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Response of Integrated Nutrient Management (INM) Practice on Growth, Yield and Quality Parameters of Fenugreek (*Trigonella corniculate* L.)

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Integrated nutrient management methods assist improve fenugreek (*Trigonella corniculate* L.) development and yield by integrating the use of organic and inorganic fertilizers. These methods enhance soil fertility, increase nutrient availability, and improve plant health, all of which lead to increased crop yield, growth and quality. Future policies must place a high priority on the economical, sustainable, and efficient use of nutrient resources for the purpose to increase agricultural output. Thus, proper crop, water, soil, and land management along with integrated

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nutrient management are necessary for sustainable agriculture. Improved soil qualities and increased nutrient availability for agricultural plants come from the use of organic manures in conjunction with inorganic fertilizers. This enhances fenugreek growth, yield, and quality measures. The synthesis of carbohydrates, phytohormones, and even biofertilizers is enhanced by a nutritious diet. It also builds up the soil's organic status, which raises the availability of other nutrients and contributes to the maximum growth of crops. Vermicompost, farmyard manure, *rhizobium*, phosphorus- and potassium-soluble bacteria (PSB) are among the materials used in methi cultivation that support sustainable agriculture by enhancing soil fertility, nutrient availability, and general crop health, all of which lead to higher methi yields and quality. Organic matter is a storehouse of nutrients; applying both organic and inorganic fertilizer together can boost yields, improve soil fertility, raise crop input-use efficiency, and reduce the need for expensive fertilizers. This crop responds effectively to N provided through a combination of organic and inorganic sources. Majority of the nitrogen applied from different sources is not used by the first crop and is always reflected in the crop that follows. Therefore, it is necessary to assess how integrated nutrition management affected fenugreek's yield and nutrient uptake.

Keywords: Fenugreek growth; yield; quality; INM; organic and inorganic fertilizers; sustainable agriculture; soil health.

1. INTRODUCTION

Kasuri methi (*Trigonella corniculata L.*) is a semi-arid crop from the family Fabaceae, subfamily Papilionaceae. The chromosomal number for this species is 2n = 16. It is a self-pollinating crop. *Trigonella corniculata L.,* often known as Kasuri methi, Champa methi, and Marwari methi, is a diffused suberect and strongly scented annual herb. It is a significant herb spice crop that is cultivated in northern India's plains throughout the winter. During the vegetative growth cycle, it maintains a rose condition. Kasuri methi provides important minerals, vitamins, and Fibers. The green leaves contain several alkaloids, including trigonelline, choline and gentianine. Moisture accounts for 86.1%, protein for 4.4%, fat for 0.9%, fibre for 1.1%, other carbs for 6%, and ash for 1.5%. Furthermore, leaves contain high levels of vitamins such as carotene (2.34 mg/100g of fresh edible section), thiamine (0.04 mg), riboflavin (0.31 mg), nicotinic acid (0.8 mg), and vitamin C (52.0 mg/100g edible portion). [1] Kasuri methi is a semi-arid crop that can reach a height of 30 cm. Its leaves have a pinnate structure, with leaflets ranging in size from 1.25 to 2.0 cm. Its blossoms are a vivid orange-yellow in colour. Pods are sickle-shaped, 1.2–2.2 cm long, and contain 4–8 seeds. Kasuri methi is primarily farmed for its leaves and seeds, which are then used as a spice to flavour and scent food items. Currently, the cultivation of Kasuri methi is limited to the northern Indian states [2].

Integrated Nutrient Management (INM) is required to produce high-quality fodder crops without harming the environment. INM is the process of using a combination of organic, inorganic, and biological components to improve soil fertility and give plants the nutrients they need. It has been demonstrated to improve the physical, chemical, and biological properties of the soil, as well as increase the availability of both native and applied nutrients. By using INM, it is possible to promote sustainable agriculture and ensure that chemical fertilizers do not negatively impact the environment [3]. The main objective of the INM goal is to find the most efficient and homogeneous combination that can result in good management, be a target for fertilizers, use their quantity and quality in a sufficient and balanced manner, and be directly absorbed by plants for increased yield without endangering the native nutrients of the soil or polluting the surrounding area. The intelligent use of the integrated nutrition management (INM) approach which is defined as a balanced combination of organic, inorganic, and bioorganic microorganisms in combinations in various practices can ultimately lead to the achievement of such a goal [4].

Integrated nutrient management involves using a minimal amount of organic and inorganic fertilizers in combination with microorganisms to maintain high yields without compromising soil nutrients or polluting the environment. Additionally, comprehensive nutrition control has numerous advantages. INM can support the conversion of marginal lands to productive ones, contributing to the policy of increasing cultivated land. In addition, the organic agricultural approach yields organic food, which many consumers prefer despite its greater cost. In this situation, organic fertilizers also because of their gradual release have a longer-lasting impact on succeeding crops than inorganic fertilizers, which are rapidly depleted by runoff to subsurface water and water leaching [5]. Under the audacious heading of employing integrated nutrient management (INM), recently intensified calls have emerged encouraging farmers and agriculture specialists to shift their awareness toward substituting a portion of inorganic fertilizers by more affordable, sustainable, efficient, and environmentally friendly nutrients that come from natural resources (compost) [6]. The integrated nutrient management system reduces the usage of chemical fertilizers and combines them with organic materials, including animal manure, crop leftovers, green manure, and compost. Organic management approaches differ from chemical fertilizer-based systems in terms of nutrient availability. Using a combination of chemical and organic fertilizers has been shown to improve crop production sustainability [7].

Farmyard manure (FYM) is a valuable organic amendment that provides a balanced combination of nutrients needed for plant growth [8]. Incorporating methi into the soil improves soil fertility, microbial activity, and nutrient absorption. Rhizobium, a nitrogen-fixing bacteria, has a symbiotic connection with legume crops such as methi. Rhizobium converts atmospheric nitrogen into plant-available form, enhancing methi growth and lowering the demand for synthetic nitrogen fertilizers. PSBs are essential for increasing plant phosphorus availability [9]. Crop nutrients significantly impact plant growth, development, and productivity. Plants require critical nutrients such as nitrogen, phosphorus, potassium, sulphur, calcium, magnesium, and micronutrients to synthesize proteins and enzymes. Adequate nutrient availability promotes root development, vegetative growth, blooming, and reproduction, resulting in increased yields and better crop quality [10]. Combining biofertilizers with organic additions like cow dung improves soil structure, microbial diversity, and nutrient levels [11]. Proper nutrient management prevents deficiencies and excesses that can harm plant health and lower agricultural yield. Optimizing soil nitrogen levels can improve crop nutrition uptake, promote sustainable agriculture, and contribute to global food security. Efficient nutrient management strategies improve crop yield, conserve soil fertility, reduce environmental impact, and promote long-term agricultural sustainability [12].

Definition of integrated nutrient management: Integrated nutrient management (INM) involves using manures, chemical fertilizers, and biological agents to promote sustainable crop productivity and soil health. INM optimizes plant nitrogen inputs by matching soil supply with crop demand, decreasing N losses, and enhancing crop output. It is the most efficient way to maximize available resources and produce crops at a lower cost. Furthermore, INM promotes organic production, which can promote sustainable agriculture and provide direct environmental advantages [13]. The combining fertilizer with organic manure improves physicochemical qualities, leading to better nutrient absorption and uptake [14].

Concept of integrated nutrient management: Integrated nutrient management (INM) is a more efficient way to maintain soil health and optimize fertilizer use while increasing crop yield. The goal is to reduce chemical fertilizer consumption, strike a balance between crop nutrient requirements, and limit environmental effects. Animal manure, particularly farmyard manure (FYM), is essential for delivering macro- and micronutrients, enhancing soil structure, and increasing fertilizer efficiency. FYM improves cation exchange capacity, keeps soil micronutrients accessible through its chelating action, and promotes soil microbial activity [15]. As organic material breaks down, the mineralization process creates organic acids that lower soil pH, increase nutrient concentrations, stimulate soil biological activity, and slow down the discharge of nutrients [16, 17]. Organic manure improves soil characteristics, increasing plant development and output due to its high organic matter content and microbial activity [18]. Optimizing all plant nutrition sources to maintain optimal soil fertility and productivity levels. Integrated nutrient management utilizes a combination of soil, water, and organic matter to achieve balanced and environmentally friendly fertilization. The approach optimizes nutrient inputs from all available sources, including inorganic and organic, to meet crop productivity targets. INM technology detects and restores micronutrient deficits, ensuring crop productivity [19].

Objective of integrated nutrient management: (1) During the cropping season, it should make more nutrients from all sources available in the soil. (2) It ought to correspond with the crop's nutritional requirements. (3) It should maximize the efficiency of the soil biosphere in relation to specific functions like the breakdown of organic matter (mineralization), the biological formation of soil structure (aggregates, bio pores), the control of pathogenic organisms by their natural enemies, etc. (4) It should prevent eutrophication of water bodies, ensure that there is no buildup of toxic metals in the soil, and minimize the losses of nutrients to the environment through surface runoff, ammonia volatilization, denitrification in the case of nitrogen, and leaching NO3 and PO4 beyond the rooting zone. Integrated nutrient management (INM) aims to maximize crop yield while preserving the soil's capacity to support future generations. To this purpose, it integrates the use of all available natural and artificial sources of plant nutrients [20]. (5) Integrated nutrient management (INM) is to optimize the advantages from all potential plant nutrient sources in an integrated manner while maintaining or adjusting soil fertility and plant nutrient supply to an optimal level for maintaining the targeted crop yield [21].

Components of integrated nutrient management: According to [3] components of INM are organic manure, biofertilizers, green manuring, green residues, sewage, and sludge.

Organic manures: Organic manures formed from plants and animals, are a valuable byproduct of farming and related sectors. Manures provide secondary and micronutrients, in addition to NPK, which are crucial for long-term production. Common organic manures include Farm Yard Manure (FYM), Enriched Organic Manure, Vermicompost, Poultry Manure, Biogas Slurry, and Urine and Liquid Manure.

Vermicompost made from cow dung and leaf litter, along with 25-50 indiv m-2 of earthworm P. corethrurus, resulted in a 57% increase in sugar content over the inorganic treatment [22].

Green manure: Green manure crops improve soil organic matter, characteristics, and nitrogen content when used in cropping systems. Legumes are commonly utilized as green manure crops due to their capacity to fix atmospheric nitrogen in root nodules through a symbiotic relationship with bacteria. Green manures are often made from the following plants: cowpea, dhaincha, sun hemp, and karanj.

Biofertilizers: Biofertilizers are liquid-based treatments containing microorganisms that promote plant growth and nutrition. Liquid biofertilizer formulations may improve crop development due to their high cell count, low contamination, and superior viability and survivability [23]. According to [24,25]. biofertilizers can be divided into five categories, including free-living bacteria, symbiotic bacteria, phosphorus-solubilizing biofertilizers, phosphorus-mobilizing biofertilizers and PGPR. Biofertilizer formulation is simple and low-cost and can include a variety of microbial strains such as Acetobacter, Azotobacter, Bacillus, Pseudomonas, Rhizobium, PGPB (plant growth-promoting bacteria), and AM (arbuscular mycorrhiza). Biofertilizers are categorized into the following groups (Fig. 2).

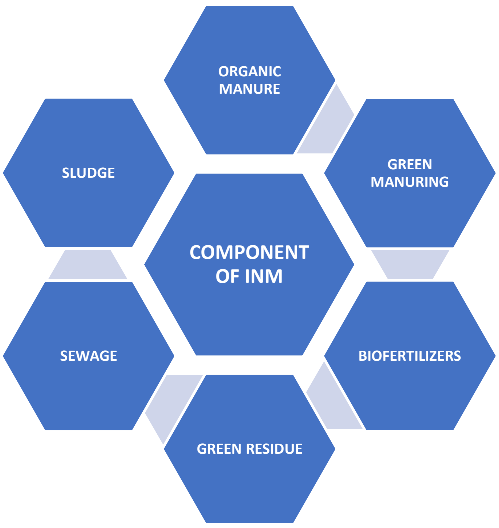

Fig. 1. Different components of integrated nutrient management

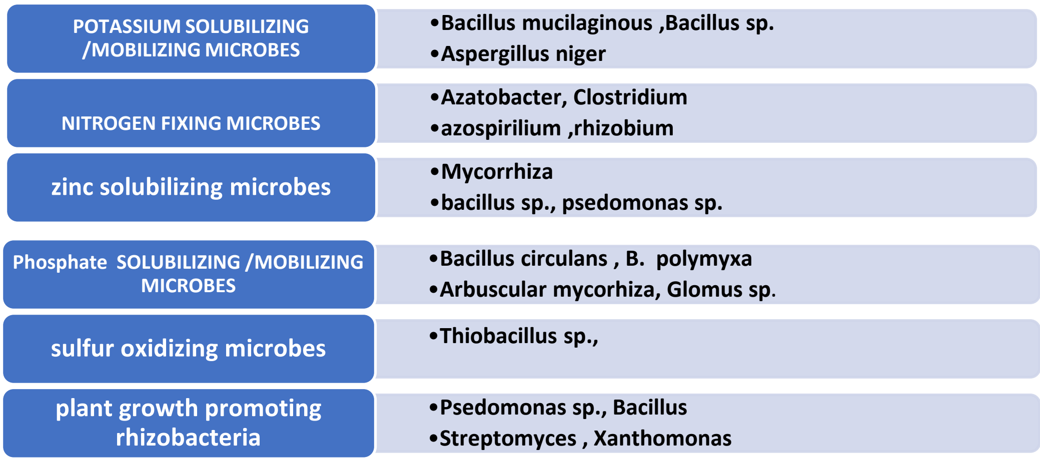

Fig. 2. different categories of Biofertilizers

Table 1. Inorganic Component of INM

	Inorganic Component of INM	
Macro nutrient	Primary (macro) nutrients	nitrogen, phosphorus, and potassium
	Secondary (macro) nutrients	calcium, magnesium, and sulphur
Micro nutrients	Boron, zinc, iron, cobalt, Copper, Molybdenum and Manganese	

Inorganic components: Plants need air, sunlight, and water to synthesize nutrients like nitrogen, phosphorus, and potassium (NPK) in the soil for crop production. The soil's nutrient reserves may be depleted by ongoing crop production if it is not managed properly. Crop yield and growth may be jeopardized as reserves are exhausted. Cumulative depletion has the potential to reduce crop yields, agricultural production, soil fertility, and eventually cause soil deterioration. The soil's nutrient reserves can be preserved and even increased with the use of methods for conserving and supplementing the soil with organic and inorganic fertilizers. [26] grouping the macronutrients into two categories: primary (macro) nutrients and secondary nutrients.

Primary (Macro) Nutrients: Primary (macro) nutrients are nitrogen, phosphorus, and potassium. They are the most frequently required in a crop fertilization program. Also, they are needed in the greatest total quantity by plants as fertilizer.

Secondary (Macro) nutrients: The secondary nutrients are calcium, magnesium, and sulphur. For most crops, these three are needed in lesser amounts than the primary nutrients. They are growing in importance in crop fertilization programs due to more stringent clean air standards and efforts to improve the environment.

Micronutrients: Micronutrients play an eminent role in plant growth, development, and metabolism. However, their deficiencies may induce several physiological disorders, diseases in plants and later can reduce the quality as well as quantity of vegetable crops [27]. Micronutrients such as boron, zinc, iron, cobalt, copper, molybdenum, and manganese help to increase post-harvest life, boost yield, quality, earliness, and fruit setting, as well as build resilience to biotic and abiotic challenges [28].

2. PRINCIPLES OF INTEGRATED NUTRIENT MANAGEMENT

Key Principles of INM. The following are the primary INM concepts that should be taken when developing integrated nutrient management strategies:

(1) Adopting INM approaches necessitates consideration of the local farming system, including soil texture, available equipment, biological conditions in the field (weeds, insects, and diseases and climate.

(2) By utilizing both nutrient sources, fertilizer input is maximized, crop utilization efficiency is increased, crop nutrient requirements are decreased, and overall expenses, food

contamination and environmental pollution are decreased.
(3) Matching the spatial and temporal requirements of crops with the nutrient sources in the soil to preserve the native soil composition.
(4) INM practice boosts crop potential, lowers fertilizer loss, and boosts profitability.
(5) It enhances the soil's physiochemical characteristics, specifically its biological and hydrological aspects.
(6) Implementing INM practices in the root zone, where nutrient conversions, solubility, availability, and release from soil to plant roots, as well as absorption, take place, is a "bottleneck" process that is the most significant process between plant and soil. This kind of workout can increase the activity of soil microorganisms to optimize biological potential [29].

2.1 Integrated Nutrient Management Benefits

The following are some benefits of the integrated nutrition management approach: (1) Integrated nutrition management is both financially and environmentally advantageous. Ensures a decrease in the careless application of chemical fertilizers, which frequently contribute to unhealthy soil and environment risks. (2) Facilitates the preservation of nutrients, enhancing soil productivity by positively influencing the chemical and biological characteristics of the soil. (3) INM not only enhances the biological health of the soil but also guarantees a consistent supply of macronutrient s and micronutrient. (4) Enhances the efficiency with which fertilizers are applied because of their positive impact on soil qualities which raises output. (5) INM contributes to soil fertility maintenance in addition to increasing productivity and profitability. In addition to increasing the productivity of vegetable crops, INM had demonstrated it contributes to soil fertility maintenance in addition to increasing productivity and profitability. In addition to increasing vegetable crop yields, INM had a positive knock-on effect on subsequent crops. (6) Guarantees superior quality in comparison to individual applications. INM facilitates the release of nitrogen and other plant nutrients at a rate determined by the crop's needs [20]. Biofertilizers are affordable, environmentally beneficial, and supply nutrients to crops over an extended period. Farmyard manure and green manure operate as soil conditioners by creating an environment favourable to the establishment of microbial populations. Organic sources improve soil characteristics and increase fertilizer efficiency. Integrating mineral fertilizers with organic manures provides a safe, cost-effective, socially responsible, and environmentally sustainable production method [30-31]. Co-applying organic manure with synthetic fertilizer minimizes inputs, reduces soil bulk density, and improves soil characteristics for inorganic fertilizer retention, leading to higher nitrogen use efficiency [32-33].

2.2 Effect of Integrated Nutrient Management on Growth and Yield on Fenugreek

Nutrients play a crucial role in crop production; however, using chemical fertilizers alone for an extended length of time may result in a loss of soil fertility and produce quality. Using organic manure in conjunction with inorganic fertilizers and biofertilizers can balance soil fertility, protect the environment, and save input costs, according to numerous workers. Kasuri methi grown using INM methods proved quite helpful in terms of quality, sustainable yield, and returns, as well as soil fertility status [34]. Practicing INM improved soil organic carbon and physicochemical qualities, resulting in higher herb and seed quality and NPK content of Kasuri methi compared to an inorganic farming system with RDF alone [2]. Applying a higher phosphorus ratio boosted plant height, possibly because of its positive influence on nitrogen transformation and glucose metabolism [35-36] reported similar results. The combination of P_2O_5 with foliar nitrogen application results in a significant improvement in growth attributes, fresh yield, and dry yield [37]. Phosphorus is necessary for methi root development, flowering, and seed generation. By assisting in the solubility of insoluble phosphorus in the soil, PSB increases crop productivity overall by making it available to methi plants. Comparably, potassium-solubilizing bacteria (KSB) increase the amount of potassium that is available to methi, another vital nutrient. For plants to blossom, bear fruit, and generally withstand stress, they need potassium. By dissolving potassium's insoluble forms in the soil, KSB improves potassium absorption [38]. Higher potassium levels may promote plant growth by increasing nutrient uptake, activating enzymatic reactions, aiding in nitrogen metabolism, and protein synthesis. This may result in increased plant height, number of branches, and dry matter production compared to lower levels of potassium fertilizer [39]. because of increased food absorption and bioactive compounds that function similarly to cytokinin and GA3. This promotes the breaking of apical dominance and leads to a rise in the number of branches, increasing the plant's AGR and CGR. The outcomes are consistent with the findings of [34, 40, 41]. [42] observed increased plant height, increased branching density per plant, plant-1 pods, seedpods, 1000 seed weight, and seed yield. Together with the inorganic nitrogen, the PSB and Rhizobium inoculation enhanced the nutrients' availability and efficiency for plant growth and seed development in the Rhizobium + PSB + 75% nitrogen treatment. This, in turn, improved cell membrane stability and reduced solute leakage from the seeds. Moreover, it resulted in the highest dry weight (81.97).

There is a substantial interaction effect between nitrogen and phosphorus with regard to plant height, dry matter accumulation, leaf area plant-1, LAI, seed, and straw yields. 20 kilograms of N were applied with 40 kg of P2O5. Additionally, to increase fenugreek growth and yield, apply 20 kg N and 40 kg P2O5 per ha, together with seed inoculation by Rhizobium sp. and phosphorus-solubilizing bacteria [43]. Compared to the control group, applying FYM 15 t ha-1 to fenugreek, there was a considerable increase in the number of branches, pods, seeds, test weight, seed weight, and seed/straw yields [44].

2.3 Effect of INM on Quality of Fenugreek

Higher amounts of phosphorus result in higher amounts of chlorophyll in leaves since phosphorus is an essential component for the manufacture of chlorophyll [14, 45]. The metabolic processes such as photosynthesis, nucleic acid, soluble protein, and glucose levels were all improved by the elevated foliar nitrogen levels. This led to the plant's luxuriant growth and higher yield of fresh produce. Phosphorus application improved the crop's availability of nutrients during the growing season, increasing assimilate synthesis and utilization in the leaves. This improved the performance of several yield attributes, including fresh leaf yield per hectare (q) and per plot (kg). Nitrogen levels greatly affect chlorophyll concentration in leaves. Greater nitrogen supply may delay leaf senescence and improve photosynthetic efficiency, leading to greater seed biomass [1]. Antioxidants can help retain ascorbic acid during dehydration and storage, improving the shelf life of dry products. Ascorbic acid decreased owing to oxidation and non-enzymatic browning during storage. Additionally, it is highly sensitive to heat. It could be lost due to the use of heat while drying. However, water blanching resulted in lower retention because ascorbic acid is water soluble and oxidizes during blanching. Maximum loss of ascorbic acid content was observed in control samples. Moreover, pre-treatment and drying processes, as well as storage periods, had a substantial impact on chlorophyll content. Pretreatments had a significant impact on chlorophyll retention, with greater levels maintained compared to the control group [46]. Higher potassium levels can increase plant development by promoting meristematic tissue, activating enzymatic activities, and aiding nitrogen metabolism. Protein synthesis may have increased plant height, branch count, and dry matter content. Production compared to lower levels of potassium fertilizer [39].

2.4 Effect of INM on Soil Health

Farmers have applied organic manure to restore soil health since ancient times. As a result, they used to spread farmyard manure frequently, right after crop harvest. As a result, the practice of applying organic manures to soil after harvesting has been linked to improving the physical, chemical, and biological characteristics of the soil as well as restoring the health of the soil, especially in marginal soils that already have low levels of organic matter and native nutrient content, low productivity, and restrictions on the availability of essential nutrients [47, 48, 49, 50, 51]. Chemical fertilizers have an impact on soil health, resulting in unsustainable yields. To improve nutrient delivery, integrated management should include chemical fertilizers, organic manures and biological inputs. Balanced fertilization involves applying vital plant nutrients in the appropriate proportion and quantity for a given soil crop situation. Unbalanced fertilizer application reduced soil fertility and productivity. An integrated plant nutrient supply system can support balanced fertilization. Integrating organic manures with optimum NPK fertilizers improves soil health and it also has ability to stabilize crop production over time [52]. Applying biofertilizers and enriched compost improved soil chemical and biological features. Furthermore, lower inorganic fertilizer doses may improve soil microbial activity and nutrient availability compared to standard fertilizer recommendations [53, 54]. Comparing integrated nutrient management (INM) to other soil management techniques, it has been shown to improve soil organic carbon [55, 56]. In addition to renewable nutrient sources, this method facilitates the efficient use of chemical fertilizers. Although organic manures regulate nutrient absorption, improve soil quality, and have synergistic effects on crop growth, chemical fertilizers can cover the crop's immediate nutritional needs [57, 58]. Microbial biomass carbon (MBC) in soil serves as both a source and a sink for biological nutrients. Management methods such as fertilizer application, tillage, and rotation can drastically affect MBC and microbial turnover, leading to decreased net N mineralization and microbial immobilization [59]. According to [60] The use of several integrated nutrient management (INM) modules resulted in significant improvements in soil quality indices, growth, and production attributes, although the use of 100% RDF produced the lowest levels of microbial biomass carbon and dehydrogenase activity. The addition of FYM increased soil aggregation and infiltration rates, resulting in a higher HC value and a direct impact on hydraulic conductivity [38]. Integrating several nutrient sources into INM enhances soil health and production, hence promoting sustainable agriculture [61]. It also mitigates the environmental impact of traditional fertilizer use [38, 62,63].

3. CONCLUSION

Integrated nutrient management (INM) techniques combine organic and inorganic inputs to promote soil fertility and plant health, which greatly increases fenugreek growth and yield. A balanced nutrient supply is ensured by combining chemical, organic, and biofertilizer manures. This increases seed production, improves root development, and increases biomass. By lowering reliance on chemical fertilizers, eliminating negative environmental effects, and enhancing soil structure, INM supports sustainable agriculture. According to studies, fenugreek plants grown under integrated nutrition management (INM) regimes had better growth characteristics, a larger yield, and higher-quality seeds than plants grown only with chemical inputs. Through increasing soil health and optimizing nutrient availability, integrated nutrient management techniques greatly increase fenugreek (*Trigonella corniculate*) growth and output. These methods are beneficial for sustainable fenugreek cultivation and increase crop yields because they improve plant development, increase productivity, and produce higher-quality crops. Therefore, INM plays a critical role in maintaining long-term soil health and fertilizer output. The combined application of inorganic chemical fertilizers and organic manures increased soil fertility and quality indicators while also increasing crop productivity. The current study concludes that applying inorganic fertilizers alone is less effective than using organic manures, biofertilizers, and inorganic fertilizers in combination to increase sweet potato yield and growth.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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