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ARISTON PUBLICATIONS
BioMed and BioSci Advances
ISSN: 3068-7314 www.aristonpubs.com/biomed-and-biosci-advances https://doi.org/10.69626/bba.2025.0169

RESEARCH ARTICLE

Evaluating Native Trichoderma Isolates for the Biocontrol of Late Blight (*Phytophthora infestans*) and Growth Enhancement in Tomato (*Solanum lycopersicum L.*)

Mat Both Dol[1], Delelegn Woyessa[1], Shiferaw Demissie[1], M. Sadre Alam Fakhri[2, *]

ABSTRACT: Biological control presents a sustainable alternative to chemical pesticides by utilizing living organisms or their byproducts to suppress plant pathogens. This study investigated the efficacy of several native Ethiopian isolates of the fungus *Trichoderma* for controlling late blight disease, caused by *Phytophthora infestans*, and for promoting growth in tomato plants (*Solanum lycopersicum* L.) under greenhouse conditions. A susceptible tomato cultivar, Moneymaker, was used in a pot experiment designed to test various *Trirchoderma* isolates, both individually and in combination with the pathogen. Key parameters including disease severity, plant growth metrics (shoot length, root length, fresh and dry biomass), and final fruit yield were meticulously recorded and analyzed. The results demonstrated a significant reduction in late blight severity in plants treated with the isolates Ju-TDc-2, Ju-TGDa-2, and Ju-TGDb-3, with disease indices as low as 8.8% compared to 19.2% in the pathogen-only control. Furthermore, these same isolates consistently enhanced plant growth, with shoot lengths reaching up to 89.67 cm and substantial increases in fresh weight and fruit yield. The study concludes that these specific *Trichoderma* isolates are highly promising biocontrol agents that effectively mitigate late blight damage while concurrently functioning as plant growth promoters. Their development into commercial bioformulations could offer Ethiopian smallholder farmers a viable, eco-friendly strategy for integrated disease management.

Keywords: Antagonistic fungi, Biological control, *Phytophthora infestans*, Plant growth promotion, *Solanum lycopersicum*, *Trichoderma* spp.

Received: 08 February 2025; Revised: 20 April 2025; Accepted: 25 June 2025; Published Online: 13 July 2025

1. INTRODUCTION

Tomato (*Solanum lycopersicum* L.), a member of the Solanaceae family, stands as one of the most economically significant and nutritionally important vegetable crops cultivated worldwide [1]. Its value extends far beyond its culinary versatility, representing a critical source of essential vitamins, minerals, and antioxidants in the human diet. In particular, tomatoes are renowned for their high concentration of vitamin C and, most notably, lycopene—a powerful carotenoid antioxidant responsible for the fruit's characteristic red hue and associated with reduced risks of certain chronic diseases [2-4]. The global importance of tomato is reflected in its production statistics, with current estimates exceeding 163.4 million tons harvested annually from over 4.6 million hectares of land [2]. In Ethiopia, tomato has emerged as a crucial cash crop, ranking 8th in annual national production and offering substantial economic opportunities for smallholder farmers [2]. The total area

[1] Department of Biology (Applied Microbiology), College of Natural Science, Jimma University, Ethiopia.
[2] Department of Biology, Gambella University, P. O. Box: 126, Gambella, Ethiopia.

* Author to whom correspondence should be addressed: fakhrimsa@gmail.com (M. Sadre Alam Fakhri)

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under cultivation has expanded to approximately 9,767.78 hectares, with a production output estimated at over 913,013.42 tons and an average productivity of 93.47 tons per hectare [2, 3]. This production occurs during both the rainy and dry seasons, the latter often relying on supplemental irrigation to sustain growth [3].

Despite its considerable potential and increasing demand, the actual production and productivity of tomato within Ethiopia remain substantially below attainable levels. This yield gap is attributed to a confluence of constraints, including a reliance on unimproved local varieties, suboptimal and traditional agronomic practices, and severe losses inflicted by a range of insect pests and devastating diseases. Among the most destructive of these pathogens is *Phytophthora infestans*, the causal agent of late blight disease. This oomycete pathogen poses a particularly severe threat to tomato cultivation in the humid and sub-humid highlands of Ethiopia, making rainy-season production a high-risk endeavor and often leading to complete crop failure [5]. In a bid to achieve economically viable yields and protect their investments, producers have increasingly intensified their reliance on synthetic chemical fungicides. These inputs, while often effective in reducing disease severity and improving short-term yield [6, 7], come with a heavy toll. The indiscriminate and unjustified use of chemical pesticides poses direct health risks to farmers, who frequently handle and apply these toxic substances without adequate personal protective equipment (PPE) [8,9]. Furthermore, consumers face potential health implications from pesticide residues on the fruit. From an agronomic perspective, the continuous application of chemicals fosters the development of resistant pathogen strains, rendering once-effective fungicides obsolete [10]. This practice also contributes to environmental degradation, disrupting beneficial soil microbiota and leading to ecological pollution.

In light of these challenges, there is an urgent and growing need for sustainable and environmentally sound alternatives for disease management. Biological control, defined as the deliberate use of living antagonistic microorganisms or their metabolic products to suppress or eradicate pathogenic populations, presents a highly promising solution [11, 12]. Within this field, fungi of the genus *Trichoderma* have garnered significant global attention for their multifaceted beneficial properties. Numerous studies have documented the remarkable ability of various *Trichoderma* species to act as potent antagonists against a wide spectrum of plant pathogens [13]. Their mode of action is complex and involves several direct and indirect mechanisms. They directly engage in mycoparasitism, coiling around and lysing the hyphae of pathogens. They also produce a diverse array of antibiotics and cell wall-degrading enzymes that inhibit pathogen growth [13-15]. Indirectly, they compete aggressively for space, nutrients, and oxygen, effectively outcompeting pathogens in the rhizosphere [16]. Beyond their biocontrol capabilities, many *Trichoderma* strains are established plant growth promoters, enhancing root development and improving nutrient uptake efficiency, which leads to more vigorous and resilient plants.

The novelty of this paper lies in its dedicated exploration and identification of *native* Ethiopian isolates of *Trichoderma* with dual efficacy against the devastating late blight disease and for growth enhancement in tomatoes. While the antagonistic potential of *Trichoderma* is known globally, the performance of these fungi is highly isolate-specific and influenced by local environmental conditions. Therefore, this research moves beyond generic assumptions by systematically screening, identifying, and validating locally sourced isolates, ensuring their suitability and adaptability for direct use within the specific agricultural contexts and challenges faced by Ethiopian farmers. This work provides a critical foundation for developing home-grown, sustainable biocontrol solutions tailored to the region's needs. Consequently, this study was specifically carried out with the objective to assess and identify the most effective native *Trichoderma* isolates for the biocontrol of late blight caused by *P. infestans* and for the enhancement of tomato growth and yield under greenhouse conditions, providing a scientific basis for their future development and field application.

2. EXPERIMENTAL DETAILS

2.1. Description of the Study Site and Period

The investigation was conducted at Jimma University, situated in Jimma Town, Oromia Regional State, Ethiopia. Jimma is the principal city in the southwestern region of the country, located at a geographic coordinate of 7°40′N 36°50′E and approximately 352 km southwest of the capital, Addis Ababa. The research activities were carried out between March and October 2019. The in-vitro component of the study, including the isolation, identification, and preliminary screening of fungal isolates, was performed at the Research and Postgraduate Laboratory within the Department of Biology. The subsequent in-vivo greenhouse experiment was conducted at the College of Agriculture and Veterinary Medicine, Jimma University. The plant material used throughout the study was the tomato (*Solanum lycopersicum* L.) cultivar 'Moneymaker', a variety known for its susceptibility to late blight. The seeds were procured from the Melkasa Agricultural Research Center, located near Adama, Ethiopia.

2.2. Experimental Design and Setup

The study employed a controlled experimental methodology. A purposive sampling technique was used to select the specific tomato cultivar based on its known susceptibility profile. The greenhouse experiment was designed following the successful identification and in-vitro screening of both pathogenic (*Phytophthora infestans*) and antagonistic (*Trichoderma* spp.) isolates. The experimental design implemented was a Randomized Complete Block Design

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(RCBD), with each treatment replicated three times. Each experimental unit (replicate) consisted of 11 pots, each containing a single plant, culminating in a total of 33 pots arranged on a greenhouse bench measuring 9.5 m by 2 m.

2.3. Preparation of Inoculum and Plant Materials

Pure cultures of the individual *Trichoderma* isolates were cultivated and maintained on Potato Dextrose Agar (PDA) medium for a duration of 7 days at room temperature. Concurrently, the pathogen *P. infestans* was cultured on Corn Meal Agar (CA) plates for 10 days to facilitate robust mycelial growth and sporangia production. To prepare the inoculum, the fungal colonies were carefully harvested by flooding the agar plates with 10 ml of sterile distilled water and gently scraping the surface with a sterile microscopic slide to dislodge spores and mycelial fragments. The resulting suspensions were then serially diluted to achieve a standardized working concentration of 10^{-5} spores/mL, as confirmed by haemocytometer counts, aiming for a final application concentration of approximately 250,000 spores/mL.

Tomato seeds of the 'Moneymaker' cultivar were subjected to surface disinfection to eliminate external contaminants. This process involved successive rinses in sterile distilled water followed by immersion in a 70% ethanol solution for a brief period. The sterilized seeds were then sown into nursery trays filled with a sterile growth medium for seedling establishment.

2.4. Greenhouse Pot Experiment and Treatment Application

After a three-week growth period in the nursery, the tomato seedlings were carefully uprooted to minimize root damage. The root systems of the seedlings designated for *Trichoderma* treatment were thoroughly inoculated by complete immersion in the respective *Trichoderma* spore suspensions for 15 minutes. Each treated seedling was then transplanted into a sterile 2-liter plastic pot filled with a sterilized potting mixture. The soil substrate was prepared in a 3:2:1 ratio of topsoil, sieved sand, and well-decomposed manure, which was sterilized by autoclaving and subsequently dried in an oven at 70°C for 24 hours to eliminate any pre-existing soil-borne pathogens.

One week post-transplantation, to allow for seedling establishment and root colonization by the biocontrol agents, the pathogen challenge was initiated. All plants, except the absolute controls, were inoculated with *P. infestans* by foliar spraying until run-off with the prepared spore suspension (250,000 spores/mL). The environmental conditions within the greenhouse were maintained to favor disease development, including high humidity and moderate temperatures.

2.5. Data Collection

Data on disease progression and plant growth parameters were systematically collected at multiple time points throughout the experiment. Disease severity (D.S.) was assessed on a regular basis using a standardized 0-5 rating scale, where 0 represented no symptoms and 5 represented complete plant death or severe infection [17, 18]. The severity index was calculated as a percentage using the formula: $D.S. = [\Sigma (n * v) / (5 * N)] * 100$, where 'n' is the number of leaves in each category, 'v' is the numerical rating of the category, and 'N' is the total number of leaves assessed.

Plant growth metrics were recorded at the termination of the experiment. The shoot length and root length of each plant were measured in centimeters using a standard ruler. The fresh weight of the entire plant was measured immediately after harvesting. The dry weight was determined after desiccating the plant material in a forced-air oven at 70°C for 24 hours until a constant weight was achieved. The total marketable fruit yield per plant was recorded in grams. Furthermore, the relative percentage yield loss was calculated for each treatment using the formula: Relative % yield loss = $[(Y_{bt} - Y_{lt}) / Y_bt] * 100$, where Y_{bt} is the yield of the best-performing treatment and Y_{lt} is the yield of the treatment in question.

2.6. Statistical Analysis

All quantitative data pertaining to disease severity, growth parameters (shoot length, root length, fresh and dry weight), and yield were compiled in Microsoft Excel and subsequently subjected to rigorous statistical analysis. A one-way Analysis of Variance (ANOVA) was performed using the General Linear Model (GLM) procedure in the SAS 9.1 statistical software package. The significance of differences among the treatment means was determined using Duncan's Multiple Range Test (DMRT) at a stringent probability level of $p \leq 0.05$. All values presented in the results are expressed as the mean of three independent replications.

3. RESULTS AND DISCUSSION

3.1. Efficacy of Trichoderma Isolates in Suppressing Late Blight Severity

The assessment of late blight development on tomato plants across the different treatments revealed significant variations in disease severity. The highest disease severity index (19.2%) was recorded in the positive control plants treated with *P. infestans* alone (Table 1). These plants exhibited classic and severe symptoms of late blight, beginning with irregular, water-soaked lesions on the younger leaves within the upper canopy. A characteristic white, cottony growth, signifying sporulation of the pathogen, was visibly abundant on the undersides of these lesions. As the disease progressed, these lesions enlarged rapidly, leading to extensive browning,

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necrosis, and eventual collapse of the foliage [19-21]. Furthermore, the pathogen successfully infected fruits at various developmental stages, causing greasy, chocolate brown, leathery rot that often encompassed the entire fruit, rendering it unmarketable.

In stark contrast, the application of *Trichoderma* isolates conferred a significant level of protection against the pathogen. Among the plants co-treated with both a *Trichoderma* isolate and *P. infestans*, the lowest disease severity was observed in those treated with isolate Ju-TDc-2 + P (8.8%), followed by Ju-TGDa-2 + P (12.1%) and Ju-TGDb-3 + P (12.8%). Notably, the disease severity in these treatments was statistically significantly lower than the pathogen-only control. Interestingly, some plants treated with *Trichoderma* isolates alone, without any pathogen challenge, also showed minimal signs of disease, with isolates Ju-TGDb-2 and Ju-TDc-2 showing a complete absence of symptoms (0%). However, a surprisingly higher severity (13.1%) was noted in plants treated only with Ju-TGDa-2, suggesting possible latent contamination or a hypersensitive response to the biocontrol agent itself in this specific isolate, a phenomenon that warrants further investigation.

The superior performance of isolates Ju-TDc-2, Ju-TGDa-2, and Ju-TGDb-3 in suppressing foliar disease, despite being applied as a root dip, strongly suggests the induction of systemic resistance within the host plant. This finding aligns with the growing body of evidence that *Trichoderma* spp. can colonize the root rhizosphere and activate physiological defense pathways throughout the plant, a process known as Induced Systemic Resistance (ISR) [22-26]. This primed state enables the plant to mount a more robust and rapid defense against subsequent pathogen attacks, such as the foliar challenge from *P. infestans* applied in this study. The mechanisms behind ISR often involve the upregulation of defense-related enzymes and the accumulation of antimicrobial compounds [27]. Furthermore, the direct antagonistic capabilities of these isolates, including mycoparasitism and the production of cell wall-degrading enzymes and antibiotics, likely contributed to reducing the initial pathogen inoculum potential in the rhizosphere, indirectly protecting the plant [13-15].

3.2. Influence of Trichoderma Isolates on Tomato Plant Growth Promotion

The results unequivocally demonstrate that specific *Trichoderma* isolates not only suppressed disease but also functioned as potent plant growth promoters. Analysis of vegetative growth parameters revealed significant differences among treatments (Table 2). The most pronounced effect on shoot elongation was observed in plants treated solely with the isolate Ju-TGDa-2, which achieved the highest average shoot length of 89.67 cm. This was significantly greater than the shoot length recorded in the pathogen-infected control plants (63.67 cm). The overall mean shoot length across all treatments was 78.7 cm. Similarly, root development was enhanced by several isolates. The highest root lengths (29.67 cm) were recorded in plants treated with Ju-TGDa-2 + P, Ju-TGDb-3 + P, and Ju-TGDb-3 alone, compared to an average of 27 cm in the pathogen-only control. The overall mean root length was 28.21 cm. This growth-promoting effect is a well-documented benefit of many *Trichoderma* species and is attributed to several mechanisms. The fungi colonize the root system, extending the effective root area and thereby dramatically improving the plant's capacity for water and nutrient acquisition from the soil [22]. Furthermore, *Trichoderma* is known to solubilize otherwise unavailable nutrients like phosphorus and iron, making them accessible to the plant [23]. Some strains also produce or modulate plant growth regulators, such as auxins, which directly stimulate root proliferation and overall plant growth [24].

Table 1. The disease severity of tomato plants treated with Trichoderma isolates against the development of late blight in Greenhouse, 2019.

Treatments	No. of plants affected (affected leaves)	Total assessed units (All leaves)	Disease severity index (%)
Ju-TGDa-2 + P	9.67bac	16	12.1
Ju-TGDa-2	7.33dcb	16.33	13.1
Ju-TGDb-1 + P	13.67ba	16	17.8
Ju-TGDb-1	2.67dc	16.33	3.3
Ju-TGDb-2 + P	12.33ba	16.33	14.8
Ju-TGDb-2	0d	14.67	0
Ju-TGDb-3 + P	10.67ba	16.67	12.8
Ju-TGDb-3	3dc	16	3.9
Ju-TDc-2 + P	7dcb	16	8.8
Ju-TDc-2	0d	15	0
P	15.33a	16	19.2
Mean	7.42	14.58	10.16
SD	6.245	4.918	

*Where: Each value is the mean of 3 replicate. Ju-TGDa-2, Ju-TGDb-1, Ju-TGDb-2, Ju-TGDb-3, and Ju-TDc-2 are Trichoderma isolates and P: P. infestans. Mean with the same letter are not significantly different at DMRT for Disease severity index ($p < 0.05$).

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Table 2. The shoot and root length of tomato plants treated with Trichoderma isolates in Greenhouse.

Treatments	Shoot length (cm)	Root length (cm)
Ju-TGDa-2 + P	75.67ba	29.67a
Ju-TGDa-2	89.67a	28.33a
Ju-TGDb-1 + P	80.67ba	28.33a
Ju-TGDb-1	85ba	27.33a
Ju-TGDb-2 + P	83ba	26a
Ju-TGDb-2	75.67ba	28a
Ju-TGDb-3 + P	74.33ba	29.67a
Ju-TGDb-3	73.67ba	29.67a
Ju-TDc-2 + P	83.67ba	27.67a
Ju-TDc-2	80.67ba	28.67a
P	63.67b	27a
Mean	78.7	28.21
SD	7.069	1.187

Where: Each value is the mean of 3 replicate. Ju-TGDa-2, Ju-TGDb-1, Ju-TGDb-2, Ju-TGDb-3, and Ju-TDc-2 are Trichoderma isolates and P: P. infestans. Mean with the same letter are not significantly different at DMRT for shoot and root length ($p < 0.05$).

Table 3. The fresh weight and dry weight of tomato plants treated with Trichoderma isolates in Greenhouse.

Treatments	Fresh weight (g)	Dry weight (g)
Ju-TGDa-2 + P	92.67ba	20bc
Ju-TGDa-2	101.67ba	25.67bac
Ju-TGDb-1 + P	98.83ba	30.67bac
Ju-TGDb-1	137.5a	34.83ba
Ju-TGDb-2 + P	106.5a	25.33bac
Ju-TGDb-2	109a	30.67bac
Ju-TGDb-3 + P	95.1ba	20.5bc
Ju-TGDb-3	110.33a	34ba
Ju-TDc-2 + P	115.5a	35.5ba
Ju-TDc-2	127.67a	43.67a
P	50b	12c
Mean	104.11	28.44
SD	22.438	8.862

Where: Each value is the mean of 3 replicate. Ju-TGDa-2, Ju-TGDb-1, Ju-TGDb-2, Ju-TGDb-3, Ju-TDc-2 are Trichoderma isolates and P: P. infestans. Mean with the same letter are not significantly different at DMRT for fresh weight and dry weight ($p< 0.05$).

The improved vegetative growth observed in this study, even in the absence of the pathogen, underscores the dual role of these isolates as both biocontrol agents and biofertilizers, which is a critical advantage for their adoption in sustainable agriculture.

3.3. Impact on Plant Biomass Accumulation and Fruit Yield

The positive effects of *Trichoderma* application translated directly into increased biomass production and, most importantly, higher fruit yield. The data on fresh and dry weights provide a clear measure of the overall plant health and vigor (Table 3). The mean fresh weight across all plants was 104.11 g, while the mean dry weight was 28.44 g. The lowest values for both parameters were predictably found in the stunted, diseased plants treated only with *P. infestans* (50 g fresh weight, 12 g dry weight). Conversely, the highest fresh and dry weights were recorded in plants treated with Ju-TDc-2 alone (127.67 g and 43.67 g, respectively) and Ju-TGDb-1 alone (137.5 g and 34.83 g, respectively). The ability of these isolates to significantly increase biomass, even under pathogen pressure, highlights their role in mitigating the stress-induced losses typically caused by disease.

The most critical economic parameter, marketable fruit yield, further solidified the superiority of the top-performing *Trichoderma* isolates (Figure 1). The highest yield was obtained from plants treated with Ju-TGDb-3 alone

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(29.47 g/plant), followed closely by Ju-TDc-2 + P (28.83 g/plant). In stark contrast, plants infected with the pathogen alone yielded no marketable fruit (0 g/plant), demonstrating the complete crop destruction potential of late blight. The relative percentage yield loss calculation starkly illustrated this impact, showing a 100% loss for the pathogen-only treatment. The losses for other treatments ranged from 33.3% for Ju-TDc-2 to 95.3% for Ju-TGDb-1, clearly identifying Ju-TDc-2, Ju-TGDa-2, and Ju-TGDb-3 as the isolates most effective at protecting yield.

The profound yield protection offered by these isolates is a direct consequence of the combined effects of disease suppression and enhanced plant vigor. By reducing the severity of late blight, the plants retained a larger photosynthetic area (canopy) for a longer duration, enabling greater resource allocation towards fruit development rather than defense. Simultaneously, the improved root systems and nutrient uptake efficiency fostered by *Trichoderma* colonization provided the necessary resources to sustain this development even under biotic stress [25-29]. This synergy between biocontrol and growth promotion is the key value proposition of using effective *Trichoderma* strains in integrated pest management programs.

3.4. Isolate Performance and Variability

The results of this study confirm that the biological control efficacy of *Trichoderma* is highly isolate-dependent [29, 32]. The exceptional performance of isolates Ju-TDc-2, Ju-TGDa-2, and Ju-TGDb-3 against *P. infestans* and in promoting plant growth can be attributed to their innate genetic capacity to efficiently express a suite of biocontrol and plant growth-promoting genes [30-32]. In contrast, the intermediate or poor performance of isolates like Ju-TGDb-1 and Ju-TGDb-2 underscores the fact that not all isolates of even the same species are equally effective. This variability can be influenced by a multitude of factors, including the specific mechanisms of antagonism employed, their adaptability to the rhizosphere environment, their efficiency in colonizing roots, and their compatibility with the host plant genotype [33].

The finding that some isolates performed well in growth promotion but less so in disease control (e.g., Ju-TGDb-1), and vice versa, suggests that these traits are not always genetically linked and can be independently expressed. This highlights the critical importance of multi-trait screening programs, like the one employed here, to identify isolates with the desired combination of properties. The failure of some isolates to consistently enhance yield, as has been reported in other studies [31], can often be linked to suboptimal environmental conditions (abiotic factors) or complex interactions with the native soil microbiota (biotic factors) that were controlled for in this greenhouse study but are prevalent in field conditions [32].

The data from this experiment provide robust evidence that the native *Trichoderma* isolates Ju-TDc-2, Ju-TGDa-2, and Ju-TGDb-3 are promising candidates for the development of a dual-purpose bio-product for tomato cultivation. Their ability to systemically reduce the severity of the devastating late blight disease while concurrently acting as plant growth promoters offers a sustainable strategy to increase yield and reduce reliance on chemical pesticides. The next crucial step is to validate these greenhouse findings through well-designed field trials and to develop stable, cost-effective formulations suitable for use by smallholder farmers.

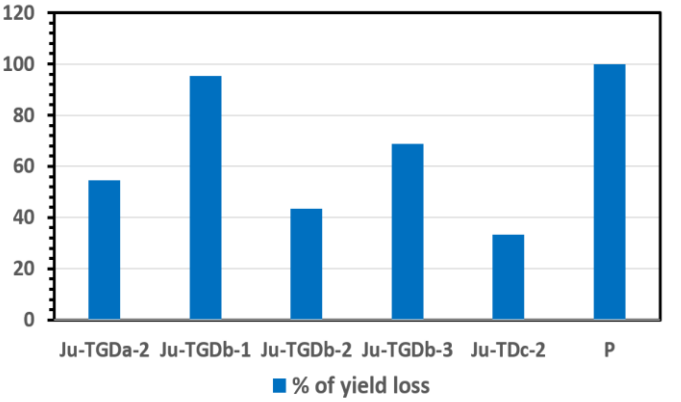

Fig. 1. The yield of tomato plants treated with Trichoderma isolates in Greenhouse. Where: Each value is the mean of 3 replicate. Ju-TGDa-2, Ju-TGDb-1, Ju-TGDb-2, Ju-TGDb-3, Ju-TDc-2 are Trichoderma isolates and P: P. infestans.

4. CONCLUSION

This study provides compelling evidence that specific native isolates of *Trichoderma* hold significant potential for the integrated management of late blight disease in tomato cultivation. The isolates Ju-TDc-2, Ju-TGDa-2, and Ju-TGDb-3 were identified as the most effective, not only for their antagonistic activity against *Phytophthora infestans* but also for their pronounced ability to enhance overall plant growth and productivity. The success of these isolates is likely attributed to a combination of mechanisms, including direct mycoparasitism, competition for space and nutrients, and the induction of systemic resistance within the tomato plants. By colonizing the root zone, these beneficial fungi appear to prime the plant's defense systems, making the foliage more resistant to the foliar pathogen, a phenomenon known as Induced Systemic Resistance (ISR). Concurrently, their presence in the rhizosphere improves root architecture and efficiency, leading to better nutrient and water uptake, which translates into superior shoot length, biomass accumulation, and ultimately, higher fruit yield, as clearly quantified in our results. The stark contrast in yield loss—reaching 100% in infected controls but significantly mitigated in *Trichoderma*-treated plants—underscores the devastating impact of late blight and the tangible economic benefit these biocontrol agents can provide. However, the variable performance of different isolates, such as the lesser efficacy of Ju-TGDb-1 and Ju-TGDb-2, highlights a critical

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point: the biocontrol activity of *Trichoderma* is highly isolate-specific and influenced by complex interactions between the fungus, the host plant, the pathogen, and the environmental conditions. Therefore, the mere presence of *Trichoderma* is not a guarantee of efficacy; careful screening and selection of potent native isolates are paramount. Based on these findings, we strongly recommend that the three promising isolates (Ju-TDc-2, Ju-TGDa-2, and Ju-TGDb-3) undergo further rigorous evaluation. Next steps must include field trials across diverse agro-ecological zones in Ethiopia to validate these greenhouse results under real-world conditions, where variables like soil type, weather, and existing microbial communities come into play. Furthermore, research must focus on developing practical, scalable, and stable formulation protocols for these isolates to ensure their viability and efficacy from production to application by farmers. Finally, a thorough assessment of their environmental impact and safety for non-target organisms is essential before widespread adoption can be promoted. The integration of these effective *Trichoderma* isolates into tomato production systems represents a forward-looking strategy to reduce dependency on chemical fungicides, lower production costs, minimize environmental pollution, and contribute to sustainable and profitable tomato farming for Ethiopian smallholders.

DECLARATIONS

Ethical Approval

We affirm that this manuscript is an original work, has not been previously published, and is not currently under consideration for publication in any other journal or conference proceedings. All authors have reviewed and approved the manuscript, and the order of authorship has been mutually agreed upon.

Funding

Not applicable

Availability of data and material

All of the data obtained or analyzed during this study is included in the report that was submitted.

Conflicts of Interest

The authors declare that they have no financial or personal interests that could have influenced the research and findings presented in this paper. The authors alone are responsible for the content and writing of this article.

Authors' contributions

All authors contributed equally to this work.

ACKNOWLEDGEMENTS

The authors would like to thank the Jimma University, Ethiopia for sponsoring this work.

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