



RESEARCH ARTICLE

Biocontrol-mediated alleviation of root-knot nematode-induced stress in groundnut (*Arachis hypogaea* L.): Effects on plant growth and yield

Vasanth Ravi Shankar¹, Swatilekha Mohanta^{2*}, Jayanta Kumar Mahalik¹, Chinmayee Patra³,
Md Mijan Hossain⁴ & Aishwarya Mangaraj⁵

¹Department of Nematology, College of Agriculture, Odisha University of Agriculture and Technology, Bhubaneswar 751 003, Odisha, India

²Department of Nematology, College of Agriculture, Odisha University of Agriculture and Technology, Chiplima 768 025, Odisha, India

³Department of Agricultural Statistics, College of Agriculture, Odisha University of Agriculture and Technology, Chiplima 768 025, Odisha, India

⁴Department of Plant Pathology, College of Agriculture, Odisha University of Agriculture and Technology, Chiplima 768 025, Odisha, India

⁵Department of Agronomy, College of Agriculture, Odisha University of Agriculture and Technology, Chiplima 768 025, Odisha, India

*Correspondence email - swatilekha.nema@ouat.ac.in

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Abstract

Management of root-knot nematode remains a major challenge in organic farming, where synthetic nematicides are avoided. A pot culture experiment was conducted at the College of Agriculture, Odisha University of Agriculture and Technology, Chiplima, during 2023–24 to evaluate the efficacy of different biocontrol agents and neem oilcake against *Meloidogyne incognita* in groundnut cv. Kalinga Groundnut-101 under organic production. Six treatments were evaluated in a completely randomised design with 5 replications. Biocontrol treatments significantly improved plant growth, yield and reduced nematode infestation compared with the inoculated check. T₃ (*Rhizobium* spp. + *Paecilomyces lilacinus*) recorded the highest numerical values for plant growth, chlorophyll content and biomass, whereas T₁ (*Rhizobium* spp. + *P. lilacinus* + *Trichoderma harzianum*) produced the highest yield, root nitrogen and crude protein content. Among the biological treatments, T₂ (*Rhizobium* spp. + *T. harzianum*) reduced root galls by 30.00 %, while T₃ reduced the soil nematode population by 14.96 % over the inoculated check. Overall, the integrated application of *Rhizobium* spp. with biocontrol agents showed promising potential as an eco-friendly alternative for improving groundnut growth and suppressing root-knot nematodes under pot conditions, although field validation is required before large-scale recommendation.

Keywords: biocontrol agents; groundnut; integrated pest management; organic farming; root-knot nematode

Introduction

Groundnut (*Arachis hypogaea* L.), commonly known as peanut, is one of the most important oilseed and food legume crops cultivated in tropical and subtropical regions. Its kernels are highly nutritious and rich in protein, edible oil, calcium, potassium, phosphorus, magnesium and vitamin E (1). Groundnut oil is widely used for culinary purposes and in the manufacture of soap, cosmetics and other industrial products, while the oilcake serves as a valuable source of livestock feed and organic manure. Being a leguminous crop, groundnut also contributes to soil fertility through biological nitrogen fixation in association with *Rhizobium* spp. Thus, the crop has considerable nutritional, agricultural and economic importance, particularly for small and marginal farmers.

India is one of the major groundnut-producing countries in the world. Groundnut is also an important oilseed crop in Odisha, where it is cultivated during both the kharif and rabi seasons under diverse agro-climatic conditions. The productivity of groundnut in Odisha was reported to be approximately 2074 kg/ha during

2023–24, indicating its significant contribution to the state's oilseed production and farm economy. Despite its economic importance, groundnut productivity is constrained by several biotic and abiotic factors, including limited availability of improved varieties, poor soil fertility, inadequate crop management practices and infestation by insect pests, pathogens and plant-parasitic nematodes (2).

Among the biotic constraints, plant-parasitic nematodes are considered important but often overlooked pests of groundnut because of their damage occurs mostly below ground and above-ground symptoms can be confused with nutrient deficiency or moisture stress. Several nematodes, including *Meloidogyne* spp., *Pratylenchus brachyurus*, *Belonolaimus longicaudatus*, *Crictonemella ornata* and *Ditylenchus africanus*, are associated with groundnut cultivation globally or in specific geographical regions (3, 4). These nematode species can damage groundnut roots, pegs, pods and hulls, thereby interfering with normal plant growth and ultimately reducing pod yield and quality. In India, *Meloidogyne arenaria* alone has been estimated to cause about 4.5 % yield loss in groundnut, corresponding to an economic loss of approximately

₹396 million based on the crop-loss assessment for 2014–15. Overall, plant-parasitic nematodes were estimated to cause about 21.3 % crop losses in India, with annual monetary losses exceeding ₹102 billion across major crops.

Root-knot nematodes (*Meloidogyne* spp.) are particularly important because of their ability to establish specialised feeding sites in host roots and continuously withdraw nutrients through their stylet (5, 6). Infection results in characteristic root galling and disrupts the normal absorption and translocation of water and nutrients, leading to reduced plant growth, stunting, chlorosis, premature wilting and poor yield (7–9). In groundnut, nematode infection may also affect pegs and developing pods, producing small brown lesions that progressively enlarge and darken with increasing severity of infection. Moreover, root-knot nematode infestation may interfere with the formation and functioning of *Rhizobium* nodules, causing infected nodules to turn brown to black and thereby adversely affecting biological nitrogen fixation.

The management of plant-parasitic nematodes in groundnut remains challenging because their subterranean habit makes early detection and timely control difficult. Although chemical nematicides can effectively suppress nematode populations, their indiscriminate or repeated use raises concerns regarding environmental contamination, pesticide residues, adverse effects on non-target and beneficial soil organisms and sustainability (10). These limitations emphasise the need to develop environmentally safe, economically viable and sustainable alternatives for nematode management. Biological control agents, particularly antagonistic fungi and bacteria, together with organic soil amendments, offer considerable potential for suppressing nematode populations while simultaneously improving soil biological activity and plant growth. Although the individual efficacy of *Paecilomyces lilacinus*, *Trichoderma harzianum*, *Rhizobium* spp. and neem cake against root-knot nematodes has been reported previously, studies comparing these biological components under a common experimental framework in groundnut are limited. Furthermore, comprehensive evaluations integrating plant growth, yield, nitrogen content and nematode suppression with multivariate statistical analyses are scarce. Therefore, the present study was undertaken to evaluate the comparative efficacy of selected fungal and bacterial biocontrol agents and an organic soil amendment, applied individually and in combination as sustainable alternatives to chemical nematicides for the management of root-knot nematode in groundnut.

Materials and Methods

The pot culture experiment was conducted at the College of Agriculture, Odisha University of Agriculture and Technology, Chiplima, Sambalpur, Odisha, India during October 2023 to February 2024, to evaluate the efficacy of different biocontrol agents and organic amendment against root-knot nematode infection in the groundnut cultivar Kalinga Groundnut-101. The experiment consisted of 6 treatments, each replicated five times and was laid out in a completely randomised design (CRD). The treatments were applied to groundnut plants grown in 8-inch diameter earthen pots.

Collection, isolation and identification of nematode

During a routine survey for plant-parasitic nematodes in various crops at the College of Agriculture, Odisha University of Agriculture and Technology, Chiplima, Sambalpur, patches of groundnut plants exhibiting yellowing and stunted growth were observed in the fields under the Odisha Mineral Bearing Areas Development Corporation (OMBADC) project for Centre of Excellence in Groundnut. Uprooted plants showed small to medium-sized, bead-like galls on the roots. Egg masses were collected from infected roots and incubated in water using a modified Baermann funnel technique to obtain second-stage juveniles (J2), which were observed under a microscope. Perineal patterns (Fig. 1) were prepared from adult females dissected from the roots and stained using a sodium hypochlorite–acid fuchsin method. Based on the morphology of J2 and characteristic perineal patterns, the nematode was identified as *Meloidogyne incognita* (11–13).

The experimental stock culture of *M. incognita* used in this study was established from a single egg mass progeny, maintained and multiplied on a susceptible brinjal variety, Pusa Purple Long. Surface-sterilised brinjal seeds were sown in 8-inch diameter earthen pots filled with sterilised soil, which had been autoclaved at 15 lb psi for 20 min. One week after germination, a single healthy seedling was retained per pot. A single egg mass collected from infected groundnut plants of the OMBADC project field was inoculated near the root zone of the brinjal seedling. After 4–5 weeks, heavily infected roots and surrounding soil served as a source for nematode multiplication and subsequent isolation for experimental use.

Isolation of nematodes from the culture pot

As required, plants were uprooted from the culture pots and the roots were thoroughly washed to remove adhering soil. Egg masses were carefully dissected from the roots and placed on tissue paper



Fig. 1. Perineal pattern of adult *Meloidogyne incognita* female.

supported by an aluminium wire gauge placed on Petri dishes containing water to facilitate hatching. The freshly hatched second-stage juveniles (J2) were surface sterilised using 0.5 % streptomycin sulphate solution for 30 min and subsequently used for experimental purposes. In addition, J2 were also extracted from the culture pot soil using the modified Cobb's sieving and decanting technique. The suspension was allowed to settle and the supernatant was gently decanted without disturbing the nematodes settled at the bottom. The collected juveniles were then used for further experimental studies.

Preparation of pot soil, treatment application and nematode inoculation

A potting mixture of sandy loam soil and well-decomposed farmyard manure was prepared in a 3 : 1 ratio, steam sterilised in an autoclave at 15 lb psi for 20 min, to eliminate indigenous soil microorganisms, including plant-parasitic nematodes, thereby ensuring a nematode-free growth medium before inoculation and air-dried before use. Earthen pots (8" diameter) were surface sterilised with 1.0 % formaldehyde solution, filled with the sterilised soil mixture at 3 kg pot⁻¹ and arranged according to the experimental layout. The experiment comprised 6 treatments with 5 replications, laid out in a CRD. Treatments (except *Rhizobium* spp.) were applied to the soil 15 days before sowing. Healthy groundnut seeds were treated with *Rhizobium* at 5 g kg⁻¹ seed and sown in the pots, followed by light mulching and regular watering. Inoculation with *M. incognita* was carried out by introducing second-stage juveniles (J2) into the root zone at a rate of 1000 J2 kg⁻¹ of soil (equivalent to 1 J2 g⁻¹ soil), 45 days after seed germination. This inoculum density corresponds to the reported economic threshold level (ETL) for *M. incognita* and was selected to establish uniform nematode infestation under pot conditions, thereby enabling reliable assessment of treatment efficacy.

The microorganisms used in the study were *Rhizobium* spp. (WP, 1 × 10⁷ CFU g⁻¹) and the biocontrol agents *T. harzianum* (WP, 2 × 10⁸ CFU g⁻¹) and *P. lilacinus* (WP, 2 × 10⁸ CFU g⁻¹). Fresh formulations within their six-month shelf life were used throughout the experiment.

The treatment details are as follows: T₁: *Rhizobium* spp. at 5 g kg⁻¹ (Seed treatment) + *P. lilacinus* at 2.5 kg ha⁻¹ (Basal application) + *T. harzianum* at 2.5 kg ha⁻¹ (Basal application), T₂: *Rhizobium* spp. at 5 g kg⁻¹ (Seed treatment) + *T. harzianum* g⁻¹ at 5 kg ha⁻¹ (Basal application), T₃: *Rhizobium* spp. at 5 g kg⁻¹ (Seed treatment) + *P. lilacinus* at 5 kg ha⁻¹ (Basal application), T₄: *Rhizobium* spp. at 5 g kg⁻¹ (Seed treatment) + Neem oilcake at 1.0 ton ha⁻¹ (Basal application), T₅: Carbofuran 3G at 33 kg ha⁻¹ (Nematicidal check for comparison) and T₆: Inoculated Check. Carbofuran 3G was included only as a standard chemical nematicide check to provide a benchmark for comparing the efficacy of the biological treatments and was not considered a component of the organic management strategy.

Observation on plant growth, yield and nematode parameters

Observations on plant growth, yield and nematode parameters were recorded, including plant height, number of branches and leaves, leaf area, chlorophyll content (a, b and total), fresh and dry shoot weight, pods per plant, pegs per branch, root length, root nitrogen and crude protein content, yield, number of galls per plant

and soil nematode population.

Plant height was measured from the base to the tip of the main shoot, while branches and leaves were counted manually at 45 days after nematode inoculation. Leaf area was determined using a SYSTRONICS Leaf Area Meter-211. Chlorophyll content was estimated by extracting 2 g of fresh leaf tissue in 80 % acetone, making up the volume and recording absorbance at 663 nm and 645 nm using a spectrophotometer.

Chlorophyll A (mg/g of tissue) =

$$\frac{12.7 \times D_{663} - 2.69 \times D_{645} \times V}{1000 \times W} \quad \text{Eq. (1)}$$

Chlorophyll B (mg/g of tissue) =

$$\frac{22.9 \times D_{645} - 4.68 \times D_{663} \times V}{1000 \times W} \quad \text{Eq. (2)}$$

Total Chlorophyll (mg/g of tissue) =

$$\frac{22.2 \times D_{645} - 8.02 \times D_{663} \times V}{1000 \times W} \quad \text{Eq. (3)}$$

Groundnut plants were harvested at 120 days after sowing to record fresh shoot weight, which was measured immediately after cutting at ground level. The shoots were then sun-dried for one week followed by oven drying at 60 °C for 48 hr to determine dry shoot weight. At harvest, observations on number of pods per plant, number of pegs per branch and root length were recorded. Roots were similarly dried and their dry weight was measured.

Root nitrogen content was estimated by the Kjeldahl method and crude protein percentage was calculated by multiplying nitrogen content by 6.25. The number of galls per plant was counted after thoroughly washing the roots. Soil nematode population was assessed from 200 g soil samples using Cobb's sieving and modified Baermann funnel techniques and second-stage juveniles were counted under a stereoscopic microscope. Final yield was determined by weighing pods after harvest.

Statistical analysis

Data were analysed using analysis of variance (ANOVA) appropriate for a CRD. Prior to analysis, the assumptions of ANOVA, including normality of residuals and homogeneity of variances, were evaluated using the Shapiro-Wilk and Levene's tests, respectively. The data satisfied these assumptions; therefore, no transformation was required. Treatment means were compared using the critical difference (CD) test at the 5 % level of significance ($p \leq 0.05$). Correlation analysis was performed to determine relationships among plant growth, chlorophyll, biomass, nutrient, yield and nematode parameters. Correlation heat maps with dendrograms and principal component analysis (PCA) were generated to visualise variable relationships and multivariate patterns. All statistical analyses were performed using R software.

Results and Discussion

Correlation between plant growth and yield of root-knot nematode-infected groundnut cultivar Kalinga Groundnut-101

The correlation analysis (Table 1) and heat map with dendrogram revealed strong associations among plant growth, yield and nematode parameters in groundnut. All correlations discussed below were significant at $p \leq 0.05$. Plant height was positively correlated with fresh shoot weight ($r = 0.853$) and dry shoot weight ($r = 0.923$), while the number of leaves showed positive correlations with yield ($r = 0.857$) and dry shoot weight ($r = 0.890$). Chlorophyll a and total chlorophyll were positively correlated with leaf area ($r = 0.936$ and $r = 0.928$ respectively) and were also positively associated with biomass, indicating that higher chlorophyll content was associated with greater plant growth and biomass accumulation (11, 12). Yield was positively correlated with fresh shoot weight ($r = 0.877$), dry shoot weight ($r = 0.849$), number of leaves ($r = 0.857$) and total chlorophyll ($r = 0.815$), indicating that these parameters were associated with higher productivity. Root dry weight was positively correlated with the number of pods per plant ($r = 0.890$) and root nitrogen content ($r = 0.853$), suggesting a close relationship between root development and plant nutritional status (13). In contrast, nematode parameters (number of galls per plant and soil nematode population) showed negative associations with most growth and yield traits, indicating that *M. incognita* infestation was associated with reduced plant growth and productivity, which is consistent with impaired root function and restricted water and nutrient uptake reported in previous studies (14). Overall, these findings indicate that lower nematode infestation was associated with improved plant growth, chlorophyll content and productivity.

The heat map (Fig. 2) further supports these findings by showing clustering of positively correlated traits such as plant height, biomass, chlorophyll content and yield into one major group. In contrast, nematode-related parameters (number of galls per plant and soil nematode population) formed a separate cluster and exhibited negative correlations with most growth and yield traits, indicating their detrimental effect on plant performance. The dendrogram clearly separated parameters into two major clusters: (i) plant growth and yield traits, which were positively interrelated and (ii) nematode parameters, which were negatively associated with plant performance (14, 15). This clustering pattern indicates a negative association between nematode infestation and plant growth including yield parameters.

Treatment effect on plant growth, yield and nematode parameters of groundnut variety Kalinga Groundnut-101

Root-knot nematode (*Meloidogyne* spp.) infection causes significant changes in plant growth and metabolism. The nematodes disrupt normal plant metabolism and induce the formation of galls on the roots. These changes adversely affect nutrient uptake, chlorophyll content, defence responses and secondary metabolism, ultimately reducing plant growth and productivity (16–18).

The results (Fig. 3, Table 2) revealed significant treatment effects ($p \leq 0.05$) on growth, yield and nematode parameters of groundnut cv. Kalinga Groundnut-101. Compared with the inoculated check, all biocontrol-based treatments improved plant growth and reduced nematode infestation to varying degrees, indicating their potential for sustainable nematode management (19–22).

Table 1. Correlation between different plant growth, yield and nematode parameters of groundnut variety Kalinga Groundnut-101

	Plant height (cm)	No. of branches	No. of leaves	Leaf area (cm ²)	Chl. A	Chl. B	Total Chl.	No. of pods/plant	No. of pegs/branch	Fresh weight of shoot (g)	Dry weight of shoot (g)	Root length (cm)	Dry weight of root (g)	Nitrogen % of root	Crude protein % of root	Yield (g)
Plant height (cm)	1															
No. of branches	0.327	1														
No. of leaves	0.758	0.794	1													
Leaf area (cm ²)	0.814*	0.652	0.752	1												
Chlorophyll A	0.767	0.765	0.809	0.936*	1											
Chlorophyll B	0.261	0.443	0.269	0.653	0.632	1										
Total Chlorophyll	0.679	0.732	0.713	0.928*	0.972*	0.795	1									
No. of pods/plant	0.637	-0.129	0.289	0.364	0.405	0.394	0.435	1								
No. of pegs/branch	0.650	0.303	0.725	0.272	0.436	-0.160	0.293	0.555	1							
Fresh wt. of shoot (g)	0.853*	0.621	0.812	0.956*	0.926*	0.685	0.930*	0.564	0.445	1						
Dry weight of shoot (g)	0.923*	0.630	0.890*	0.932*	0.924*	0.510	0.876*	0.545	0.594	0.974*	1					
Root length (cm)	0.784	0.271	0.644	0.696	0.478	0.091	0.401	0.193	0.318	0.659	0.715	1				
Dry weight of root (g)	0.423	-0.035	0.131	0.404	0.448	0.714	0.565	0.890*	0.217	0.563	0.453	-0.020	1			
Nitrogen % of root	0.290	0.367	0.332	0.508	0.567	0.906*	0.716	0.634	0.143	0.658	0.513	-0.014	0.853*	1		
Crude protein % of root	0.290	0.367	0.332	0.508	0.567	0.906*	0.716	0.634	0.143	0.658	0.513	-0.014	0.853*	1	1	
Yield (g)	0.631	0.725	0.857*	0.741	0.794	0.646	0.815*	0.509	0.563	0.877*	0.849*	0.448	0.508	0.755	0.755	1

The values having * marks are highly significantly positively correlated.

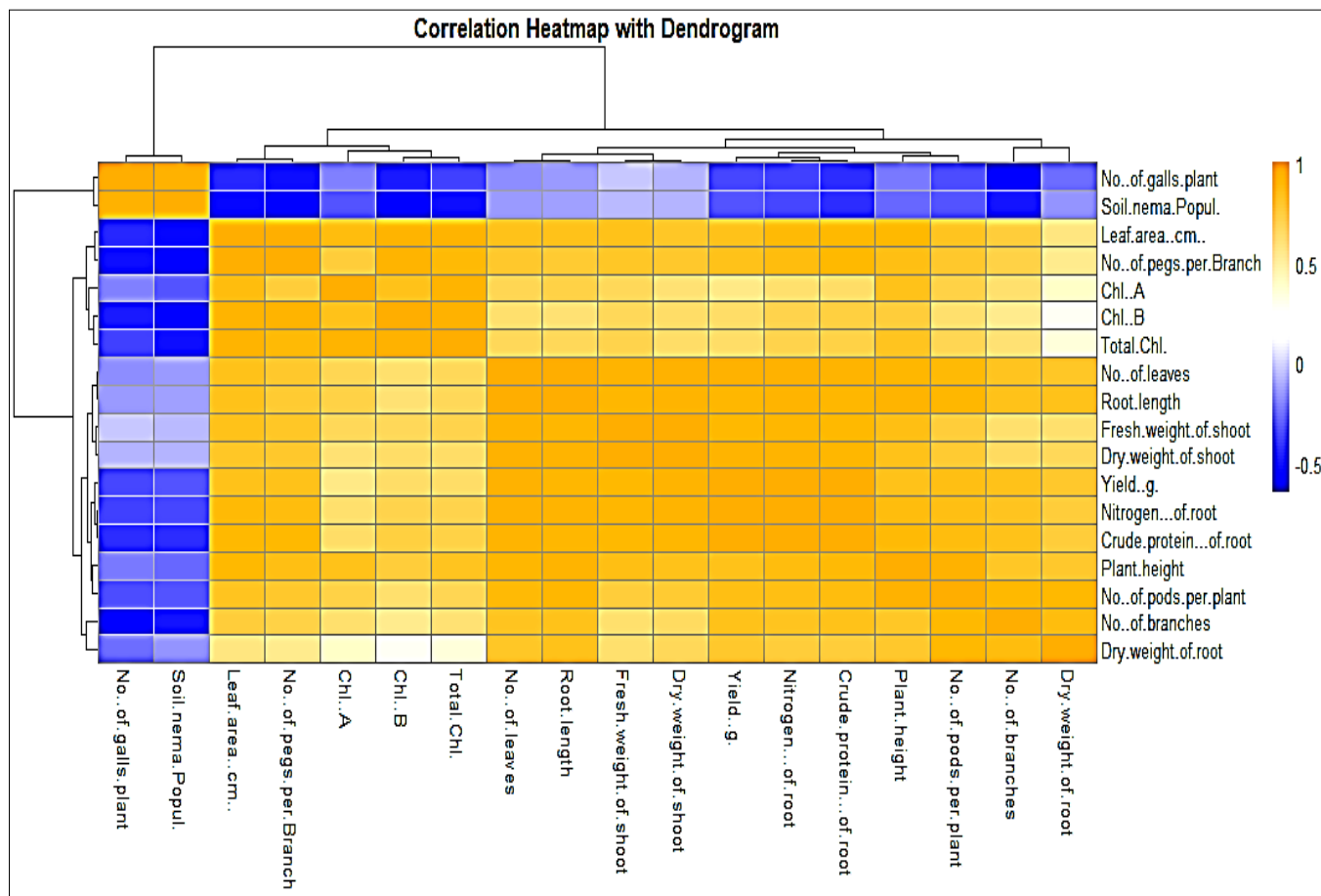


Fig. 2. Correlation heatmap with dendrogram of different plant growth, yield and nematode parameters of groundnut variety Kalinga Groundnut-101.

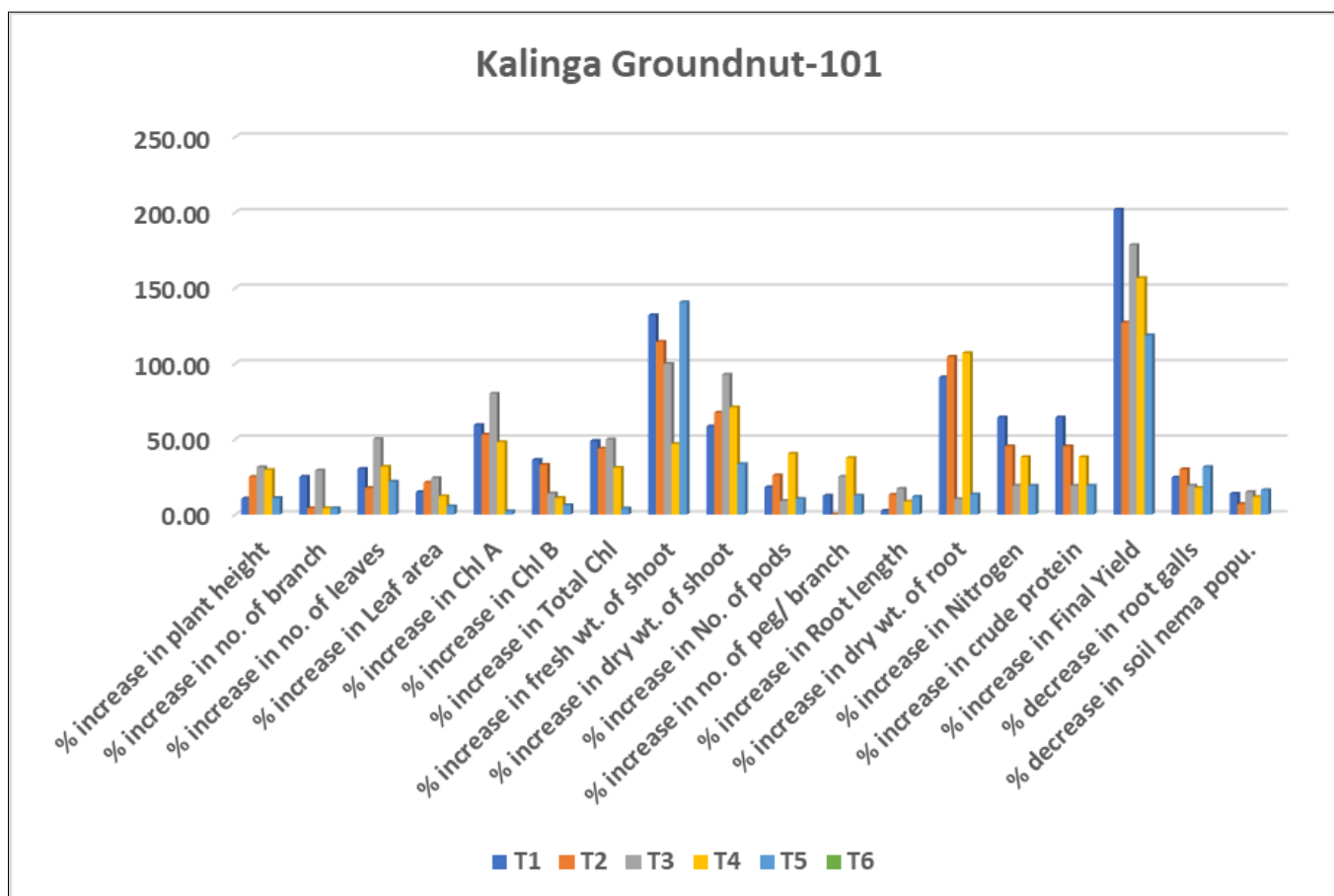


Fig. 3. Bar diagram showing percentage increase or decrease in treatment effects on growth, yield and nematode parameters of groundnut variety Kalinga Groundnut-101 compared to control.

Table 2. Treatment effect on plant growth, yield and nematode parameters of groundnut variety Kalinga Groundnut-101

Treatment	Plant height (cm)	No. of branches	No. of leaves	Leaf area (cm ²)	Chl. A	Chl. B	Total Chl.	Fresh weight of shoot (g)	Dry weight of shoot (g)	No. of pods per plant	No. of pegs per Branch	Root length (cm)	Dry weight of root (g)	Nitrogen % of root	Crude protein % of root	No. of galls/ plant	Soil nema. Popul.	Yield (g)
T ₁	21.27	10.00	61.67	28.07	2.26	1.64*	3.90	41.43	11.52	30.33	3.00	24.40	4.42	0.23*	1.44*	32.67	230.33	46.98*
T ₂	24.03	8.33	55.67	29.57	2.17	1.60	3.78	44.04	12.19	32.33	2.67	26.93	4.73	0.20	1.27	30.33	248.67	35.34
T ₃	25.27*	10.33*	71.00*	30.33*	2.56*	1.37	3.93*	46.10*	14.02*	28.00	3.33	27.87*	2.55	0.17	1.04	35.00	227.33	43.33
T ₄	24.93	8.33	62.33	27.40	2.10	1.34	3.44	40.78	12.44	36.00*	3.67*	25.83	4.79*	0.19	1.21	35.67	236.00	39.92
T ₅	21.33	8.33	57.67	25.77	1.45	1.28	2.73	32.56	9.71	28.33	3.00	26.60	2.62	0.17	1.04	29.67	224.00	34.02
T ₆	19.23	8.00	47.33	24.42	1.42	1.21	2.63	23.23	7.28	25.67	2.67	23.80	2.31	0.14	0.88	43.33*	267.33*	15.56
Mean	22.68	8.89	59.28	27.59	1.99	1.41	3.40	38.02	11.19	30.11	3.06	25.91	3.57	0.18	1.15	34.44	238.94	35.86
SEm	2.36	0.72	4.79	2.22	0.12	0.08	0.14	4.94	1.82	4.05	0.36	2.22	0.47	0.02	0.09	4.13	5.64	3.58
CD	7.27	2.22	14.75	6.83	0.36	0.22	0.40	15.22	5.60	12.48	1.11	6.83	1.44	0.05	0.29	12.72	17.39	11.04
CV	18.02	14.03	13.99	13.92	23.05	12.57	17.28	22.50	28.14	23.30	20.41	14.82	22.73	14.32	14.32	20.76	4.09	17.31

* Mark indicates 5 % level of significance.

SEm: standard error of mean; CD: critical difference; CV: coefficient of variation.

Among the treatments, T₃ (*Rhizobium* spp. + *P. lilacinus*) recorded higher plant growth parameters, including plant height (25.27 cm), number of branches (10.33), leaves (71.00) and leaf area (30.33 cm²) than the inoculated check, likely due to improved nutrient uptake and root health (23). *Paecilomyces lilacinus* suppresses nematodes by parasitising eggs, thereby reducing egg hatch and gall formation (24–26). Reduced nematode infestation was associated with improved biomass accumulation and plant growth (27), while its combined use with *Rhizobium* spp. and other biocontrol agents may further enhance its effectiveness (28, 29).

Nematode infection is known to reduce chlorophyll content through impaired water and nutrient uptake (30–33). In the present study, T₃ recorded the highest chlorophyll a (2.56), total chlorophyll (3.93), fresh shoot weight (46.10 g) and dry shoot weight (14.02 g), all of which were significantly higher than those of the inoculated check ($p \leq 0.05$). T₁ (*Rhizobium* spp. + *P. lilacinus* + *T. harzianum*) recorded the highest chlorophyll b content (1.64), which was also significantly higher than the inoculated check. These improvements in chlorophyll content may have contributed to enhanced photosynthetic efficiency and plant vigour under reduced nematode stress (34).

Root and nutrient-related parameters also varied significantly among the treatments. T₃ recorded the maximum root length (27.87 cm), while T₄ (*Rhizobium* spp. + neem oilcake) recorded the highest root dry weight (4.79 g). T₁ recorded the highest root nitrogen (0.23 %) and crude protein (1.44 %) contents, suggesting that integrated application of *Rhizobium* spp. and biocontrol agents improved plant nutritional status under reduced nematode infestation (35–37).

Among the yield attributes, T₄ recorded the highest number of pods per plant (36.00) and pegs per branch (3.67), while T₁ produced the highest yield (46.98 g). These values were significantly higher than those of the inoculated check ($p \leq 0.05$), indicating the synergistic effects of integrated biological treatments on crop productivity (38).

Nematode parameters exhibited the opposite trend to plant growth and yield attributes. The inoculated check (T₆) recorded the highest number of galls per plant (43.33) and soil nematode population (267.33), indicating severe nematode infestation. Among the biological treatments, T₂ (*Rhizobium* spp. + *T. harzianum*) recorded the lowest number of galls per plant (30.33), representing a 30.00 % reduction over the inoculated check, whereas T₃ (*Rhizobium* spp. + *P. lilacinum*) recorded the lowest soil nematode population (227.33), corresponding to a 14.96 % reduction. Both treatments significantly reduced nematode infestation compared with the inoculated check ($p \leq 0.05$). The nematicidal check (T₅) was the most effective treatment, recording the lowest number of galls per plant (29.67) and soil nematode population (224.00), corresponding to reductions of 31.54 % and 16.21 %, respectively. The reduction in gall formation and soil nematode population observed in the biocontrol treatments may be attributed to the antagonistic activity of *T. harzianum* and *P. lilacinum*. *T. harzianum* suppresses nematodes through mycoparasitism, production of hydrolytic enzymes and induction of plant defence responses, whereas *P. lilacinum* parasitises nematode eggs and females, thereby reducing egg hatch and subsequent population build-up (39).

Scree plot of principal components of Kalinga Groundnut-101

In this plot (Fig. 4), PC1 explains the largest proportion of variance (74.7%), indicating that most of the variability in the data is captured by the first component. The PC2 contributes an additional 12.9%, bringing the cumulative variance explained by the first two components to about 87.6%, which is quite high. The remaining components (PC3–PC6) contribute very little variance (7.8%, 3.7%, 0.9% and 0%), showing a sharp decline after PC1. The clear “elbow” in the plot occurs after the second component, suggesting that only the first two principal components are sufficient to explain most of the variation in the dataset. This implies that the complex relationships among plant growth, chlorophyll content, nutrient status, yield and nematode parameters can effectively be reduced to two major underlying factors. Such patterns are commonly reported in multivariate analyses where the first few components capture most of the variability (40).

Principal component analysis biplot of variable contributions of Kalinga Groundnut-101

The PCA was interpreted based on the loading matrix and its biplot representation. The first two principal components, PC1 (74.7%) and PC2 (12.9%), together explained 87.6% of the total variation, indicating that these components adequately represented the dataset (Fig. 5) (40, 41). Growth and yield parameters were closely clustered, reflecting their strong positive association and their coordinated response to improved root health, nutrient uptake, higher chlorophyll content and improved plant vigour. In contrast, the number of galls and soil nematode population were positioned in the opposite direction, demonstrating their negative association with plant growth and productivity. This separation suggests a negative association between *M. incognita* infestation and plant growth traits. Conversely, biocontrol treatments were associated with improved plant growth, chlorophyll content, nutrient status and yield, together with lower nematode infestation.

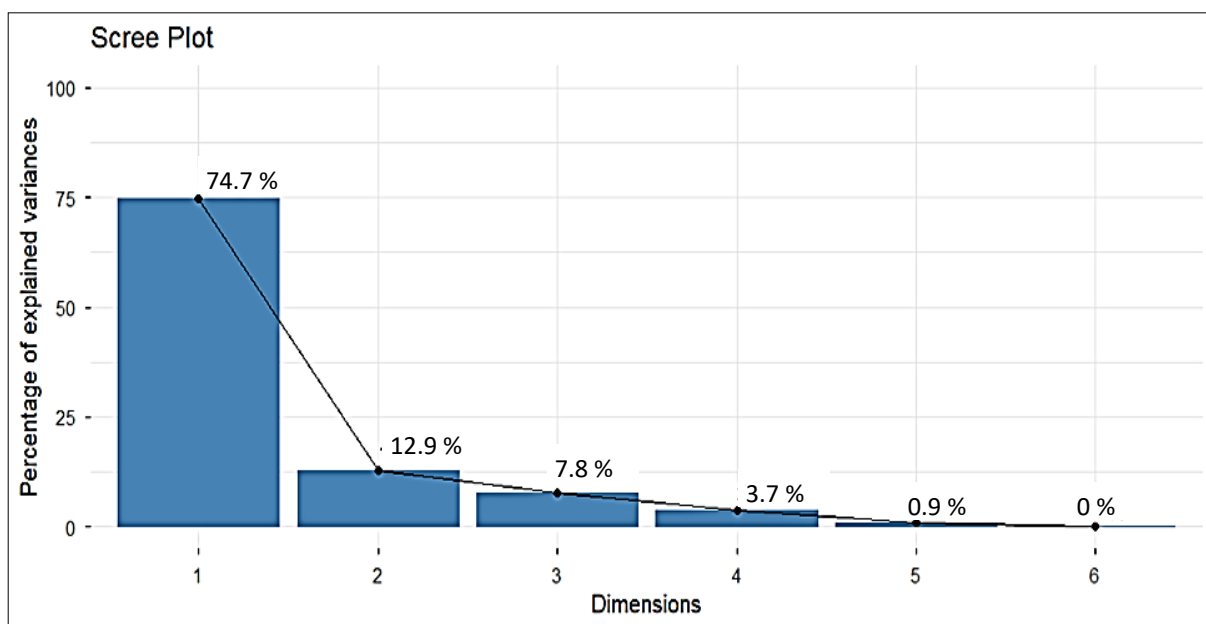


Fig. 4. Scree plot of principal components of Kalinga Groundnut-101.

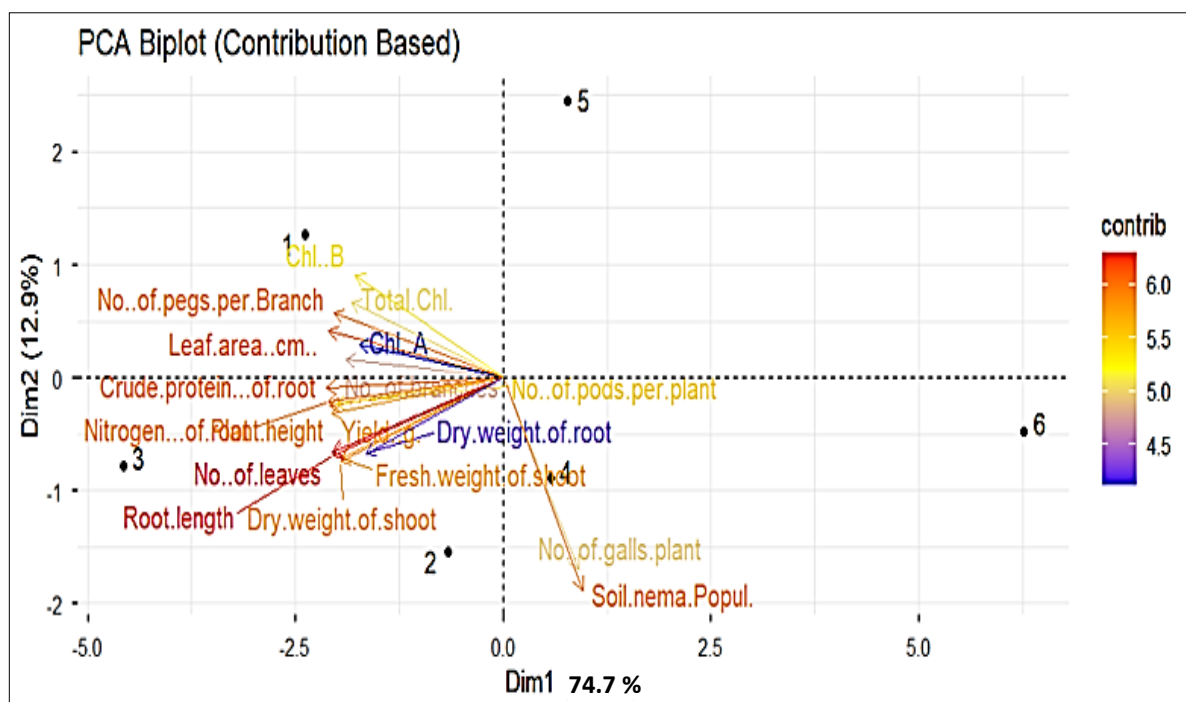


Fig. 5. Principal component analysis (PCA) biplot of variable contributions of Kalinga Groundnut 101.

Conclusion

The present study demonstrated that *Meloidogyne incognita* infestation was associated with reduced growth and yield of groundnut cv. Kalinga Groundnut-101 under pot conditions. The integrated use of *Rhizobium* spp. with fungal biocontrol agents effectively suppressed root-knot nematode infestation while improving plant growth, biomass, yield and nutritional quality compared with the inoculated control. These findings indicate that integrating beneficial microorganisms can enhance plant performance and reduce nematode damage, offering a sustainable and environmentally friendly alternative to sole reliance on chemical nematicides. However, as the study was conducted under controlled pot conditions, further multi-location field evaluations are required to validate the consistency, efficacy and economic feasibility of this integrated biocontrol approach before recommending its large-scale adoption in groundnut cultivation.

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Authors' contributions

VRS, SM and MMH conducted the experiment. SM and AM prepared the manuscript. CP contributed to data analysis using statistical methods and JKM contributed to manuscript correction and editing. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors do not have any conflicts of interest to declare.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used ChatGPT to improve the clarity and language of the text. The authors carefully reviewed and edited the content after using this tool and take full responsibility for the accuracy and integrity of the final manuscript.

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