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RESEARCH ARTICLE

Sustainable insect pest management in groundnut using organic amendments and bio-fertilizers: A field-based evaluation

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Abstract

Groundnut cultivation is significantly affected by insect pests such as thrips, leafhoppers, *Spodoptera litura, Helicoverpa armigera* and *Aproaerema modicella*, leading to yield losses. Excessive reliance on chemical insecticides has led to environmental concern such as pesticide residues, biodiversity loss and soil degradation, necessitating a shift towards organic alternatives. This study investigates the efficacy of organic amendments and bio-fertilizers in managing major pests and promoting natural enemy populations in groundnut cultivation. Field trials were conducted in two seasonal environments: *Kharif* 2022 and *Rabi* 2022-2023. Field trials evaluated the impact of various organic amendments (FYM, vermicompost, neem cake, poultry manure) and bio-fertilizers (Phosphobacteria and *Rhizobium*) on pest populations and the abundance of natural enemies in groundnut fields. Results showed that neem cake and vermicompost treatments significantly reduced thrips populations and minimized damage caused by *S. litura*, *H. armigera* and *A. modicella* compared to the control. Additionally, these treatments enhanced the populations of natural enemies such as spiders (3.83/10 plants) and ladybird beetles (9.5/10 plants). Moreover, Phosphobacteria application significantly increased spider populations, potentially due to improved soil health and enhanced prey availability, suggesting its role in promoting natural biocontrol agents. Economic analysis revealed that neem cake and Phosphobacteria treatments increased groundnut yield, achieving benefit-cost ratios of 1:2.47 and 1:2.85, respectively, highlighting their economic viability. These findings highlight the importance of organic amendments and bio-fertilizers in sustainable pest management practices, offering practical solutions for enhancing crop productivity and profitability while minimizing environmental impact.

Keywords: economic benefit, groundnut, insect pest management, neem cake, phosphobacteria, vermicompost

Introduction

Groundnut, or peanut (*Arachis hypogaea* L.), is an important oilseed legume crop of tropical and sub-tropical regions, valued for its high protein and oil content, making it a key crop for food, fodder and industrial applications. India is the second-largest producer of groundnut, with an annual production of approximately 6.73 million tons, despite having the largest area under cultivation (1). China remains the leading producer. Groundnut kernel and oil are widely used in Indian cuisine, while the residual cake serves as valuable manure and animal feed. For these reasons, the crop has attained the status of 'King of Oilseeds' (2). The major groundnut-producing states in India include Gujarat, Andhra Pradesh, Tamil Nadu, Karnataka and Telangana contributing to the largest share in the country's groundnut production. However, India still lags behind, contributing 19% to global groundnut production, whereas China accounts for 34% (3). Groundnut cultivation in India faces multiple challenges, including rising temperatures, erratic rainfall and biotic stresses. Among these, insect pest infestations significantly impact yield and quality. Among these stresses, biotic factors like insect pests and diseases pose major constraints for groundnut production in India (4, 5). Common pests affecting groundnuts include leafhoppers, thrips, aphids, whiteflies and pod borers (5, 6), which inflict damage across different growth stages, affecting both vegetative and reproductive parts (7).

Integrated Pest Management (IPM) strategies incorporate cultural practices like raising taller cereals as border crop in groundnut, sesame (8, 9) along with biological control and judicious insecticide use in groundnut, onion are essential for sustainable pest management (10 - 12). While chemical insecticides have been the primary means of pest control, their overuse has led to critical issues such as insecticide resistance, pest resurgence and environmental contamination, necessitating a shift toward organic and environmentally sustainable alternatives. Organic amendments, such as use of organic manures, use of border crops and bio-fertilizers (Phosphobacteria, *Rhizobium*), offer promising long-term solutions for sustainable pest management in groundnut cultivation. Previous research indicates that border cropping with cereals like sorghum and pearl millet can reduce Peanut Bud Necrosis Disease (PBND) and insect pest incidence, enhancing natural enemy populations (8). Building upon these findings, the current study investigates the role of organic amendments in pest control.

The study showed that border cropping of groundnut with sorghum and pearl millet significantly reduced the incidence of Peanut Bud Necrosis Disease (PBND). This border cropping approach was also effective in reducing infestations of key pests such as thrips, leafhoppers, Cutworm -*Spodoptera litura,* gram pod borer-*Helicoverpa armigera* and groundnut leaf miner- *Aproaerema modicella* in groundnut (8) and other oilseeds crop (9). Additionally, these border crops increased the populations of natural enemies, such as coccinellids and spiders, which act as biocontrol agents by targeting various insect pest life stages and reducing damage within the groundnut ecosystem (8). This study underscores the importance of organic approaches in mitigating pest pressures within groundnut ecosystems. It highlights the need for continued research and adoption of organic practices to ensure sustainable groundnut cultivation in the face of evolving challenges.

According to recent agricultural statistics released by the Ministry of Agriculture & Farmers Welfare, Government of India (https://desagri.gov.in/statistics-type/advance-estimates/), India produced approximately 8.65 million tons of groundnuts during the year 2023 -24. Despite this robust production, insect pests remain a serious concern, with yield losses estimated between 21.31% and 42.30% (7). This highlights the need for continuous research and adaptive management strategies to ensure sustainable groundnut cultivation. In this regard, organic amendments and bio - fertilizers emerge as critical components for long-term sustainable pest management solutions. As a continuation of our earlier work (8), this study evaluates the effectiveness of organic amendments in controlling major insect pests such as *S. litura, A. modicella, H. armigera,* as well as sucking insect pests like thrips and leafhoppers in two seasonal environments (*Kharif* and *Rabi*). Neem and neem-based products were explored for their significant potential as organic amendments, contributing to environmental sustainability, improved health and better nutrition. Neem cakes and neem leaves are the excellent examples, being used as organic manure, biopesticide, fertilizer coating agent, soil conditioner in the pesticide free farming systems (13). Vermicompost also effectively fits into the organic farming by its insecticidal property reported against *Plutella xylostella* in cabbage (14) and *Earias vitella* in Bhendi (15). Our study explores the effects of different organic amendments and the use of bio-fertilizers in curtailing insect pests within the groundnut ecosystem.

Materials and Methods

Field experiments at two environmental conditions

Field experiments were conducted during *Kharif* 2022 (June 2022 to September 2022) and *Rabi*-summer 2022-23 (December 2022 to April 2023) at the Regional Research Station (11.30°N and 79.26°E and 46.7 m above MSL), Vriddhachalam, Cuddalore District, Tamil Nadu, India. Soil type is red laterite / sandy soil. Maximum temperature varies from 30 to 40°C and minimum temperature ranges from 18 to 24°C. The annual mean rainfall is 1200 mm. The medium duration (100-105 days) Groundnut variety VRI 2, which is the most popular among farmers and susceptible check for all the germplasm screening trial was used for this experiment. Groundnut seeds were sown in plots measuring 5 × 4 m^2, with each plot containing 12 rows. Row spacing was maintained at 30 cm and plant spacing at 10 cm. All the recommended agronomic practices, except plant protection measures, were followed as per [source, e.g., ICAR guidelines]. The experiment evaluated the efficacy of eight treatments, which included organic amendments namely, “T1-Farmyard Manure” (FYM) (12.5 t/ha), “T2 - vermicompost” (2.5t/ha), “T3-neem cake” (250kg/ha), “T4-Poultry manure” (5t/ha) and application of bio-fertilizers *viz*., “T5 -Phosphobacteria” (2kg/ha)and “T6-*Rhizobium”* (2kg/ha), “T7-recommended dose of NPK fertilizers” (25:50:75 kg/ha) and “T8 - control”. Each treatment was replicated three times in a randomized block design (RBD) and the treatments were imposed as basal application. In addition, Gypsum at 120 kg/ha was applied during the second -hand weeding at 40 days after sowing (DAS).

Observations on insect pests and natural enemies

Observations on insect pests were recorded at 30 DAS or at the first detected incidence of pest infestation, whichever occurred earlier. For sucking insect pests, observations were recorded on 10 randomly selected plants per plot. The number of aphids was counted within a 2 cm shoot length, thrips were counted on three terminal buds per plant and leafhoppers were counted per leaf on the top, middle and bottom canopy levels. For defoliators, percent damage was calculated based on number of plants damaged out of 100 plants in a plot. The population of sucking insect pests and defoliators damage was recorded on vegetative and flowering stage (20 - 30 DAS), reproductive stage (45 -60 DAS) and at 80-90 DAS (a week or two before harvest). Similarly, natural enemies *viz*., ladybird beetles, spiders and their egg masses/10 plants were also recorded.

Collection of yield data and economic cost

At physiological maturity, identified by the browning of inner shell layer, wet pods were harvested, stripped and sun-dried. Then the weight of dry pod and haulm was recorded using the platform weighing steel scale on the net plot area basis which was converted into kg/ha for statistical interpretations. Economic analysis was conducted based on dry pod and haulm yield, cost of cultivation, gross return and net return.

Statistical analysis

Data were analyzed using the software package OPSTAT version (16). Population data were square root transformed and the percentage infestation data were arcsine transformed. Cost-benefit ratio (C: B) was worked out based on the pod and haulm yield.

Results

Organic amendments and bio-fertilizers on major insect pest population (*Kharif* 2022)

A field trial was conducted during *Kharif* 2022 to study the effects of different organic amendments (treatments T1 to T8) on sucking insect pests (thrips and leaf hoppers) and damage percentages by defoliators (*S. litura, H. armigera* and *A. modicella*). Observations were recorded at three different time points - 30 DAS, 60 DAS and 80 DAS in response to organic manure namely farmyard manure (FYM - 12.5 t/ha; T1), vermicompost (2.5t/ha; T2), neem cake (250 kg/ha; T3), poultry manure (5t/ha; T4) and bio-fertilizers *viz*., Phosphobacteria (2 kg/ha; T5), *Rhizobium* (2 kg/ha; T6), recommended dose of fertilizers (25:50:75 kg/ha; T7) and control (T8) were included. At 30 DAS, T2 significantly reduced the population of all insect pests studied. By 60 DAS, both T2 and T3 treatments were effective in controlling pest populations. However, at 80 DAS, T3 recorded lowest population for both the sucking pests, demonstrating its effectiveness in later crop stages. Defoliator damage caused by *S. litura* was effectively controlled by T5, T6 and T7 treatments. Damage caused by *H. armigera* and *A. modicella* was significantly reduced in plots treated with FYM (T1). Overall, during the *Kharif* 2022 season, soil supplemented with vermicompost during the vegetative stages, while neem cake during the reproductive and later phases of the groundnut growth proved effective in controlling most of the insect pests studied. In the later crop stages, neem cake and vermicompost proved to be the most effective treatments in reducing pest populations, as shown in Table 1.

Organic amendments and bio-fertilizers on natural enemies population (*Kharif* 2022)

Observations were made to study the impact of organic amendments and bio-fertilizers on the population of natural enemies in the groundnut ecosystem during the *Kharif* 2022. The effect of different treatments, such as (T1), vermicompost (T2), neem cake (T3), poultry manure (T4), Phosphobacteria (T5), *Rhizobium* (T6), NPK (T7) and Control (T8), was recorded for their effects on spider and ladybird beetle populations. Table 2 shows the observations made on the mean spider populations and ladybird beetle populations on 10 plants at different growth stages (vegetative, reproductive, maturity) in response to different organic amendments. Treatment T5 resulted in a higher number of spiders (3.83) compared to the other treatments. Control treatment (T8) showed the highest ladybird beetle population and spider population at the maturity stage. A higher number of spiders was observed during the vegetative and reproductive stages, whereas ladybird beetles were present throughout all three stages, with the highest numbers recorded at the maturity stage across all treatments. This implies that the spider population is effective during the early stages while ladybird beetles are more efficient bio-control agents throughout the crop developmental stages. Soil treatment with Phosphobacteria influences and increases the growth of natural enemies in the groundnut ecosystem.

Table 1. Effect of organic amendments and bio-fertilizers on major insect pests in groundnut ecosystem during *Kharif* 2022

Treatments	Sucking pest population (Nos/3 leaves/plant)						Defoliators damage (%)								
	Thrips			Leaf hopper			Cutworm-*Spodoptera litura*			Gram pod borer-*Helicoverpa armigera*			Groundnut leafminer - *Aproaerema modicella*		
	30DAS	60DAS	80DAS	30DAS	60DAS	80DAS	30DAS	60DAS	80DAS	30DAS	60DAS	80DAS	30DAS	60DAS	80DAS
T1	4.7 (2.4)	5.1 (2.4)	1.9 (1.6)	5.3 (2.5)	5.9 (2.6)	8.6 (3.0)	0.5 (1.2)	0.7 (1.3)	0.4 (1.2)	0.2 (1.09)	0.3 (1.14)	0.3 (1.15)	0.5 (1.23)	1.3 (1.48)	0.3 (1.15)
T2	3.7 (2.1)	3.9 (2.2)	1.9 (1.7)	5.0 (2.4)	5.4 (2.5)	9.4 (3.2)	0.2 (1.1)	0.2 (1.09)	0.5 (1.2)	0.1 (1.06)	0.2 (1.09)	0.5 (1.20)	0.3 (1.12)	1.3 (1.48)	0.4 (1.21)
T3	4.1 (2.2)	3.7 (2.2)	1.3 (1.5)	5.6 (2.5)	4.6 (2.3)	8.1 (2.9)	0.3 (1.1)	0.2 (1.09)	0.4 (1.18)	0.3 (1.15)	0.4 (1.18)	0.6 (1.26)	1.0 (1.40)	1.2 (1.44)	0.5 (1.18)
T4	4.1 (2.2)	3.7 (2.2)	1.7 (1.6)	6.0 (2.6)	5.1 (2.4)	9.1 (3.1)	0.5 (1.2)	0.5 (1.20)	0.4 (1.17)	0.3 (1.14)	0.5 (1.21)	0.4 (1.18)	1.0 (1.40)	1.5 (1.52)	0.4 (1.18)
T5	4.9 (2.4)	4.5 (2.4)	2.1 (1.7)	6.3 (2.7)	6.0 (2.6)	9.7 (3.2)	0.4 (1.1)	0.5 (1.21)	0.3 (1.15)	0.3 (1.12)	0.4 (1.18)	0.7 (1.28)	0.7 (1.28)	2.7 (1.84)	0.4 (1.15)
T6	4.1 (2.2)	3.6 (2.1)	2.1 (1.7)	5.7 (2.5)	4.9 (2.4)	9.5 (3.2)	0.3 (1.12)	0.5 (1.21)	0.3 (1.15)	0.1 (1.06)	0.3 (1.15)	0.4 (1.17)	0.7 (1.28)	1.3 (1.48)	0.3 (1.15)
T7	4.4 (2.3)	4.7 (2.4)	1.8 (1.6)	5.5 (2.5)	5.5 (2.5)	9.7 (3.2)	0.3 (1.12)	0.4 (1.18)	0.3 (1.15)	0.1 (1.06)	0.3 (1.12)	0.6 (1.25)	0.6 (1.26)	1.5 (1.51)	0.3 (1.57)
T8	4.6 (2.3)	7.2 (2.8)	3.3 (2.0)	8.1 (3.0)	8.5 (3.0)	12.0 (3.5)	1.4 (1.5)	2.8 (1.94)	2.4 (1.84)	1.6 (1.6)	3.3 (2.05	2.1 (1.76)	1.6 (1.60)	3.6 (2.13)	1.5 (1.15)
C.D.	**N/A**	**0.4**	**0.2**	**0.2**	**0.32**	**N/A**	**0.2**	**0.23**	**0.23**	**0.17**	**0.23**	**0.20**	**0.22**	**0.41**	**0.06**
SE(m)	**0.078**	**0.1**	**0.01**	**0.08**	**0.10**	**0.14**	**0.07**	**0.07**	**0.08**	**0.05**	**0.07**	**0.06**	**0.07**	**0.13**	**0.02**
SE(d)	**0.110**	**0.25**	**0.12**	**0.12**	**0.14**	**0.20**	**0.11**	**0.11**	**0.11**	**0.08**	**0.11**	**0.09**	**0.10**	**0.19**	**0.03**
C.V.	**5.8**	**9.6**	**9.1**	**5.56**	**6.91**	**7.65**	**11.15**	**10.30**	**10.60**	**8.06**	**10.30**	**9.02**	**9.66**	**14.43**	**2.7**

Values are mean of three replications and values in the parenthesis are square root transformed values for sucking pests and arc sign transformed for defoliators damage percentage.

Table 2. Impact of organic amendments and bio-fertilizers on natural enemies population in groundnut ecosystem during *Kharif* 2022

Treatment details	Ladybird beetle population/10 plants			Mean	Spider population/10 plants			Mean
	V	R	M		V	R	M	
T1-FYM @12.5t/ha	5.3 (2.5)	5.9 (2.6)	8.1 (2.9)	6.43	3.7 (2.1)	3.9 (2.2)	1.9 (1.7)	3.17
T2-Vermicompost @ 2.5t/ha	6.0 (2.6)	5.1 (2.4)	9.7 (3.2)	6.93	4.7 (2.4)	5.1 (2.4)	1.3 (1.5)	3.70
T3-Neemcake @ 250kg/ha	5.6 (2.5)	4.6 (2.3)	8.6 (3.0)	6.27	4.1 (2.2)	3.7 (2.2)	1.8 (1.6)	3.20
T4-Poultry Manure@ 5t/ha	5.0 (2.4)	5.4 (2.5)	9.4 (3.2)	6.60	4.1 (2.2)	3.7 (2.2)	1.9 (1.6)	3.23
T5-Phosphobacteria @ 2kg/ha	6.3 (2.7)	6.0 (2.6)	9.7 (3.2)	7.33	4.9 (2.4)	4.5 (2.4)	2.1 (1.7)	3.83
T6-Rhizobium@ 2kg/ha	5.7 (2.5)	4.9 (2.4)	9.5 (3.2)	6.70	4.1 (2.2)	3.6 (2.1	2.1 (1.7)	3.27
T7-NPK (62.5:125:187.5 kg/ha)	5.5 (2.5)	5.5 (2.5)	9.1 (3.1)	6.70	4.4 (2.3)	4.7 (2.4)	1.7 (1.6)	3.60
T8-Control	8.1 (3.0)	8.5 (3.0)	12.0 (3.5)	9.53	4.6 (2.3)	7.2 (2.8)	3.3 (2.0)	5.03
C.D.	**0.2**	**0.32**	**N/A**		**N/A**	**0.4**	**0.2**	**-**
SE(m)	**0.08**	**0.10**	**0.14**		**0.08**	**0.1**	**0.01**	**-**
SE(d)	**0.12**	**0.14**	**0.20**		**0.11**	**0.25**	**0.12**	**-**
C.V.	**5.565**	**6.910**	**7.65**		**5.85**	**9.6**	**9.1**	**-**

Values are mean of three replications and values in the parenthesis are square root transformed values. V - Vegetative stage; R -Reproductive stage; M - Maturity stage.

Organic amendments and bio-fertilizers on major insect pests population (*rabi*/summer 2022-23)

During *rabi*/summer (2022-23), field trials were conducted to study the efficacy of organic amendments on major pests, namely thrips, leaf hopper, *S. litura, H. armigera* and *A. modicella* in groundnut cultivation. Observations were made for sucking and defoliating insect pests as per the procedure followed during *Kharif* season and the results were shown in Table 3. The plants were provided with eight different organic supplementations namely FYM (T1), vermicompost (T2), neem cake (T3), poultry manure (T4), Phosphobacteria (T5), *Rhizobium* (T6), NPK (T7) and Control (T8). At 30 DAS, T2 effectively controlled the population of thrips, while T3 effective against other pests such as leaf hopper, *S. litura, H. armigera* and *A. modicella*. T3 reduced populations of thrips and leaf hopper, as well as the damage percentage caused by *S. litura, H. armigera* and *A. modicella* at 60 DAS. At 60 DAS, T4 reduced thrips populations, whereas T2 and T5 showed siginificant against *S. litura*. At 80 DAS, T3 was effective against thrips, leaf hopper and *H. armigera*, T5 reduced *S. litura.* Additionally, T1 and T4 significantly reduced the populations of *A. modicella.* These observations showed that the treatment with neem cake @ 250 kg/ha (T3) was the most effective organic amendment for controlling the mentioned major pests during the *rabi* 2022-23 season.

Organic amendments and bio-fertilizers effect on natural enemies population (*rabi*/summer 2022-23)

During the *rabi*/summer season 2022-23, field experiments were conducted to study the impact of various organic amendments and bio-fertilizers on the population of natural enemies in the groundnut ecosystem. Table 4 showed the ladybird beetles and spiders populations per 10 plants across all treatments. The observed data indicates varying degrees of influence on spider population ranging from 3.2 (T2) to 3.8 (T1) from the applied organic inputs and bio-fertilizers compared to 5.2 (T8) (Fig. 1). Similarly, for ladybird beetle populations, the number varied from 8.0 (T3) to 9.5 (T5) compared to 13.2 (T8). T8 showed higher populations of ladybird beetles and spiders, which could suggest the prevalence of higher number of insect pest attracting natural enemies due to less effective pest control in the absence of organic inputs or bio-fertilizers.

Table 3. Effect of organic amendments and biofertilizers on major insect pests in groundnut ecosystem during *Rabi*/summer 2022-2023

Treatments	Sucking pest population (Nos/3 leaves/plant)						Defoliators damage (%)								
	Thrips			Leafhopper			*Spodopteralitura*			*Helicoverpaarmigera*			*Aproaeremamodicella*		
	30DAS	60DAS	80DAS	30DAS	60DAS	80DAS	30DAS	60DAS	80DAS	30DAS	60DAS	80DAS	30DAS	60DAS	80DAS
T1	3.8 (2.2)	4.2 (0.1)	1.0 (1.4)	4.4 (2.3)	5.0 (2.4)	7.7 (2.9)	10.5 (18.9)	10.7 (19.1)	12.2 (20.5)	2.93 (8.7)	4.93 (12.5)	5.60 (13.4)	3.2 (10.4)	5.13 (13.1)	4.8 (12.6)
T2	2.8 (1.9)	3.0 (0.1)	1.0 (1.4)	4.7 (2.4)	4.5 (2.3)	8.5 (3.1)	9.06 (17.5)	10.2 (18.6)	11.6 (19.8)	2.83 (8.3)	4.73 (12.4)	5.40 (13.2)	3.43 (10.5)	4.47 (12.1)	4.9 (12.8)
T3	3.2 (2.0)	2.8 (0.1)	0.5 (1.2)	4.1 (2.2)	3.7 (2.2)	7.2 (3.0)	8.5 (16.9)	10.2 (18.6)	10.53 (18.9)	2.20 (7.8)	4.0 (11.4)	4.80 (12.5)	2.47 (9.0)	2.83 (9.7)	5.0 (12.9)
T4	3.2 (2.0)	2.8 (0.1)	0.8 (1.3)	5.1 (2.5)	4.2 (2.3)	8.2 (3.1)	10.5 (18.9)	10.5 (18.9)	12.2 (20.4)	3.03 (9.0)	4.40 (11.9)	5.33 (13.1)	4.73 (12.5)	4.23 (11.8)	4.9 (12.7)
T5	3.8 (2.4)	3.8 (0.2)	1.2 (1.5)	5.8 (2.7)	5.8 (2.6)	8.6 (3.2)	9.50 (17.5)	10.2 (18.0)	10.3 (18.15)	3.3 (9.5)	4.4 (11.18)	5.7 (14.28)	4.6 (12.28)	4.7 (11.84)	5.4 (13.2)
T6	3.6 (2.2)	3.6 (0.2)	1.5 (1.6)	5.4 (2.5)	4.5 (2.4)	8.5 (3.2)	10.15 (18.5)	10.4 (18.2)	10.5 (18.25)	3.1 (8.5)	3.38 (11.15)	4.4 (12.17)	4.58 (12.28)	4.3 (11.8)	5.6 (13.5)
T7	3.4 (2.6)	4.8 (0.4)	1.6 (1.8)	5.2 (2.5)	5.2 (2.5)	8.9 (3.2)	11.42 (18.5)	10.5 (18.9)	11.2 (18.5)	3.0 (9.2)	4.3 (12.00)	4.6 (12.25)	4.62 (12.30)	4.5 (11.50)	5.2 (15.2)
T8	3.7 (2.2)	6.3 (0.6)	2.4 (1.8)	7.2 (2.8)	7.6 (2.9)	11.1 (3.4)	15.5 (23.2)	15.5 (23.2)	18.33 (25.3)	5.23 (12.5)	11.0 (19.2)	13.0 (21.1)	7.47 (15.8)	10.0 (18.4)	8.2 (16.7)
C.D.	**0.01**	**0.03**	**0.04**	**0.02**	**0.02**	**0.01**	**0.99**	**1.2**	**1.9**	**1.8**	**3.03**	**2.2**	**2.2**	**1.4**	**0.3**
SE(m)	**0.004**	**0.009**	**0.014**	**0.005**	**0.006**	**0.003**	**0.32**	**0.37**	**0.63**	**0.60**	**0.98**	**0.73**	**0.73**	**0.45**	**0.09**
SE(d)	**0.005**	**0.013**	**0.020**	**0.007**	**0.009**	**0.004**	**0.46**	**0.53**	**0.88**	**0.85**	**1.39**	**1.04**	**1.03**	**0.63**	**0.14**
C.V.	**0.31**	**0.72**	**1.73**	**0.35**	**0.46**	**0.17**	**2.92**	**3.4**	**5.3**	**11.5**	**12.8**	**8.8**	**10.5**	**5.8**	**1.3**

Values are mean of three replications and values in the parenthesis are square root transformed values for sucking pests and Arc sign transformed for defoliators damage percentage

Table 4. Impact of organic amendments and bio - fertilizers on natural enemies population in groundnut ecosystem during *Rabi*/summer 2022-2023

Treatment details	Ladybird beetle population/10 plants			Mean	Spider population/10 plants			Mean
	V	R	M		V	R	M	
T1-FYM@12.5t/ha	6.48 (2.7)	8.05 (2.9)	10.72 (3.3)	8.42	4.52 (2.3)	5.52 (2.5)	1.52 (1.6)	3.86
T2-Vermicompost @ 2.5t/ha	6.02 (2.6)	6.72 (2.7)	12.76 (3.6)	8.40	3.26 (1.0)	4.05 (2.2)	2.56 (1.8)	3.29
T3-Neemcake @ 250kg/ha	6.80 (2.7)	6.05 (2.6)	11.35 (3.4)	8.07	4.05 (1.2)	4.52 (2.3)	2.52 (1.7)	3.50
T4-Poultry Manure@ 5t/ha	7.3 (2.8)	6.74 (2.7)	12.74 (3.6)	8.93	3.56 (2.1)	4.8 (2.4)	2.45 (1.7)	3.44
T5-Phosphobacteria @ 2kg/ha	7.79 (2.9)	8.06 (2.9)	12.76 (3.6)	9.54	4.50 (2.3)	4.05 (2.2)	2.45 (1.8)	3.70
T6-Rhizobium@ 2kg/ha	6.9 (2.7)	6.52 (2.7)	12.72 (3.6)	8.71	4.12 (2.2)	3.5 (2.1)	2.57 (1.87)	3.34
T7-NPK (62.5:125:187.5 kg/ha)	6.72(2.7)	7.38 (2.8)	12.05 (3.5)	8.72	4.59 (2.3)	4.20 (2.2)	2.56 (1.87)	3.78
T8-Control	10.15(3.3)	12.0 (3.5)	17.38 (4.2)	13.18	5.08 (2.4)	7.05 (2.8)	3.58 (2.1)	5.24
C.D.	**0.07**	**0.10**	**0.09**	-	**0.005**	**0.007**	**0.008**	-
SE(m)	**0.02**	**0.03**	**0.03**	-	**0.002**	**0.002**	**0.003**	-
SE(d)	**0.03**	**0.05**	**0.04**	-	**0.002**	**0.003**	**0.004**	-
C.V.	**1.5**	**2.0**	**1.4**	-	**0.117**	**0.156**	**0.257**	-

Values are mean of three replications and values in the parenthesis are square root transformed values. V- Vegetative stage; R-Reproductive stage; M- Maturity stage.

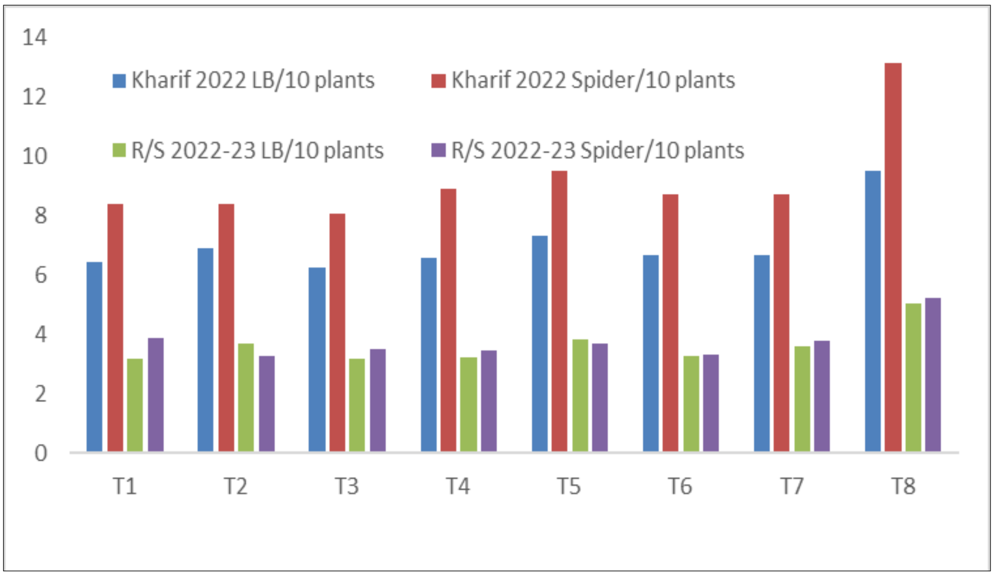

Fig. 1. Population of natural enemies of major pests during two seasons (*Kharif* and *Rabi*/Summer). Farm Yard Manure (T1), Vermicompost (T2), Neem Cake (T3), Poultry Manure (T4), Phosphobacteria (T5), *Rhizobium* (T6), NPK (T7) and Control (T8)

Yield and cost-benefit analysis of organic amendments and bio-fertilizers

The economic outcomes of different treatments on groundnut cultivation during the *Kharif* and *rabi* seasons of 2022-2023 were assessed in terms of yield, input costs and net returns (Fig. 2). During the *Kharif* season 2022, treatment costs, including application charges, varied significantly. The highest cost was incurred in T4 at INR 50,300, while the lowest costs were recorded for T5 and T6 at INR 460 (Table 5). Yield parameters varied across treatments, with pod yield ranging from 1,516 to 1,866 kg/ha and haulm yield from 4.0 to 4.7 t/ha. The economic returns, including pod rates (Rs 90/kg) and fodder rates (Rs 1/kg), resulted in gross returns ranging from INR 1,36,440 to INR 1,67,940. The cost of cultivation (COC) includes from seed cost, sowing, weeding, earthing up and harvesting charges plus treatment cost varied between INR 4,300 and INR 4,600. Net returns, reflecting profits, ranged from INR 40,970 to INR 1,11,980, while the benefit-cost ratio (BCR) varied from 1.37 to 2.85. Treatment T5 (Phosphobacteria @ 2 kg/ha) demonstrated the highest BCR, highlighting its economic feasibility for groundnut cultivation.

Table 5. Yield parameters, net returns and benefit cost ratio as influenced by application of organic amendments and bio-fertilizers in groundnut during *Kharif* 2022

	Cost (INR)	Pod (kg/ha)	Haulm (t/ha)	Increase over control (%)	Pod rate (INR)	Fodder rate (INR)	Gross return (INR)	COC+ Trt cost (INR)	Net return (INR)	BCR
T1	10300	1691	4.6	11.5	1,52,190	4600	1,56,790	70,300	86,490	2.23
T2	17800	1808	4.5	19.3	1,62,720	4500	1,67,220	77,800	89,420	2.15
T3	7800	1808	4.7	19.3	1,62,720	4700	1,67,420	67,800	99,620	2.47
T4	50300	1633	4.3	7.7	1,46,970	4300	1,51,270	1,10,300	40,970	1.37
T5	460	1866	4.5	23.1	1,67,940	4500	1,72,440	60,460	1,11,980	2.85
T6	460	1750	4.4	15.4	1,57,500	4400	1,61,900	60,460	1,01,440	2.68
T7	2800	1750	4.3	15.4	1,57,500	4300	1,61,800	62,800	99,000	2.58
T8	-	1516	4.0	-	1,36,440	4000	1,40,440	60,000	80,440	2.34

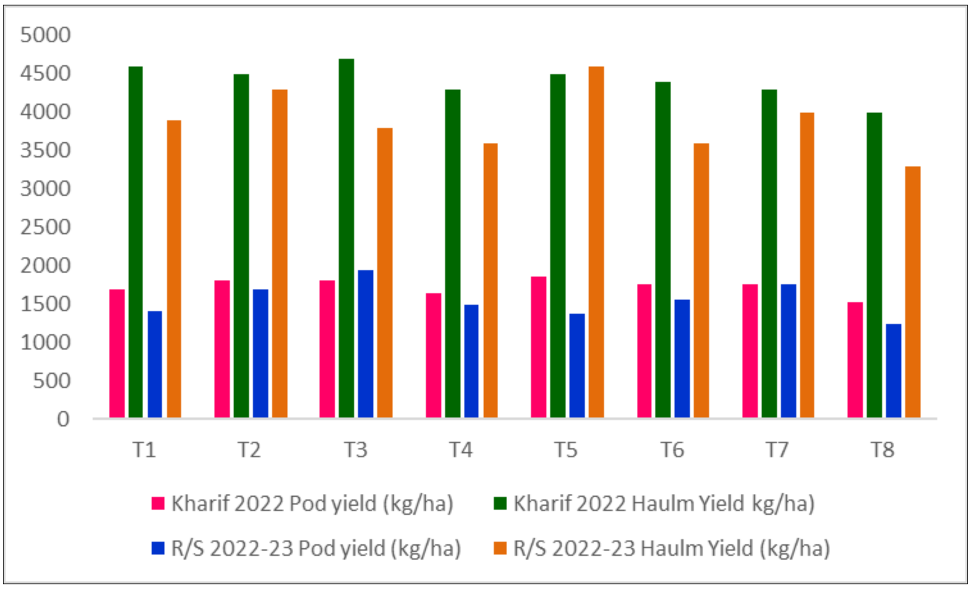

Fig. 2. Effect of organic amendments and bio-fertilizers on groundnut yield during *Kharif* 2022 and *Rabi*/summer 2022-2023. Farm Yard Manure (T1), Vermicompost (T2), Neem Cake (T3), Poultry Manure (T4), Phosphobacteria (T5), *Rhizobium* (T6), NPK (T7) and Control (T8).

During the *rabi* 2022–2023 season, yield improvements varied among treatments compared to the control, with pod yield ranging from 1,236 to 1,936 kg/ha and haulm yield from 3.3 to 4.6 t/ha (Table 6). The highest pod yield was recorded in T3 (Neem cake treatment). The highest haulm yield was recorded in T5. When considering the cost of cultivation plus treatment, net returns varied from 27,670 INR to 1,10,240 INR per hectare, while benefit-cost ratios ranged from 1.25 to 2.62. The highest BCR was recorded for T3 (2.62) followed by T2 (2.58). These data collectively highlight the economic viability and profitability of different groundnut cultivation strategies, guiding farmers in making informed decisions to optimize their yields and returns.

Discussion

Groundnut is an economically significant legume crop that contributes to food security, nutrition and livelihoods. It serves as a valuable source of protein, fats and essential nutrients for millions of people worldwide (17). However, groundnut cultivation is often challenged by various pests, including thrips, leafhoppers, *S. litura*, *H. armigera* and *A. modicella*. These pests collectively pose significant threats to groundnut production, causing substantial yield losses and reductions in nutritional quality, resulting in estimated annual losses exceeding millions of dollars globally (18-21). Thrips and leafhoppers are major vectors of plant viruses such as Groundnut Bud Necrosis Virus (GBNV) and Peanut Witches Broom Phytoplasma (PnWB), both of which cause significant yield losses (22,23,24). Similarly, larvae of *S. litura* and *H. armigera* feed extensively on groundnut foliage and pods, causing severe defoliation, pod damage and yield reduction (19). *A. modicella*, commonly infests groundnut leaves, impairing photosynthesis, reducing pod development and ultimately diminishing yield (25). Effective management strategies, including IPM and organic amendments, are essential for sustaining groundnut production and ensuring food security. This study evaluated the efficacy of organic amendments and bio-fertilizers on the above major insect pests and their natural enemies in the groundnut ecosystem. Organic amendments like neem cake are compatible with soil microorganisms, improves rhizosphere microflora and ensures stable soil structure, high water holding capacity and aeration in the soil for better root development and ultimately enhance the vigour and immunity of the crop plants against biotic stress like insect pest attack (13). It also highlighted the yield advantage and benefit-cost ratio of each of the seven treatments (T1 to T7) compared to the control (T8). Vermicompost (T2), neem cake (T3) and Phosphobacteria (T5) proved effective over major pest under study, providing potential economic benefits to farmers over conventional chemical pesticide application.

Table 6. Yield parameters, net returns and benefit cost ratio as influenced by application of organic amendments and bio-fertilizer in groundnut during *Rabi*/summer 2022-2023

Treatment	Cost (INR)	Yield		Increase over control (%)	Cost of pod (INR)	Cost of fodder (INR)	Gross return (INR)	COC+ Trt cost (INR`)	Net return (INR)	BCR
		Pod(kg/ha)	Haulm (t/ha)							
T1	10300	1411	3.9	14.2	1,26,990	3900	1,30,890	70,300	60,590	1.86
T2	17800	1691	4.3	36.8	1,52,190	4300	1,56,490	77,800	78,690	2.01
T3	7800	1936	3.8	56.6	1,74,240	3800	1,78,040	67,800	1,10,240	2.62
T4	50300	1493	3.6	20.8	1,34,370	3600	1,37,970	1,10,300	27,670	1.25
T5	460	1376	4.6	11.3	1,23,840	4600	1,28,440	60,460	67,980	2.12
T6	460	1551	3.6	25.5	1,39,590	3600	1,43,190	60,460	82,730	2.36
T7	2800	1761	4.0	42.5	1,58,490	4000	1,62,490	62,800	99,690	2.58
T8	-	1236	3.3	-	1,11,240	3300	1,14,540	60,000	54,540	1.91

Trt - Treatment; COC - Cost of Capital; BCR - benefit cost ratio

Effect of treatments during *Kharif* 2022 and *rabi*/summer 2022 -23 on major insect pests

Throughout the *Kharif* 2022 and *rabi/summer* 2022-23 seasons, neem cake and vermicompost effectively controlled major pests, including thrips, leafhoppers, *S. litura, H. armigera* and *A. modicella,* as demonstrated by reduced pest populations and damage percentages. Additionally, the application of Phosphobacteria bio-fertilizer also reduced the damage caused by *S. litura* in both the seasons. Moreover, FYM treatment effectively reduced damage caused by *A. modicella* during the later growth stages (60 - 80 DAS) in both *Kharif* and *rabi* season experiments. The replicated field study conducted across two seasons demonstrated the effectiveness of organic amendments, with treatments such as neem cake, vermicompost and Phosphobacteria achieving the lowest pest damage percentages compared to the control.

Neem cake versus commercial pesticides for managing major pests

Among different treatments, neem cake (250 kg/ha) applied plot recorded reduced thrips, leaf hopper and other major pest populations compared to control plot during reproductive phase of groundnut. Basal application of neem cake (250 kg/ha) and vermicompost (1 t/ha) were effective in keeping the sucking pest's density under check compared to insecticides like fipronil and dicofol and second spray at 30 days after treatment with fenpyroximate and spinosad (26). In other crop ecosystems also, the efficacy of neem cake in bringing down the pest populations was reported. Reduced population of sucking insect pests in mango (27), BPH in rice (28), leaf hoppers, aphids, whiteflies and mites' population reduction in cotton (29), spider mites, leaf hoppers, aphids and whiteflies in okra (30), aphids in brinjal (31). Neem cake (250 kg/ha) applied plot recorded significantly highest red chilli yield (10.42 q/ha) (26). The reduction in insect pest population by neem cake might be due to the natural predators and parasites of pests like pollinators, honeybees were not destroyed thereby, allowing these natural enemies to keep a check on the pest population in cropping ecosystem (14). Besides, due to its systemic action, seedlings can absorb and accumulate the neem compounds to make the whole plant pest resistant and to ward off the sucking insect pests, which attacks the crop in early growth phase.

Soil microbes influence plant response to insect pests

Soil microbes have already been shown to play crucial role in influencing plant response to above ground insects pest (32,33). For instance, studies have shown that inoculating *Arabidopsis* roots with *Bacillus velezensis* can lead to reduction in the feeding and growth rates of *Myzus persicae* aphids, while the presence of arbuscular mycorrhizal fungi such as *Rhizophagus irregularis* has been found to induce resistance in potato plants against cabbage looper *Trichoplusiani* (34,35). These findings offer promising prospects for introducing beneficial soil microbial species to enhance crop growth while simultaneously mitigating insect pests in sustainable agriculture practices.

Practical approach to pest control through organic amendments and bio-fertilizers

A practical approach to pest control using organic amendments and bio-fertilizers is essential for fostering resilient and sustainable groundnut farming. Incorporating organic amendments like farmyard manure and vermicompost, improves soil structure, nutrient availability (N and P) and microbial diversity, enhancing groundnut growth. These amendments contribute to a robust soil microbiome that can deter pests and promote overall plant health through increased plant height, number of branches per plant, leaf area index, number of nodules per plant leads to more pod yield and haulm yield (36) and basal application of Phosphobacteria releases phosphorus (P) and minerals, which help to improve plant growth and produce more yield (37). Adopting bio-fertilizers containing beneficial microorganisms specific to groundnut cultivation, such as those that facilitate nitrogen fixation or enhance nutrient absorption, strengthens the plants' natural defences against pest pressures by releasing secondary metabolites (38).

Furthermore, implementing integrated pest management (IPM) practices tailored to groundnut crops involves strategic crop rotation, intercropping with pest-repelling plants and promoting the presence of natural enemies like predators (8). Applying organic amendments at critical growth stages (e.g., early vegetative and pod formation stages) ensures optimal nutrient availability, strengthens plant resilience and reduces pest susceptibility. By adopting sustainable approaches, groundnut farmers can effectively manage pests, improve soil health and enhance long-term productivity while minimizing environmental impact.

Farmer-centric approach

A farmer - centric approach is essential for developing practical and economically viable recommendations to enhance groundnut cultivation, based on the findings from Tables 5 and 6.Table 5 highlights the significant impact of organic amendments and bio - fertilizers on yield parameters, net returns and benefit-cost ratio (BCR), with certain treatments showing superior benefits. Treatments T5 and T6, involving the application of Phosphobacteria and *Rhizobium*, respectively, demonstrated promising outcomes with increased pod yield (23.1% and 15.4%), gross return (Rs 1,72,440 and Rs 1,61,900) and benefit-cost ratio (1:2.85 and 1:2.68). These treatments can be recommended to farmers aiming for optimal economic returns and sustainable cultivation practices. Treatment 8 (control) appears to support a higher population of ladybird beetles and spiders, probably due to the increased density of the insect pest population. Farmers may benefit from adopting practices that promote natural enemy abundance, contributing to integrated pest management. Considering these findings, a farmer-centric recommendation would involve promoting the adoption of treatments T5 and T6 for improved yield and economic returns. Simultaneously, encouraging practices that enhance the population of natural enemies, such as conserving habitats and minimizing pesticide use, can contribute to sustainable pest management. Application of vermicompost and biofertilizers was found to control major pests in most vegetable crops and even in bean plants due to the secretion of phenolic compounds, flavones, ascorbic acid induction in root exudates (38,39). This holistic approach aligns to optimize agricultural productivity while minimizing environmental impact, providing farmers with practical and effective strategies for successful groundnut cultivation.

Conclusion

This study highlights variations in sucking pest populations and defoliator damage across different treatments and growth stages of groundnut during the *Kharif* 2022 and *Rabi*/ Summer 2022-2023 seasons. Each treatment demonstrated distinct effects on pest population dynamics and crop damage, indicating differences in their efficacy for pest management. Notably, treatment with vermicompost, neem cake and Phosphobacteria at 2 kg/ha consistently maintain relatively lower pest populations and damage percentages while enhancing natural enemy populations, indicating their potential effectiveness for pest control. Conversely, control plants had higher pest populations and damage levels, reinforcing the effectiveness of organic amendments in pest management. As a result, these treatments consistently showed higher groundnut yields in terms of pods, haulm yield and biomass across both *Kharif* and *Rabi* seasons, thereby reflecting positively on net profit and BCR. The significant differences between treatments, as indicated by Critical Difference (CD) values, highlight the importance of selecting appropriate agricultural interventions to effectively reduce insect pest pressure. This study provides valuable insights into the efficacy of organic amendments and bio-fertilizers in managing insect pests in groundnut ecosystems, aiding in the optimization of pest control strategies for sustainable crop production. Organic amendments and bio-fertilizers are pivotal components in nurturing a robust soil microbiome, fostering an environment conducive to enhancing agricultural productivity. These amendments, such as farmyard manure and vermicompost, infuse the soil with a rich diversity of organic matter, providing a habitat for a myriad of beneficial microorganisms. This microbial diversity is fundamental in promoting nutrient cycling, as microorganisms break down complex organic compounds into more accessible forms, thus maintaining a balanced nutrient profile in the soil. Furthermore, microbial activity improves soil structure by forming aggregates, enhancing water infiltration and root penetration and preventing soil erosion.

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Authors' contributions

PI and GG worked on conceptualization. PI, MP and CH have done formal analysis. PI, GG and AM carried out funding acquisition. PI and GG prepared the original draft. VR and BM wrote, reviewed and edited the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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