. The positive effect of intercropped legumes on enhancing NUE (nitrogen use efficiency) has, however, been reported in a wide range of intercropping systems and is discussed here (Thun 2013).

Legumes as smoother crop

Generally, the amount of crop-weed competition is modified by the crops grown together. According to a study by Yadav *et al.* (2012), a pigeonpea-based intercropping system reduced the loss of weed nutrients. In contrast to sesame, cowpea did well in preventing weed growth under a dense canopy. Another trial revealed that intercropping of smother crops, such as green gram or cowpea with pigeon peas and sorghum, significantly suppressed weed growth and was comparable in efficacy as that of hand weeding. The more efficient during later phases was cowpea, and in the earlier ones - green gram (Barod *et al.* 2017).

Legumes as green manure

To maximum yield with sustainability in the system, replacement of soil nutrients is necessary and quite frequent in rice-based cropping systems. Exploiting legumes for nutrient recycling is one potential aspect of integrated nutrient management in a cropping system. Summer green manuring epitomizes full recycling (Paul *et al*. 2014). Farmers then abandoned green manuring on the assumption that with fertilizer, economically valuable crops could be grown. The rising concerns over the loss of soil quality and the exorbitant price of fertilizer revived interest in green manuring. The main reason farmers use green manuring is to reduce their expenditure on chemical fertilizers. In the beginning, even before artificial fertilizers had come in a big way, green manuring with legumes like Crotolaria or Sesbania used to be done in rice-growing regions of the Indian subcontinent (Gupta *et al*. 2020). It may not only improve soil fertility but also increase rice and following crop yields. According to Shinde *et al.* (2017), upon decomposition, green manure becomes soluble for micronutrients in soil like Zn, Fe, Mn, and Cu, besides nitrogen, phosphorus, and potassium. This therefore gives the notion that nutrient deficiencies can be reduced by green manuring through the recycling of nutrients. This increases the effectiveness of applied plant nutrients in crops by reducing N leaching and gaseous losses (Shinde *et al*. 2017). If you inter the green manure one day before transplanting, you may harvest your rice 15-20 days earlier than usual and thus can sow your wheat crop when it is ready (Gautam *et al*. 2021). Incorporation of 6–8 week old sunnhemp or dhaincha green manure crops in rice fields can meet as much as 50% of the total N requirement with a substantial residual effect on the succeeding wheat crop (Patel *et al.* 2024). These crops accumulate about 3-4 t/ha dry matter and 100-120 kg N/ha (Chaudhary *et al*. 2018). According to Tiwari *et al*.

(2004), the use of *Sesbania rostratra* as green manure produced maize yields with 30 g N/ha comparable to those obtained with 90 g N/ha applied alone, saving 60 kg N. Decomposition in soil by a sunhemp or dhaincha plant begins the moment it is turned under during flowering. The heterotrophic bacteria hydrolyze simple sugars, starches, hemicelluloses, amino acids, amides, and aldehydes that are present in green leaves, flowers, immature pods, and vegetative buds, bringing about fast decomposition. Two days later, ammonia is formed. Such liberators are called "Rapid-N" systems (Singh 2020).

Older woody parts, whether shoots or roots, have more complexed lignin molecules, making them more resistant to decomposition. Biological activity on these parts is referred to as "Slow-N" releasing because it occurs very slowly (Sierota *et al*. 2016). Since the old shoots, roots, and other woody portions are comprised of already complex lignin molecules, the material in this component resists degradation. On these areas, which have been called "Slow-N" liberators, biological processes occur almost at a snail's pace. The first fraction, Rapid-N, provides nitrogen during seedling and early tillering stages, as well as second and third fractions. Slow-N, which make up 20-50% of total N, contributes to nutrition during the reproductive phase of a crop. Within just over two weeks, Sesbania released nearly 40 percent of its carbon and 80 percent of its nitrogen (Li *et al.* 2023). Within 5 to 10 days lying in waterlogged soil, the ammonium-N increases to as high as 15-30 ppm. Nitrogen released serves early rice growth. If it is not timed to coincide with crop development requirements, it could be lost through leaching and other means from the system (Chen *et al*. 2022).

Impact of integrated nutrient management (INM) on environment sustainability

INM related with soil properties

Soil physical condition and soil health are both improved additional effectively by integrated nutrient management strategy than comparison to continuous inorganic cultivation. Through the integrated nutrient management to determining the effectiveness of soil properties such as texture, structure, pH, organic matter content, and microbial activity, which is play a critical role for influences nutrient use efficiency and enhanced crop output. Pareek and Yadav, (2011), reported to nutrient applications to sandy soils with low CEC should be smaller and more frequent to prevent leaching, but amendments to increase aeration and drainage may be necessary for clayey soils with high CEC, which can retain nutrients better. Soil testing plays an essential role for INM because it allows farmers to determine the soil's health and nutrient availability, which in turn helps them decide when, how much, and what kind of fertilizer to use. Integrated Nutrient Management (INM) is a method for reducing environmental degradation and maintaining soil productivity over the long term by increasing soil organic carbon, water retention, and beneficial microbial activity through the incorporation of organic inputs such as compost or green manure. According to Panda *et al.* (2012), restoring soil health is just one of the many benefits of using beneficial bacteria and organic amendments in cowpea cultivation, to increased growth, yield, nodulation, and profitability. Additionally, they found that in terms of profitability and yield, organic amendments were on par with the control, which was the recommended RDF. In addition, Chesti and Ali (2012) found that after harvesting green gram, the availability of nitrogen, phosphorus, and potassium in the soil was greatly enhanced by applying organic manures. Singh *et al.* (2018) demonstrated that soil organic carbon content (SOC), availability of soil nutrients, microbial biomass carbon (MBC), and dehydrogenase activity (DHA) were all enhanced when applied were combined inorganic and organic nutrient sources.

INM for sustainable crop production

Nutrient imbalances, inefficiency, and environmental contamination result outcomes through the applying inorganic fertilizers to excess, while soil fertility depletion occurs from applying nutrients insufficiently. To address these issue farmers are turning to cultivated with integrated nutrient management practices, which is not only benefit in current crop with balanced macro and micronutrient but also have a significant impact on subsequent crop grown using alternative cropping practices (Kemal and Abera 2015). But it is required in bulk as it contains in less proportion. Soil fertility status in legume-based cropping systems, including urd bean, mung bean etc, can be maintained through proper use of integrated nutrient management, which eliminates both over- and under-applications. This allows for sustainable crop productivity. There are synergistic and complimentary impacts from integrated applications of nutrients. Instead of relying solely on organic with mineral fertilizers, several studies have shown that INM boosts soil fertility and long-term crop yields (Ananda *et al*. 2022). Chemical fertilizers applied in equal parts with organic manures considerably enhanced sustainable crop production, nutrient uptake, and soil nutrient status in legume-based cropping systems. According to Selim (2020) sustainably increased crop yield, nutrient uptake, and soil nutrient status in cropping systems based on legume; to improve crop yield, plant nutrient uptake, and soil nutrient status in cropping systems, it is common practice to mix inorganic fertilizers with various organic manures in varying quantities.

CONCLUSION

It is high time to go for the sustainability philosophy of INM, because this enhances crop yields without influencing the environment. Furthermore, it does not create any threats to the native nutrients available in the soil. Enhanced fertility is directly related to a friendly environment for beneficial organisms. Balancing can also be done to the macro as well as micronutrients in this concept, since it can match the absorption of the nutrients. Moreover, the application of several organic resources has been observed to improve the productivity of crops; a factor that scientists often emphasize. Enhanced delivery of nutrients by the different bio-fertilizers results in significant rise in success during harvesting. Legume crops symbiosis with rhizobium helps them fix ample amount of atmospheric nitrogen. Several studies have indicated different techniques of INM improved nutrient uptake in legumes. Soil physical and chemical qualities are both enhanced by INM, according to a large body of worldwide research. With the use of organic amendments, legume was able to enhance its nitrogen fixation by improving its nodulation. Additionally, several studies have shown that soil organic carbon plant metabolism is improved when inorganic and organic nutrient sources are combined. Finally, this review illustrates the breadth of utilizing beneficial microbes, organic and inorganic nutrient sources.

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