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Plant Density, Trichoderma, And Effective Microorganisms on Sesame Yield (Sesamum Indicum L.), Pichari

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ABSTRACT
This study aimed to evaluate the effect of plant density, Trichoderma harzianum, and effective microorganisms (EM) on the agronomic performance of sesame (Sesamum indicum L.) under tropical conditions in Pichari, Peru. A 2×2×2 factorial arrangement was established within a randomized complete block design (RCBD), with eight treatments and three replications. Five variables were measured: plant height, fruiting height, capsule length, number of capsules per plant, and grain yield. Data were analyzed using ANOVA and Tukey's test ($p < 0.05$). Significant differences were found for plant height ($p = 0.0147$), number of capsules per plant ($p = 0.0140$), and grain yield ($p = 0.0197$), primarily due to the application of T. harzianum and its interaction with EM ($p = 0.0424$). The highest yield (1252.00 kg/ha) was achieved with 143,000 plants/ha combined with T. harzianum. These results suggest that T. harzianum, alone or in synergy with EM, significantly enhances sesame yield, making it a viable sustainable strategy for high-humidity tropical environments.
Keywords: *Trichoderma harzianum, effective microorganisms, plant density, bioinputs, agronomic yield, Sesamum indicum L..*

INTRODUCTION

The cultivation of sesame (Sesamum indicum L.) is gaining increasing global relevance due to its versatility in the food, pharmaceutical, and cosmetic industries. Global sesame production reached 6.6 million tons in 2023, with more than 70% concentrated in Asia and Africa (Food and Agriculture Organization of the United Nations – FAO, 2023). Sudan produced 1.02 million tons, while India contributed 825,000 tons to the international market (United Nations Conference on Trade and Development – UNCTAD, 2018). These volumes mainly supply China, Japan, Turkey, and South Korea, which together account for over 58% of global imports (Inter-American Development Bank – IDB, 2021). The international market shows high demand for quality seeds, driven by the consumption of healthy products rich in unsaturated oils and antioxidants (UNCTAD, 2024). However, sesame cultivation faces significant phytosanitary constraints. The main pests include the sesame weevil (Smicronyx spp.) and the fall armyworm (Spodoptera frugiperda), while the most common diseases are Fusarium wilt (Fusarium oxysporum), powdery mildew (Oidium spp.), and leaf spot caused by Cercospora sesami. These factors negatively impact productivity, grain quality, and post-harvest shelf life, affecting competitiveness in international markets.

In Latin America, sesame cultivation is irregularly distributed, with greater development in countries with tropical and subtropical climates. Paraguay leads regional production with over 45,000 hectares cultivated and an average yield of 1.1 tons per hectare, generating an annual output of more than 49,500 tons (Inter-American Development Bank – IDB, 2021). It is followed by Mexico with 22,000 hectares and Brazil with 15,800 hectares, while Nicaragua and Venezuela show more modest production levels. The expansion of sesame cultivation is limited by the use of local landraces with low genetic potential, limited mechanization, and recurrent phytosanitary problems (Colorado-Pérez et al., 2023). The most common pests include Helicoverpa armigera and the sesame thrips (Frankliniella schultzei), while fungal diseases such as leaf blight and root rot cause significant losses, particularly under high humidity conditions. Despite its export potential, the region's yield remains below the global average, limiting competitiveness and integration into high-standard markets such as the European Union (Pérez et al., 2024).

In Peru, sesame cultivation is primarily concentrated in the regions of Piura, Lambayeque, Ica, and La Libertad, which together account for 94% of national production (Acosta-Román et al., 2023). In 2023, a total of 4,210 hectares were cultivated, producing 5,210 tons, with an average yield of 1.24 tons per hectare. Piura led with 2,180 hectares and a production of 2,970 tons (Ministry of Agrarian Development and Irrigation of Peru – MIDAGRI, 2025). Peruvian sesame exports reached 2,600 tons, primarily destined for Japan and South Korea. However, the crop faces multiple agronomic challenges. The most common pests include the fruit borer (Ephestia kuehniella) and aphids (Aphis gossypii), while diseases such as anthracnose and root rot caused by Rhizoctonia solani hinder crop development during vegetative and reproductive stages. The lack of improved varieties, inefficient irrigation systems, and poor soil management continue to negatively affect productivity and the final product's quality.

Sesame (Sesamum indicum L.) cultivation presents high nutritional and economic value, yet faces considerable phytosanitary challenges that significantly reduce yield. Various studies have identified insects such as Antigastra catalaunalis, Spilosoma obliqua, aphids, thrips, and whiteflies as the main pests of sesame, capable of causing yield losses exceeding 70% if not properly controlled (Dwarka et al., 2024). These pests not only reduce productivity but also affect seed quality, with their incidence varying according to environmental conditions, crop phenology, and geographical region. In the West Gondar zone of Ethiopia, for example, Antigastra and aphids reached 100% prevalence in some areas, while diseases such as Cercospora leaf spot and bacterial blight showed severities of up to 90.4% and 88.5%, respectively (Kefale et al., 2021).

In this context, the Integrated Pest Management (IPM) approach has gained prominence in sustainable production systems. One of its pillars is the use of biological control agents. Mishra et al. (2021) successfully documented the use of parasitoids such as Cotesia plutellae and Trichogramma chilonis, along with nuclear polyhedrosis virus (HaNPV) and entomopathogenic fungi like Metarhizium anisopliae and Verticillium lecanii, achieving over 70% effectiveness in reducing populations of Helicoverpa armigera and Phthorimaea operculella. This type of control, in addition to being effective, helps reduce dependence on chemical insecticides and their environmental side effects. Agroecological practices such as intercropping have also been shown to enhance biological pest control. In trials with the VRI-2 sesame cultivar, intercropping with pearl millet, sorghum, and castor significantly reduced Antigastra populations, decreasing larval presence to 0.4 larvae per plant and capsule damage to less than 5%, while increasing yields to over 600 kg/ha (Sheeba Jasmine et al., 2020). This practice also promoted higher abundance of natural enemies such as lady beetles and spiders, strengthening agroecosystem defenses.

Alemu and Taye's (2022) review in Ethiopia further validates IPM effectiveness through a combination of botanical insecticides like neem extract (5 ml/L), pheromone traps (15 traps/ha), and the release of T. chilonis (50,000/ha every 7 days), achieving pest infestations below 10% in field trials. These practices are not only effective but also scalable for smallholders in tropical regions. Postharvest storage is another critical stage for sesame protection against secondary pests. Berhe et al. (2023) evaluated different storage systems over six months and found that hermetic PICS and SGP bags kept weight losses under 2% and germination rates above 90%, unlike jute and polypropylene sacks, which showed infestations of up to 120 insects/kg, mainly Corcyra cephalonica and Tribolium spp. These findings reaffirm the importance of physical environmental control as a barrier to pest development.

Additionally, characterizing pest species and their population dynamics has enabled better timing of interventions. Ram et al. (2025) conducted weekly monitoring in Gujarat, identifying population peaks of thrips (6.82/3 leaves), jassids (6.10), whiteflies (6.70), and aphids (2.44/plant) between weeks 13 and 15 of the crop cycle, positively correlated with maximum temperature. Similarly, El-Shannaf et al. (2024) reported peak populations in Egypt of Empoasca spp. (49.5/leaf) and Myzus persicae (43.25/leaf), suggesting treatment initiation when aphid numbers exceed 30 per leaf. Such data help establish Economic Threshold Levels (ETL) to optimize control measure applications. Roy (2022), for instance, defined cultivar-specific ETLs for sesame, finding that 'Rama' was the most efficient, with a yield of 857.09 kg/ha and higher profitability. Another important factor is the role of weeds in disease incidence. Gedifew and Earecho (2024) found that early manual weeding and the use of biological products reduced bacterial blight incidence and controlled broadleaf weeds, which, if unmanaged, can reduce yields by up to 20%. This evidence reinforces the power of cultural practices within IPM strategies.

Research has also advanced in the use of beneficial fungi such as Trichoderma spp., known for their antagonistic properties against pathogens and their ability to induce systemic resistance in plants. Oyesola et al. (2024) describe Trichoderma's modes of action, including the production of chitinases and glucanases, as well as competitive exclusion for space and nutrients, resulting in more vigorous plant development. Poveda (2021) further reports insecticidal and repellent effects of Trichoderma against lepidopterans, attributed to volatile metabolites. The potential of Trichoderma is enhanced when coinoculated with other beneficial microorganisms. Guzmán-Guzmán et al. (2023) demonstrated that T.

harzianum and T. virens effectively reduce populations of nematodes and phytopathogenic fungi while stimulating secondary biomass production. Additionally, Yao et al. (2023) found that root-applied Trichoderma reduced soilborne disease severity by 60% and improved nutrient uptake. These effects have been confirmed in both controlled and open-field conditions. Harman (2024), for example, observed yield increases exceeding 25% in crops such as maize and tomato following seed treatment with Trichoderma. The versatility of this fungus is also evident in its interaction with arthropod pests. Monte (2023) describes the evolution of Trichoderma as an entomopathogenic fungus, producing metabolites such as 6-pentyl-α-pyrone and 1-octen-3-ol, which act as indirect repellents and parasitoid attractants. These compounds have shown inhibitory effects on mosquito larvae, suggesting broader applications in crop protection and public health. Likewise, field trials with tomato demonstrated that T. harzianum strain T22 reduced the abundance of mites (Tetranychus urticae) and flea beetles (Chaetocnema tibialis), while increasing productivity and positively altering the beneficial arthropod community (Caccavo et al., 2022).

Tyśkiewicz et al. (2022) also confirmed that Trichoderma stimulates the production of phytohormones and ACC deaminase, promoting plant growth and reducing diseases such as Botrytis and Alternaria by 40–70%. These reductions were achieved via soil application or irrigation. In a complementary onion study, Yağmur et al. (2024) combined T. harzianum with Funneliformis mosseae, reducing Fusarium disease severity from 90% to 68%, while significantly improving root colonization and phosphorus uptake. Awal et al. (2024) highlight that repeated application of Trichoderma, along with practices like crop rotation and soil solarization, can reduce Fusarium spp. incidence by up to 70%. This strategy not only improves soil health but also enhances long-term system stability, reinforcing Trichoderma's role as a multifunctional tool in sustainable agriculture.

Overall, the literature demonstrates that effective pest and disease control in sesame cultivation requires a multifaceted approach. The integration of biological, cultural, physical, and rational chemical methods—supported by deep knowledge of the crop ecosystem—can significantly reduce economic losses and improve system sustainability. Scientific research has generated a robust set of strategies, from the use of parasitoids and intercropping to the application of beneficial fungi like Trichoderma spp., offering viable alternatives for both smallholders and large-scale producers, with positive impacts on productivity, environmental health, and agricultural resilience.

SESAME (Sesamum indicum L.) CULTIVATION IN PERU

Sesame (Sesamum indicum L.) is an oilseed crop of growing importance in Peruvian agriculture, recognized for its high oil content (ranging between 45% and 58%), its nutritional value, and its adaptability to warm climates. Its oil is considered to be of higher quality than that of other oilseeds such as soybean, sunflower, or oil palm, due to its high concentration of unsaturated fatty acids and antioxidant compounds (Bustamante et al., 2001).

In Peru, sesame cultivation is mainly concentrated in the regions of Piura, Lambayeque, Ica, and La Libertad, which together account for approximately 94% of the national cultivated area (Acosta-Román et al., 2023). In addition, expansion is being promoted in Amazonian regions such as Pichari (Cusco), with institutional support (MIDAGRI, 2025). The producing areas present favorable agroclimatic conditions, especially well-drained alluvial soils, tropical and subtropical climates, and optimal temperatures ranging from 25°C to 35°C.

Planting and Population Density

Planting is predominantly carried out manually, with seeds distributed in furrows spaced 60–70 cm apart between rows and 10–15 cm between plants. Optimal planting densities range between 110,000 and 150,000 plants per hectare (Montoya et al., 2019; Melgarejo et al., 2020). Trials conducted by Montoya et al. (2019) identified that a density of 143,000 plants/ha, in combination with biological treatments, increased efficiency in yield-related variables.

Genetic Material and Breeding

Regarding national germplasm, promising varieties such as Aceitera Mejorada and Criolla de Reque have been identified. These were selected at the Vista Florida Experimental Station – Chiclayo, with average yields of 898 and 767 kg/ha, respectively, and phenological cycles of 102 to 110 days (MIDAGRI, 2025). Additionally, through individual selection, the "Campo Verde" line was developed, adapted to ultisol soils and capable of achieving yields of up to 0.8 t/ha.

Agronomic Management and Cultural Practices

Productive management includes basic practices such as manual weeding, thinning, pest control, and manual harvesting. Fertilization is adjusted according to soil analysis and is complemented with biostimulants such as vermicompost, leachates, and effective microorganisms (Héctor-Ardisana et al., 2021). In areas with significant phytosanitary pressure, preventive management includes the application of Trichoderma spp., whose beneficial effects on plant growth, resistance, and yield have been documented by Oyesola et al. (2024) and Ruiz & Blandón (2021). These authors highlight its root colonization capacity, production of antifungal metabolites, and suppression of pathogens such as Fusarium.

Trichoderma harzianum, in particular, has demonstrated its ability to increase plant height, the number of capsules per plant, and grain yield in sesame production systems. These outcomes were confirmed in recent field trials in Pichari (Galindo et al., 2024).

Pests and Diseases

The main pests reported in Peru include Spodoptera frugiperda, Aphis gossypii, Frankliniella schultzei, and Ephestia kuehniella (Colorado-Pérez et al., 2023; Dwarka et al., 2024). Major diseases include anthracnose, leaf spot caused by Cercospora sesami, and root rot caused by Rhizoctonia solani (Melgarejo et al., 2020). Integrated Pest Management (IPM), which combines biological, cultural, and rational chemical control strategies, is the most recommended approach in sustainable contexts (Mishra et al., 2021).

Harvest and Postharvest

Harvesting is conducted when 70–80% of the capsules have reached physiological maturity. Plants are cut and left to dry either in the field or under shelter before threshing. Seeds must be stored with moisture content below 9% to prevent infestations by insects such as Tribolium spp. or Corcyra cephalonica (Berhe et al., 2023). The adoption of postharvest technologies, such as the use of hermetic bags (PICS), improves seed preservation and reduces losses.

Based on the considerations outlined above, the objectives are formulated as follows: To evaluate the effect of plant densities, Trichoderma harzianum, and effective microorganisms on the yield of sesame (Sesamum indicum L.) in Pichari Baja, at 577 meters above sea level, Cusco, 2024. Accordingly, the specific objectives are:

1. To evaluate the effect of plant densities and T. harzianum on the yield of sesame (Sesamum indicum L.) in Pichari, 577 meters above sea level, Cusco, 2024.
2. To evaluate the effect of plant densities and effective microorganisms on the yield of sesame (Sesamum indicum L.) in Pichari, 577 meters above sea level, Cusco, 2024.

Hypothesis: The combined application of Trichoderma harzianum and effective microorganisms (EM), particularly under higher planting density conditions, significantly enhances the agronomic performance of sesame (Sesamum indicum L.), as measured by plant height, number of capsules per plant, and grain yield, compared to individual or non-biological treatments in humid tropical environments.

METHOD

The study was conducted during the 2024 agricultural season at the Pichari Baja Experimental Center, located in the district of Pichari, province of La Convención, Cusco region, at an altitude of 577 meters above sea level (12°13′00″ south latitude, 73°49′30″ west longitude). The experimental area has a warm-humid tropical climate, with an average temperature of 24 °C and an annual rainfall of approximately 1,100 mm, mainly distributed between November and April. The soil is sandy-loam in texture, with good drainage and a pH ranging from 6.3 to 6.8—conditions well suited for the cultivation of Sesamum indicum L.

A Randomized Complete Block Design (RCBD) was used, with a 2×2×2 factorial arrangement consisting of two levels of planting density (119,000 and 143,000 plants/ha), with or without application of Trichoderma harzianum, and with or without application of Effective Microorganisms (EM), resulting in a total of eight treatments. Each treatment was replicated in three blocks, yielding 24 experimental units. Each plot measured 14 m^2 (4 rows, each 4 meters long, spaced 0.70 m apart). Ten plants per plot were randomly selected from the central rows to avoid edge effects, totaling 240 plants evaluated.

Planting was done manually using locally sourced seeds that were previously selected and disinfected. Trichoderma harzianum was applied directly to the base of the plants 15 days after emergence (DAE), using a liquid suspension with a concentration of 1×10^7 CFU/mL, prepared in the laboratory. Effective Microorganisms were applied as a foliar spray at a 10% concentration at 20 and 40 DAE. Both bio-inputs were produced under controlled conditions, following activation and multiplication protocols described by Héctor-Ardisana et al. (2021), and their viability was verified prior to application. Throughout the 110-day crop cycle, conventional agronomic practices were carried out, including manual weeding, thinning, pest control with natural extracts, and gravity-based irrigation depending on soil moisture.

The variables evaluated were grouped into two categories: growth variables (reproductive height and plant height) and yield variables (capsule length, number of capsules per plant, and grain yield in $kg \cdot ha^{-1}$). Plant height was measured from the base to the tip of the last capsule, while reproductive height corresponded to the distance from the root collar to the beginning of the productive raceme. Harvesting was done manually, and yield was determined by weighing the dry grain from each plot using a precision digital scale, with the results extrapolated to a per-hectare basis.

Statistical analysis was performed using RStudio v.4.3.1. Analysis of variance (ANOVA) was applied to detect significant differences among treatments. When significant effects were found ($p < 0.05$), Tukey's Honest Significant Difference (HSD) test was used for multiple comparisons. Prior to this, the assumptions of residual normality (Shapiro-Wilk test) and homogeneity of variances (Levene's test) were verified and satisfied for all evaluated variables. The results were presented in tables including coefficients of variation (CV) and mean values per treatment.

Table 1. Treatments evaluated in a 2×2×2 factorial arrangement under a randomized complete block design (RCBD).

Treatment	Planting Density (plants/ha)	T. harzianum	Effective Microorganisms (EM)
T1	119,000	Without application	Without application
T2	119,000	With application	Without application
T3	119,000	Without application	With application
T4	119,000	With application	With application
T5	143,000	Without application	Without application
T6	143,000	With application	Without application
T7	143,000	Without application	With application
T8	143,000	With application	With application

Note. Each treatment was replicated three times, with 10 plants evaluated per experimental unit.

RESULTS AND DISCUSSION

Growth Variables:

Reproductive Height

Reproductive height was recorded by measuring from the base of the plant to the node bearing the first group of capsules, using a measuring tape. The data were consolidated using an observation sheet.

Plant Height

Shortly before harvest, the height of 10 plants per experimental unit was measured, with the plants selected from the central row of each plot. Measurements were taken from the base of the plant to the tip of the last capsule using a measuring tape. This information was consolidated for all treatments evaluated in each of the sesame cultivation experiments.

Table 2 Analysis of variance for the growth variables of sesame (Sesamum indicum L.) with Trichoderma and EM, Pichari, 577 m a.s.l., Cusco.

F.V.	gl	Reproductive Height		Plant Height	
		CM	p-value	CM	p-value
Block	2	20.79	0.8392	945.38	0.0056
Treatment	7	118.57	0.4634	191.04	0.2282
Density (D)	1	1.50	0.9115	287.04	0.1487
T. harzianum (T)	1	37.50	0.5805	57.04	0.5068
Effective Microorganisms (M)	1	42.67	0.5558	22.04	0.6784
D x T	1	2.67	0.8822	1.04	0.9280
D x M	1	468.17	0.0654	15.04	0.7317
T x M	1	253.50	0.1634	950.04	0.0147
D x T x M	1	24.00	0.6577	5.04	0.8424
Error	14	117.13		122.90	
Total	23				
CV (%)		8.03		5.33	
Average		143.83		207.88	

For reproductive height, no significant differences were found between block, treatment, planting density, T. harzianum (T), effective microorganisms (M), or the interactions D × T, D × M, T × M, and D × T × M (p-value > 0.05). The coefficient of variation was 8.03%, indicating adequate control of factors not accounted for in the study. The overall mean reproductive height was 143.83 cm (Table 2).

For plant height, a significant difference was observed in the main effect of block (p-value = 0.0056) and in the interaction between T. harzianum (T) and effective microorganisms (M) (p-value = 0.0147). No significant differences were found for treatment, planting density, T. harzianum (T), effective microorganisms (M), or the interactions D × T, D × M, and D × T × M (p-value > 0.05). The coefficient of variation was 5.33%, indicating adequate control of unmeasured factors. The overall mean plant height was 207.88 cm (Table 2).

Tabla 3 Tukey's test for the effect of planting density, T. harzianum, and EM on the growth variables of sesame (Sesamum indicum L.), Pichari, 577 m a.s.l., Cusco.

F. V.	Factors			Reproductive Height	
	D	Th	EM	cm	
Interaction D x Th x EM	119000	0	1	144.67	a
	143000	1	0	141.00	a
	119000	1	1	137.00	a
	143000	0	1	136.67	a
	143000	0	0	134.33	a
	119000	1	0	130.00	a
	119000	0	0	128.67	a
	143000	1	1	126.33	a
				Reproductive Height cm	
Interaction Th x EM		0	1	226.67	a
		1	0	211.67	a
		0	0	202.17	a
		1	1	201.00	a
				Reproductive Height cm	
Interaction D x Th x EM	143000	0	1	218.67	a

143000	1	0	215.67	a
119000	0	1	214.67	a
119000	1	0	207.67	a
143000	0	0	206.67	a
143000	1	1	204.33	a
119000	1	1	197.67	a
119000	0	0	197.67	a

As presented in Table 3, reproductive height ranged from 126.33 cm to 144.67 cm. The highest value was recorded in the treatment with EM at 119,000 plants/ha (T7), whereas the lowest was observed in the combination of T. harzianum and EM at 143,000 plants/ha (T4). These results suggest a slight advantage of lower planting density in promoting reproductive height, although the differences were not statistically significant. Reproductive height was not significant, as also reported by Montoya et al. (2019), where growth variables (reproductive height and plant height) were not influenced by any of the experimental treatments, including the absence of fertilization.

The individual means for each treatment can be found in Table 3. Mean values ranged from 201.00 to 216.67 cm for treatments t4 (with T. harzianum × Effective Microorganisms) and t7 (with Effective Microorganisms), respectively. The treatment with Effective Microorganisms stands out compared to treatments with T. harzianum × Effective Microorganisms, which differ significantly.

As shown in Table 3, the highest plant height (218.67 cm) was recorded in the treatment with 143,000 plants/ha and EM, while the lowest (197.67 cm) occurred in the control with 119,000 plants/ha. This suggests a positive interaction between high planting density and EM application.

The plant height of the local variety was significant and is lower than that reported by Melgarejo et al. (2020). With regard to plant height (ADP) in sesame, no statistically significant differences were observed ($p > 0.05$) and an average of 263.83 cm was obtained. This result is consistent with Zarate et al. (2011), who reported a mean of 229 cm with no significant differences between densities. Beltrão et al. (2001) mention that varieties classified as giant and indeterminate growth can reach up to 300 cm in height, which is the group to which “Escoba blanca” belongs.

Yield Variables:

Capsule Length

The length of the capsules was measured using a measuring tape, recording the distance from the base to the tip of each capsule.

Number of Capsules per Plant

The number of capsules was recorded by counting all capsules on each evaluated plant. For this assessment, 10 plants from the middle section of each row were selected to avoid border effects in each treatment.

Grain Yield

After harvesting the grains from each experimental unit, they were weighed using a Henkel 5kg Digital Stainless Steel Scale. The yield was then recorded in kilograms per plot and subsequently estimated in kilograms per hectare.

Table 4 Analysis of variance for the yield variables of sesame (Sesamum indicum L.) with Trichoderma and EM, Pichari, 577 m a.s.l., Cusco.

F.V.	gl	Capsule Length		Capsules per Plant		Grain Yield	
		CM	p-value	CM	p-value	CM	p-valor
Block	2	0.0017	0.8956	1584.91	0.0979	5674.01	0.6657
Treatment	7	0.02	0.3915	1169.60	0.1223	28591.18	0.1109
Density (D)	1	0.0267	0.2037	608.03	0.3212	8085.01	0.4526
T. harzianum (T)	1	0.0417	0.1178	4532.00	0.0140	93887.55	0.0197

Effective Microorganisms (M)	1	0.0067	0.5158	169.60	0.5956	21247.45	0.2309
D × T	1	0.0150	0.3343	74.91	0.7235	55.51	0.9499
D × M	1	0.0000	>0.9999	1187.23	0.1727	1658.34	0.7316
T × M	1	0.0150	0.3343	1597.40	0.1178	67553.87	0.0424
D × T × M	1	0.0150	0.3343	18.03	0.8620	7650.51	0.4648
Error	14	0.0150		574.94		13544.36	
Total	23						
CV (%)		4.18		31.58		10.36	
Average		2.93		75.93		1123.15	

For capsule length, no significant differences were found between block, treatment, planting density, T. harzianum (T), effective microorganisms (M), or the interactions D × T, D × M, T × M, and D × T × M (p-value > 0.05). The coefficient of variation was 4.18%, indicating adequate control of unmeasured factors in the study. The overall mean capsule length was 2.93 cm (Table 4).

For the number of capsules, a significant difference was found for T. harzianum (p-value = 0.0140). No significant differences were found between block, treatment, density, effective microorganisms (M), or the interactions D × T, D × M, T × M, and D × T × M (p-value > 0.05). The coefficient of variation was 31.58%, indicating adequate control of unmeasured factors in the study. The overall mean number of capsules was 75.93 capsules (Table 4).

For grain yield, significant differences were observed for T. harzianum (T) (p-value = 0.0197) and for the T × M interaction (p-value = 0.0424). No significant differences were found for block, treatment, density, effective microorganisms (M), or the interactions D × T, D × M, and D × T × M (p-value > 0.05). The coefficient of variation was 10.36%, indicating adequate control of unmeasured factors in the study. The overall mean grain yield was 1,123.15 kg/ha (Table 4).

Table 5 Tukey's test for the effect of planting density, and inoculation with T. harzianum and EM on the yield variables of sesame (Sesamum indicum L.), Pichari, 577 m a.s.l., Cusco.

F. V.	Factors			Capsule lenght		
	D	Th	EM	cm		
Interaction D x Th x EM	143000	1	0	3.07	a	
	143000	1	1	3.00	a	
	143000	0	1	2.97	a	
	119000	1	1	2.93	a	
	119000	0	1	2.90	a	
	119000	1	0	2.90	a	
	119000	0	0	2.87	a	
	143000	0	0	2.83	a	
				Number of Capsules conteo		
Trichoderma harzianum Th		1		89.67	a	
		0		62.18		b
				Grain Yield kg/ha		
Interaction D x Th x EM	143000	1	1	98.87	a	
	119000	1	0	96.27	a	
	143000	1	0	94.07	a	
	143000	0	1	82.43	a	
	119000	1	1	69.47	a	
	119000	0	1	63.57	a	
	119000	0	0	54.27	a	
	143000	0	0	48.47	a	
				Grain Yield kg/ha		

Trichoderma harzianum Th		1		1185.70	a	
		0		1060.61		b
				Grain Yield kg/ha		
Interaction Th x EM		1	0	1209.00	a	
		1	1	1162.40	a	b
		0	1	1143.42	a	b
		0	0	977.80		b
				Grain Yield kg/ha		
Interaction D x Th x EM	143000	1	0	1252.00	a	
	119000	0	1	1172.83	a	
	143000	1	1	1171.73	a	
	143000	1	0	1166.00	a	
	119000	1	1	1153.07	a	
	119000	0	1	1114.00	a	
	119000	0	0	988.13	a	
	143000	0	0	967.47	a	

As shown in Table 5, capsule length varied between 2.83 cm and 3.07 cm. The highest value was obtained in the treatment combining T. harzianum with 143,000 plants/ha (T2), indicating a slight positive effect of this bio-input at higher planting density. However, differences were not statistically significant.

The results obtained for capsule length fall within the range reported by Montoya et al. (2019). In the four variables measured (capsule length, capsules per plant, seeds per capsule, and yield), chemical fertilization resulted in significantly higher values. For capsule length and the number of seeds per capsule, both biol treatments produced similar results and outperformed the unfertilized control. For the number of capsules per plant, biol 2 (bioactivated from Bbo Agro, S.A.) outperformed biol 1. Apparently, the number of capsules per plant had the greatest influence on yield, as both variables followed a similar pattern in the ranking of the treatments studied. Finally, lack of fertilization resulted in the lowest values across all variables.

The individual means for the number of capsules per plant for each treatment, as shown in Table 5, ranged from 48.47 to 98.87 capsules/plant for treatments T1 (without T. harzianum and effective microorganisms, at 143,000 plants/ha) and T4 (with T. harzianum and effective microorganisms, at 143,000 plants/ha), respectively. The treatment with 143,000 plants/ha, T. harzianum, and EM stands out significantly compared to treatments without biological inoculation.

The values obtained for the number of capsules per plant are higher than the range reported by Melgarejo et al. (2020). Van Humbeeck and Oviedo (2012) observed that by planting 50 plants per m^2, they achieved up to 220 capsules per plant, evidencing the direct influence of planting density on yield. During the experiment, rainfall distribution was favorable, sufficiently meeting the crop's water requirements, which could explain the high values observed.

Regarding grain yield, the treatments showed statistically significant differences. Mean values ranged from 967.47 to 1,252.00 kg/ha; the latter recorded for treatment T2 (with T. harzianum, 143,000 plants/ha). This treatment significantly outperformed T5 (without T. harzianum, EM, 119,000 plants/ha). These results are consistent with those reported by Melgarejo et al. (2020), Carreño and Rojas (2013), and Zárate et al. (2011), who note that planting density and the use of bio-inputs significantly influence sesame yield. The yields obtained are within the range reported by DISE (2003) and Cristaldo (2007), who observed values between 900 and 1,500 kg/ha. Comparatively, these results exceed the national averages of Ecuador (760 kg/ha, FAO, 2018) and approach the upper limits reported for Paraguay (Zárate et al., 2011).

The assessment of sesame yield in this study demonstrates the agronomic efficacy of using Trichoderma harzianum, especially in combination with effective microorganisms and high planting densities. Nevertheless, variability in responses was observed, suggesting the need to investigate compatibility between strains, application frequency, and the specific agroecological conditions that modulate the effects of bio-inputs.

Therefore, it is recommended to develop complementary studies that include soil analysis, evaluation of native microbiota, dose-response trials, and validation of integrated management protocols, in order to establish more precise technical guidelines for the sustainable improvement of sesame yield under tropical conditions.

CONCLUSIONS

The present study demonstrates that the application of Trichoderma harzianum and effective microorganisms generates differential effects on key variables of sesame (Sesamum indicum L.) cultivation, particularly during the reproductive stages. Statistically significant differences were observed in plant height as a result of the interaction between T. harzianum and effective microorganisms, regardless of planting density. In this context, combined treatments achieved mean plant heights exceeding 200 cm, reflecting a synergistic effect on the vegetative development of the crop.

Similarly, the number of capsules per plant and grain yield were significantly influenced by the individual application of T. harzianum as well as by its interaction with effective microorganisms. Plants treated with this beneficial fungus produced an average of 89.67 capsules per plant, while grain yield reached up to 1,252 kg/ha in the most efficient treatments, surpassing the averages reported in previous studies conducted in similar contexts. These results highlight the potential of T. harzianum not only as a biocontrol agent but also as a promoter of agricultural yield under tropical conditions.

In contrast, structural variables such as reproductive height and capsule length did not show significant differences among treatments, suggesting that their phenotypic expression may depend more on genotypic and edaphoclimatic factors than on bio-input interventions. Nevertheless, favorable agronomic trends were identified in treatments with higher planting densities, opening up possibilities for optimizing integrated crop management based on density, biofertilization, and local soil conditions.

The main limitations of this study include the restricted duration of the experimental cycle, which prevented evaluation of the long-term persistence of microbial effects, as well as the absence of characterization of the soil microbiome before and after applications, which limits the understanding of root colonization dynamics. Furthermore, the use of a single formulation per bio-input restricts the extrapolation of results to other production conditions and to other types of strains or microbial consortia. Consequently, it is recommended that future research consider multifactorial designs including the evaluation of different strains, formulations, doses, and methods of bio-input application, complemented by microbiological analyses of the rhizosphere and soil. Extending trials to multiple cropping cycles, together with the incorporation of water management practices, crop rotation, and precision agriculture technologies, will make it possible to validate the stability of the observed effects and strengthen the productive sustainability of sesame cultivation in Peru and in other regions with similar agroecological profiles.

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