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Effect of Integrated Nitrogen Management and Spacing on Soil Fertility Status and Soil Microbial Properties in Kalmegh (*Andrographis paniculata*)

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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

The adoption of integrated nitrogen management (INM); which entails the combined application of organic and inorganic nitrogen sources; has been widely recognised for its role in improving nutrient availability; enhancing soil fertility; and promoting sustainable agricultural production systems. A field experiment was conducted to investigate the influence of integrated nitrogen management and plant geometry on soil fertility parameters and soil microbial properties in Kalmegh (*Andrographis paniculata* Nees.); a medicinally important crop. The experiment was laid out in a factorial randomised block design (FRBD); comprising four nitrogen source treatments with varying proportions of vermicompost and inorganic fertilisers; in combination with three plant spacing levels; thereby enabling a comprehensive assessment of their interactive effects on soil health indicators. Soil samples collected after harvest were analyzed for available nitrogen (N); phosphorus (P_2O_5); potassium (K_2O); and populations of major soil microorganisms such as actinomycetes; bacteria; and fungi. The results indicated that integrated nitrogen management had a significant influence on soil fertility status and microbial activity. Application of 100 per cent nitrogen through vermicompost resulted in significantly higher available soil nutrients; recording 189.90 kg ha^{-1} of nitrogen; 24.91 kg ha^{-1} of phosphorus; and 375.76 kg ha^{-1} of potassium; compared to treatments receiving nitrogen solely through inorganic fertilizers. Vermicompost-based treatments also markedly improved soil biological properties by enhancing microbial populations; with the highest counts of actinomycetes (3.92×10^4 cfu g^{-1}); bacteria (28.49×10^6 cfu g^{-1}); and fungi (4.39×10^5 cfu g^{-1}). This improvement may be attributed to increased organic matter content; better nutrient availability; and favorable soil conditions that support microbial proliferation. Plant spacing significantly influenced soil nutrient availability and bacterial population. Wider spacing (30 × 15 cm) resulted in higher available nitrogen; while spacing of 20 × 20 cm recorded higher phosphorus availability. The closest spacing (30 × 10 cm) registered maximum potassium availability and bacterial population. However; plant spacing did not significantly affect actinomycetes and fungal populations. Interaction effects between nitrogen sources and plant geometry were found to be non-significant for soil fertility and microbial parameters. The study concludes that integrated nitrogen management; particularly the application of vermicompost; combined with appropriate plant spacing; plays a crucial role in improving soil fertility status and enhancing soil microbial activity in Kalmegh cultivation; thereby contributing to sustainable soil health and long-term productivity.

Keywords: Kalmegh; integrated nutrient management; vermicompost; soil fertility; microbial population; plant geometry.

1. Introduction

Andrographis paniculata is an important medicinal herb extensively employed in traditional systems of medicine, including Ayurveda, Unani, and Siddha, owing to the presence of its principal bioactive constituent, andrographolide. Among the diverse medicinal flora, *Andrographis paniculata* (Nees), commonly referred to as Kalmegh, holds particular prominence. Kalmegh (*Andrographis paniculata* Burm. f. Nees) is a bitter-tasting annual herb belonging to the family Acanthaceae and is widely recognised as the “king of bitters” due to its intense bitterness and therapeutic significance.

Enhancing dry matter accumulation in Kalmegh is a critical determinant for improving both biomass yield and the concentration of pharmacologically active compounds. In this context, agronomic interventions such as efficient nitrogen management and appropriate plant spacing are pivotal in regulating plant growth, resource utilisation, and overall productivity (Zaman *et al.*, 2021; Hassan & Pailan, 2022; Qiao *et al.*, 2024). Furthermore, the implementation of integrated nitrogen management (INM), which integrates organic and inorganic sources of nitrogen, has been demonstrated to improve nutrient availability, maintain soil health, and promote sustainable crop production systems (Shelke *et al.*, 2024; Bhakar *et al.*, 2025; Reddy *et al.*, 2026).

Nitrogen is a key nutrient governing physiological growth, nutrient accumulation, and uptake in medicinal plants such as Kalmegh (*Andrographis paniculata*) (Basak et al., 2020). Tiwari *et al.* (2012) reported that the application of different nitrogen sources and levels significantly influenced physiological parameters, nutrient content, and nutrient uptake in Kalmegh. The use of organic nitrogen sources resulted in higher nutrient content and uptake compared to inorganic sources, indicating their positive role in improving nutrient availability and soil fertility (Kushwah *et al.,* 2023; Sarkar *et al.,* 2025). Furthermore, nitrogen application up to 60 kg ha^{-1}

significantly enhanced physiological growth and nutrient dynamics, emphasizing the importance of optimal nitrogen level management for maximizing nutrient use efficiency and sustaining soil health in Kalmegh cultivation (Jnanesha et al., 2024).

Kalmegh is distributed throughout India, occurring naturally in moist deciduous forests as well as in plain regions. Nitrogen plays a vital role in the growth and development of this crop, as it is a key constituent of chlorophyll, proteins, enzymes and structural components of plant cells. Adequate nitrogen supply promotes luxuriant foliage growth and enhances overall plant vigor at different growth stages (Kumar et al., 2022). For sustainable organic cultivation of medicinal plants like Kalmegh, it is crucial to identify suitable organic sources of nitrogen along with their optimum application rates to enhance yield and quality without adversely affecting soil health.

Efficient nitrogen management in Kalmegh improves chlorophyll content, photosynthetic efficiency and ultimately enhances andrographolide synthesis. The integrated application of organic and inorganic nutrient sources, particularly the use of vermicompost, has been reported to improve nitrogen uptake, biomass accumulation and herbage yield. In addition, appropriate plant spacing plays a significant role in improving light interception and air movement within the crop canopy, minimizing interplant competition and increasing dry matter production.

The entire aerial portion of the plant, including stem, leaves and inflorescence, constitutes the medicinal drug owing to the presence of andrographolide, which is the principal bioactive compound. This compound is well known for its therapeutic properties and is widely used in the treatment of liver and digestive disorders, as a vermifuge, antibiotic and antipyretic. Kalmegh is also extensively used in traditional medicine for managing ailments such as typhoid, malaria, fever and liver cirrhosis. The leaves and stems are the primary plant parts utilized for the extraction of medicinally important phytochemicals.

Kalmegh leaves contain several bioactive constituents such as andrographolide, neo-andrographolide, homo-andrographolide, andrographesterol and andrographone. Among these, andrographolide, a bitter diterpene lactone, and neo-andrographolide, a comparatively non-bitter compound, are considered the most important. The andrographolide content in the plant generally ranges from 0.81 to 2.78 per cent, though its concentration varies among different plant parts and across geographical regions. Being a secondary metabolite, andrographolide synthesis is influenced by seasonal variations, climatic conditions and its distribution within different tissues of the plant. In this context, the present study was undertaken with the objective of evaluating post-harvest soil nutrient status and microbial dynamics under varying nutrient management practices and plant spacing regimes.

2. Materials and Methods

The field experiment was conducted during the kharif season of 2024–25 at the AICRP on Medicinal and Aromatic Plants and Betelvine, Nagarjun Medicinal Plants Garden, Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola. The experimental site is located in a subtropical region at 20°40′35″ N latitude and 76°59′10″ E longitude, with an altitude of 307.42 m above mean sea level. The area receives an average annual rainfall of 750–950 mm. The experimental soil was clayey in texture (52.00% clay), with low available nitrogen (183 kg ha^{-1}) and medium levels of available phosphorus (P_2O_5: 21 kg ha^{-1}) and potassium (K_2O: 349 kg ha^{-1}).

During the kharif season of 2024–25, a total rainfall of 955.1 mm was recorded over 44 rainy days, which was approximately 31% higher than the normal rainfall. Initially, inadequate rainfall resulted in delayed and uneven germination of Kalmegh seeds. Subsequently, excessive rainfall during the early growth stage led to temporary waterlogging, adversely affecting seedling establishment and early growth. However, as the season progressed, the distribution of rainfall and prevailing weather conditions became favourable, leading to improved plant stand and vigorous vegetative growth. Adequate soil moisture, coupled with optimum temperature and relative humidity, facilitated enhanced leaf development, branching, and plant height, thereby improving photosynthetic efficiency and ultimately increasing dry foliage yield. Although no rainfall was received towards the terminal stage, timely harvesting immediately after the initiation of flowering ensured satisfactory crop performance.

The vermicompost used in the study was prepared at the Centre for Organic Agriculture and Training, Department of Agronomy, Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola. The experiment was laid out in a factorial randomised block design (FRBD) with three replications, comprising four nitrogen source treatments and three plant spacing levels, resulting in twelve treatment combinations. The nitrogen treatments included: N_1 (75% nitrogen through vermicompost + 25% recommended dose of nitrogen (RDN) through inorganic fertilisers), N_2 (50% vermicompost + 50% RDN through inorganic fertilisers), N_3 (100% nitrogen through vermicompost), and N_4 (100% RDN through inorganic fertilisers). The spacing treatments were S_1 (20 × 20 cm), S_2 (30 × 10 cm), and S_3 (30 × 15 cm).

The recommended dose of fertilisers (RDF) for the crop was 80:50:30 kg N:P_2O_5:K_2O ha^{-1}. In treatments involving inorganic fertilisers, 50% of the nitrogen, along with the full dose of phosphorus and potassium, was applied as a basal dose at the time of transplanting, while the remaining 50% nitrogen was top-dressed at 30 days after transplanting (DAT). Urea, single super phosphate (SSP), and muriate of potash (MOP) were used as sources of nitrogen, phosphorus, and potassium, respectively.

Seeds were initially sown in a nursery on raised beds. Healthy and disease-free seedlings were transplanted at 50 days after sowing (DAS), when they attained a height of 8–10 cm. The crop was harvested in the last week of November following the initiation of flowering in Kalmegh.

3. Results and Discussion

3.1 Soil Parameters

Available NPK (kg ha^{-1}) in Soil: The data on available nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) in the soil after harvest, as influenced by different nitrogen sources and plant geometries, are presented in Table 1. The mean available nitrogen, phosphorus, and potassium contents were 185.85 kg ha^{-1}, 23.59 kg ha^{-1}, and 365.60 kg ha^{-1}, respectively. When compared with the initial soil nutrient status (N: 182 kg ha^{-1}, P_2O_5: 25 kg ha^{-1}, and K_2O: 347 kg ha^{-1}), a noticeable improvement in available nitrogen and potassium was observed after harvest. This increase clearly indicates the positive influence of nitrogen source treatments and plant geometry on nutrient dynamics and residual soil fertility following crop cultivation.

Table 1. Available NPK of Kalmegh as influenced by nitrogen sources and plant geometry

Treatments	Available NPK (Kg ha^{-1})		
	N	P_2O_5	K_2O
Factor A: Sources of N applications			
N_1: 75% N through vermicompost + 25% RDN through inorganic fertilizer	186.42	24.08	369.51
N_2: 50 % N through vermicompost + 50 % RDN through inorganic fertilizer	185.52	23.18	363.07
N_3: 100% N through vermicompost	189.90	24.91	375.76
N_4: 100 % RDN through inorganic fertilizer	181.56	22.20	354.08
SE (m) ±	**1.40**	**0.21**	**1.40**
CD at 5 %	**4.11**	**0.63**	**4.10**
Factor B: Spacing			
S_1: 20x20 cm	185.14	23.92	365.63
S_2: 30x10 cm	183.99	23.22	368.23
S_3: 30x15 cm	188.42	23.64	362.95
SE (m) ±	**1.21**	**0.18**	**1.21**
CD at 5 %	**3.56**	**0.54**	**3.55**
Int. (N X S)			
SE (m) ±	**2.43**	**0.37**	**2.42**
CD at 5 %	**NS**	**NS**	**NS**
CV %	**2.26**	**2.71**	**1.15**
GM	**185.85**	**23.59**	**365.60**
Initial	**182**	**25**	**347**

3.2 Available Nitrogen (kg ha^{-1})

Effect of Nitrogen Sources: The effect of nitrogen sources on available nitrogen in soil was found to be significant. The highest available nitrogen content was recorded in treatment N_3 (100% N through vermicompost) with 189.90 kg ha^{-1}, which was significantly superior over all other treatments. However, it was found at par with N_1 -75% N through vermicompost + 25% RDN through inorganic fertilizer (186.42 kg ha^{-1}), and the lowest available nitrogen (181.56 kg ha^{-1}) was observed under N_4 (100% RDN through inorganic fertilizer).The superior performance of vermicompost-based treatments (particularly N_3) can be attributed to enhanced microbial activity, better mineralization, and sustained release of nitrogen, resulting in improved N availability in the soil post-harvest. These results were in agreement with the findings of Thakur *et al*. (2015).

Effect of Spacing: Plant spacing exerted a significant influence on the availability of nitrogen in the soil. The highest available nitrogen content (188.42 kg ha^{-1}) was recorded under S_3 (30 × 15 cm), which was statistically at par with S_1 (20 × 20 cm). The lowest available nitrogen (183.99 kg ha^{-1}) was observed under S_2. Under wider spacing, nitrogen uptake per plant was higher due to reduced inter-plant competition. Population (S_3). These results were in agreement with the findings of Verma *et al*. (2024).

Interaction Effect: The interaction between nitrogen sources and spacing on available nitrogen was found to be non-significant in soil after harvest of crop.

3.3 Available Phosphorus (kg ha^{-1})

Effect of Nitrogen Sources: Nitrogen source treatments exerted a significant influence on the availability of phosphorus in soil after harvest. The highest available phosphorus content (24.91 kg ha^{-1}) was recorded under N_3 (100% nitrogen through vermicompost), which was significantly superior to all other treatments. The next best treatment was N_1 (75% nitrogen through vermicompost + 25% recommended dose of nitrogen through inorganic fertilizer), while the lowest available phosphorus content was observed under N_4 (100% RDN through inorganic fertilizer). The increased phosphorus availability under vermicompost-based treatments may be attributed to the production of organic acids during organic matter decomposition. These acids help solubilize insoluble phosphorus fractions and reduce phosphorus fixation in soil, thereby enhancing its availability to plants. These results were in agreement with the findings of Thakur *et al*. (2015).

Effect of Spacing: Spacing also had a significant impact on available phosphorus. The highest P_2O_5 content was observed in S_1 20 x 20 cm (23.92 kg ha^{-1}), which was at par with S_3- 30x 15 cm (23.64 kg ha^{-1}) but significantly higher than S_2 30x 10 cm (23.22 kg ha^{-1}). These results were in agreement with the findings of Verma *et al*. (2024)

Interaction Effect: The interaction between nitrogen source and plant spacing was found to be non-significant for available phosphorus in soil after harvest of crop.

3.4 Available Potassium (kg ha^{-1})

Effect of Nitrogen Sources: Available potassium in soil after harvest was significantly influenced by different nitrogen sources. The highest available potassium content (375.76 kg ha^{-1}) was recorded under N_3 (100% N through vermicompost), which was significantly superior to all other treatments. This was followed by N_1 (75% N through vermicompost + 25% recommended dose of nitrogen through inorganic fertilizer) with 369.51 kg ha^{-1}. The lowest available potassium content (354.08 kg ha^{-1}) was observed under N_4 (100% RDN through inorganic fertilizer). The higher potassium status under vermicompost-based treatments may be attributed to the direct addition of potassium through organic manures and improved potassium retention in soil. Organic acids released during decomposition reduce potassium fixation by clay minerals, thereby enhancing potassium availability in the soil. These results were in agreement with the findings of Thakur *et al*. (2015).

Effect of Spacing: Spacing also significantly influenced available potassium. The maximum K_2O was recorded under S_2 (368.23 kg ha^{-1}), which was significantly higher than S_3 (362.95 kg ha^{-1}) but at par with S_1 (365.63 kg ha^{-1}). These results were in agreement with the findings of Verma et al. (2024).

Interaction Effect: The interaction between nitrogen sources and spacing on available potassium content was found to be non-significant.

Soil Biological Properties: The data on soil microbial count including Actinomycetes, bacteria, and fungi as influenced by different nitrogen sources and plant geometries are presented in Table 2. The general mean values for Actinomycetes, bacteria, and fungi were 3.57 × 10^4 cfu g^{-1}, 26.65 × 10^6 cfu g^{-1} and 4.04 × 10^5 cfu g^{-1}, respectively. These values showed a notable enhancement over the initial microbial counts actinomycetes 3.41 × 10^4 cfu g^{-1}, Bacteria 26.45 × 10^6 cfu g^{-1} and Fungi 3.85 × 10^5 cfu g^{-1}.

Table 2. Soil biological properties of Kalmegh as influenced by nitrogen sources and plant geometry

Treatments	Soil microbial count		
	Actinomyces count (cfu 10^4 g^{-1})	**Bacteria count (cfu 10^6 g^{-1})**	**Fungi count (cfu 10^5 g^{-1})**
Factor A: Sources of N applications			
N_1: 75% N through vermicompost + 25% RDN through inorganic fertilizer	3.67	27.39	4.12
N_2: 50% N through vermicompost + 50% RDN through inorganic fertilizer	3.43	26.6	3.98
N_3: 100% N through vermicompost	3.92	28.49	4.39
N_4: 100 % RDN through inorganic fertilizer	3.26	24.13	3.69
SE (m) ±	**0.05**	**0.15**	**0.05**
CD at 5 %	**0.14**	**0.44**	**0.14**
Factor B: Spacing			
S_1: 20x20 cm	3.57	26.40	4.04
S_2: 30x10 cm	3.57	27.63	4.08
S_3: 30x15 cm	3.57	25.93	4.01
SE (m) ±	**0.04**	**0.13**	**0.04**
CD at 5 %	**NS**	**0.38**	**NS**
Int. (N X S)			
SE (m) ±	**0.08**	**0.26**	**0.08**
CD at 5 %	**NS**	**NS**	**NS**
CV %	**4.07**	**1.69**	**3.51**
GM	**3.57**	**26.65**	**4.04**
Initial	**3.41 X 10^4**	**26.45 X 10^6**	**3.85 X 10^5**

Effect of Nitrogen Sources: Nitrogen sources significantly influenced soil microbial populations, including actinomycetes, bacteria, and fungi. The highest microbial counts were recorded with the application of 100% recommended dose of nitrogen through vermicompost (N_3), followed by N_1 (75% RDN through vermicompost + 25% RDN through inorganic fertilizer). In contrast, the lowest populations of actinomycetes, bacteria, and fungi were observed under 100% RDN through inorganic fertilizer (N_4). Among all nitrogen sources, the use of vermicompost as the sole nitrogen source markedly enhanced soil microbial activity. This improvement can be attributed to the increased supply of organic carbon and readily available substrates provided by vermicompost, which stimulate microbial growth and activity, thereby improving overall soil biological health.

Effect of Plant Geometry: Among the three plant spacings tested, bacterial population was significantly influenced, whereas actinomycetes and fungal populations were not significantly affected. The highest bacterial count (27.63 × 10^6 cfu g^{-1}) was recorded in 30 × 10 cm spacing (S_2).

Interaction Effect: The interaction effect of nitrogen sources and plant geometry on microbial populations (Actinomycetes, bacteria and fungi) was found to be non-significant.

4. Conclusion

The study revealed that soil chemical and biological properties of Kalmegh were significantly influenced by nitrogen sources and plant geometry. Application of 100% N through vermicompost (N_3) resulted in the highest post-harvest availability of N, P and K and improved soil fertility due to better mineralization and nutrient release. Among spacings, 30 × 15 cm improved available N, 20 × 20 cm enhanced available P and 30 × 10 cm increased available K. Soil microbial populations were significantly higher under vermicompost application, indicating improved soil biological health. Plant geometry influenced only bacterial population, while interaction effects were non-significant for both soil nutrients and microbial parameters.

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 the writing or editing of this manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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