Integrated Management of *Fusarium* diseases in tomato (*Solanum lycopersicum* L.) in Burkina Faso

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Abstract

Tomato (*Solanum lycopersicum* L.) is an economically important vegetable in Burkina Faso. Grown for local consumption and for export to neighboring countries, the tomato significantly contributes to food and nutrition security. However, poor soil fertility and disease are significant constraints to tomato production. Indeed, crop losses can be very high due to *Fusarium* disease, which negatively affects crop yields and farmers' incomes. An agro-ecological approach has been adopted to control this disease and ensure sustainable tomato production. A two-year experiment was conducted using a Split-plot design with four replications to assess a production system combining two factors: (1) biofertilizers to restore soil fertility and (2) biopesticides to biocontrol fungal diseases, particularly fusariosis. Biofertilizer efficacy was compared with that of NPK, which is a chemical fertilizer. Across the treatments (compost, bokashi, and essential oil formulations), results showed a significant reduction of the fungus's impact. The average disease score of 1.5 observed with application of biofertilizers was significantly lower than the control score of 4.25. Results also indicate a higher average yield of 16.16 t/hawith compost, achieved through effective control of Fusarium diseases using biological control agents. In contrast, NPK fertilizers, which provide nutrients for growth but do not address Fusarium pressure, have a significantly reduced yield of 13.87 t/ha when compared to biofertilizers. Finally, the R^2 (0.75) proves that our work could be used for healthy, sustainable tomato production.

Key words: biofertilizers, biopesticides, Burkina Faso, integrated management, tomato.

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Lutte intégrée contre les maladies causées par Fusarium chez la tomate (Solanum lycopersicum L.) au Burkina Faso

Résumé

La tomate (Solanum lycopersicum L.) est un légume économiquement important au Burkina Faso. Cultivée pour la consommation locale et l'exportation, la tomate contribue significativement à la sécurité alimentaire et nutritionnelle. Cependant, la faible fertilité des sols et les maladies constituent des contraintes pour sa production. En effet, les pertes de récoltes dues à la maladie du Fusarium peuvent être très élevées, ce qui impact négativement les rendements agricoles et les revenus. Une approche agroécologique a été adoptée pour lutter contre cette maladie et garantir une production durable de tomates. Une expérience de deux ans a été menée à l'aide d'un dispositif en Split plot avec quatre répétitions afin d'évaluer deux facteurs : (1) des biofertilisants pour restaurer la fertilité des sols et (2) des biopesticides pour lutter biologiquement contre la fusariose. L'efficacité des biofertilisants a été comparée à celle du NPK. L'ensemble des traitements (compost, bokashi et formulations d'huiles essentielles), les résultats ont montré une réduction significative de l'impact du champignon. Le score moyen de la maladie de 1,5 observé avec les biofertilisants était nettement inférieur au score du témoin (4,25). Les résultats indiquent un rendement moyen plus élevé (16,16 t/ha) avec le compost, obtenu grâce à une lutte efficace contre le Fusarium. Le NPK, fournissant des nutriments pour la croissance mais ne traitent pas la pression du Fusarium, a un rendement nettement réduit de 13,87 t/ha par rapport aux biofertilisants. Enfin, le R2 (0,75) prouve que nos travaux pourraient être utilisés pour une production de tomates saine et durable.

Mots clés : biofertilisants, biopesticides, Burkina Faso, lutte intégrée, tomate.

Introduction

Tomato is an annual plant in the Solanaceae family, grown for its widely consumed fruit. Tomatoes are an excellent source of vitamins C, A, E and K which boost the immune system, promote iron absorption and protect against cardiovascular disease (NIKIÈMA *et al.*, 2011; Qiu *et al.*, 2022). In Burkina Faso, tomato production amounted to 313,578.14 tons from 18,243 ha in 2022 and was the most important vegetable crop, ahead of onions (FAOSTAT, 2023). Over the past three years (2020–2023), tomato production in Burkina Faso has experienced notable fluctuations. According to available data, the production volume increased significantly, rising from approximately 281,000 tons in 2020 to 313,580 tons in 2022, marking a 7.55% increase from 2021 and an overall 11.59% growth over three years (FAOSTAT, 2023). Despite this growth, production levels remain influenced by challenges such as limited irrigation infrastructure, soil degradation, and pest-related losses (FAOSTAT, 2023; SCHIFFERS, 2011). Despite its importance, the tomato is susceptible to several fungal diseases, including Fusarium wilt. Losses due to *Fusarium* are significant both in the field and under glass (NUSRET *et al*., 2004). In managing this disease, most farmers apply significant, often excessive, amounts of phytosanitary products, some of which are highly toxic (SON *et al*., 2018). As a result, some of the most toxic pesticides commonly used to protect cotton crops are also applied to tomato crops (TARNAGDA *et al*., 2017).

Consequences include poisoning of applicators and animals, exposure of consumers to residues in harvested products, and environmental pollution (LEHMANN *et al*., 2018). To find an alternative to this situation, an agro-ecological approach to Fusarium wilt management is being considered, using the effects of biofertilizers and biopesticides. Indeed, *Fusarium* is a soil-borne pathogenic fungus that thrives in soil and affects a wide range of plants, causing significant agricultural losses. Its soil-borne life is intricate, involving multiple stages and interactions with its environment. The capability to reside in the soil, surviving as dormant or active spores (macroconidia, microconidia, and chlamydospores), enables the fungus to be resilient and persist in the absence of a host for several years. *Fusarium* can also grow on crop residues or woods left in the soil, promoting its multiplication and spread (PÉREZ-GARCÍA *et al*., 2011; LUGTENBERG *et al*., 2013). Biofertilizers are composed of living microorganisms that colonize the rhizosphere, promoting plant growth through natural biological processes. These microorganisms convert insoluble soil nutrients into soluble forms, facilitating their uptake by plants. Examples include processes like rock phosphate solubilization and nitrogen fixation (GEISER *et al*., 2021). The beneficial microorganisms in biofertilizers improve soil microflora, enhance soil health, support plant growth, and provide protection against pests and diseases. Key microbial inoculants used in biofertilizers include nitrogen-fixing bacteria, phosphate-solubilizing bacteria, sulfur and zinc solubilizers (e.g., Vesicular-Arbuscular Mycorrhizae, VAM), and plant growth-promoting rhizobacteria (PGPR) (SEENIVASAGAN *et al*., 2021; DEEPAK *et al*., 2014). Biopesticides, including essential oils, are increasingly recognized as effective natural solutions against soil-borne pathogens like *Fusarium*. Essential oils such as thymol, eugenol, Lippia, Cymbopogon, Ocimum and citronella have demonstrated antifungal activity by disrupting fungal cell membranes and metabolic processes (SOGOBA, 2022). In addition, essential oils are gaining traction as eco-friendly biopesticides. For instance, studies by (ZAKER, 2016) and (MITHILA, 2024) highlighted the potential of clove oil and tea tree oil in reducing *Fusarium* infection in crops like tomatoes and wheat. The antifungal activity of these oils complements microbial strategies, offering a comprehensive, sustainable approach to pest and disease management.

In this context, the main objective of this study is to find a sustainable solution to control fusariosis. It aims to combine biofertilizers and biopesticides to reduce the pathogenicity of the fungus and significantly increase tomato yield, while respecting the environment.

Material and methods

Study site

Field Location: The study was conducted in the central zone of the country, exactly in Ouagadougou, geolocated at 12°19'49.0" north latitude and 1°32'32.9" west longitude. The site is located in a northern Sudanese climate, with annual rainfall ranging between the isohyets 600-900 mm per year. The soil is sandy-loam with the estimated proportion 30% content of sand and 70% loam.

Plant material: The biological material consisted of 04 hybrid tomato varieties: PETOMECH (V1), UC 82 B (V2), COBRA 26 (V3) and MONGAL (V4). The PETOMECH variety is tolerant of verticillium wilt; UC 82 B is tolerant of verticillium wilt and stemphylliosis; COBRA 26 is tolerant of Bacterial Wilt and TYLCV (Tomato Yellow Leaf Curl Virus); and MONGAL is tolerant of Bacterial Wilt (TECHNISEM, 2016). An onion variety (PREMA) was used to allow a mycorrhizal association with the tomato varieties, aiming to strengthen the root system.

Fertilizers used

The biofertilizers used were compost, bokashi, and manure, both before and after transplanting. The association of mycorrhizotrophic plants with tomatoes was used in the nursery. The mineral fertilizer used as a control was NPK. For the production of biofertilizers, biodegradable materials obtained from farmers were used. These include manure, *Albizia lebbeck* leaves, poultry droppings, ash, clay, rice husks, maize bran, charcoal powder, straw, baker's yeast, sugar and water.

Essential oils of *Lippia multiflora*, *Cymbopogon citratus* and *Ocimum basilicum*, extracted using the hydrodistillation technique, were used for foliar treatment.

Methodology

Nursery: The nursery plots were set up as raised beds, 20 cm high and 1 m² in surface area, separated by a 0.5 m alley. To sterilize and disinfect the soil from telluric micro-organisms, each plot was sprayed with 10 liters of boiling water. The plots were then covered with black plastic sheeting for 24 hours to preserve and optimize the effect of the heat. Tomato seedlings were sown in furrows 20 cm apart in each plot. In each furrow, a total of one hundred (100) seeds including seventy (70) seeds of the tomato variety combined with thirty (30) seeds of a mycorrhizotrophic plant (onion) were shown in order to facilitate mycorrhization. The seedlings were watered daily and kept in the nursery for 28 days before transplanting.

Experimental design

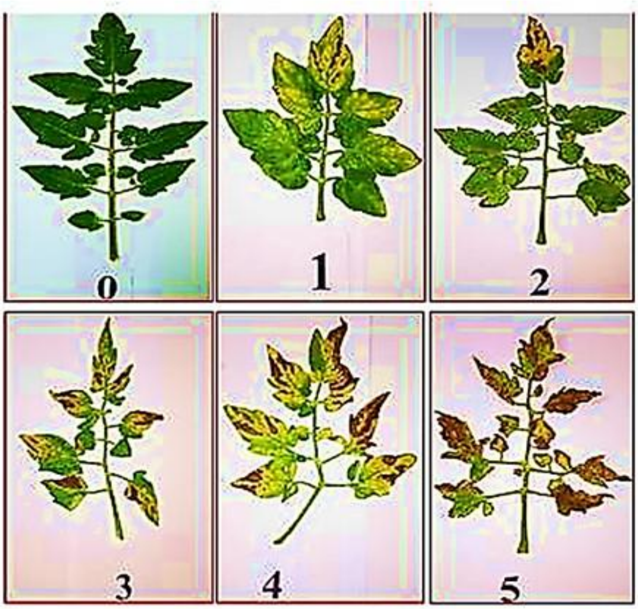
The experimental design used was a Split-plot design with four replications with factor 1 being tomato varieties and factor 2 being fertilization and essential oil formulatios, on four replications.

The plot size was 2.4 m x 2 m, and each replicate had a total of five plots, including the control, giving 20 plots for the four replicates. These replicates were separated from each other by 0.5m and 4 parallel rows were established on the plots to accommodate our four varieties with a distance of 0.5m between the rows. the following treatments were applied:

the control no fertilizer (T0), Compost (T1), Bokashi (T2), Organic manure (T3), and chemical fertilizer-NPK (T4). Each biofertilizer was associated with a biopesticide formulation (F1 applied first, then F2) to evaluate their role in managing *Fusarium* in tomato production.

Setting up and running the trial: Setup process began with weeding and deep plowing one month prior to transplanting on field. The individual plots were then prepared and well-leveled to ensure even distribution of fertilizer. Six pockets were planted in each row, with one tomato plant per pocket and a distance of 0.4 m between the pockets. In terms of fertilizer rates used for amendments, 2.5Kg/m^2 was used for Compost, Bokashi and organic manure before transplanting, 1.5Kg/m^2 at flowering and fruiting, and NPK was applied at a rate of 45g/m^2. Weeds in the plots were removed to clean the plots before they were plowed and thereafter, each soil amendment was applied. Amended plots were watered for 3 days before drilling to promote microbial activity and decomposition.

The essential oil formulations, F1 and F2, were used as biopesticides to control pathogens, particularly tomato Fusarium. The F1 formulation was prepared by mixing 5mL of Lippia multiflora and 3 mL of Cymbopogon citratus in 5 L of water. Formulation F2 was obtained by mixing 5 mL *of Lippia multiflora* and 3mL of Ocimum basilicum in 5L of water. Five mL of glycerine was added to each formulation to dilute the oils and facilitate their mixing with the water. The applications of the formulations were scheduled based on the vegetative stages of the crops and the appearance of fusariosis symptoms. These symptoms were observed and graded using the 5-point disease severity grading scale proposed by (PANDEY *et al*., 2003) (Figure 1).



0 No infection

1 One or two necrotic spots on a few of the plant's lower leaves, covering **1- 10%** of the plant's leaf surface
2 A few isolated spots on the leaves, covering **11-25% of** the plant's leaf surface
3 Many spots have coalesced on the leaves, covering **26-50% of the** plant's leaf surface.
4 Irregular, shattered leaves and submerged lesions with prominent concentric rings on the petiole, stem and fruit; covering **51-75% of** the plant's leaf surface.
5 Entire plants are wiped out, and leaves and fruit begin to fall off, covering more than 75% of the plant's leaf surface.

Figure 1 : Disease score scale and description of the scale.

Observations and parameters measured: Observations and measurements were conducted to assess the severity of fusariosis disease, plant size and tomato fruit yield. In the nursery, the size of the seedlings for each variety was assessed by selecting and fixing 12 seedlings per variety, measuring them with a tape measure. The data from the seedlings was recorded. After transplanting, parameters such as plant height and fusarium disease scores were evaluated every 20 DAT (Days After Transplanting) based on the type of fertilizer variety. Measurements were carried out by selecting three plants of each variety from an elementary plot. Disease severity was assessed using the six-point rating scale (0-5) described by (PANDEY *et al.*, 2003), where each score corresponds to a specific level of disease intensity.

Assessments were conducted at 21, 28, and 35 days after transplanting. Based on these severity ratings (Symptom Assessment Scale), disease incidence (DI) was calculated following the formula of (SONG *et al.*, 2004).

$$\text{DI (\%)} = \frac{\sum(\text{Values } \times \text{Number of infedted plants})}{(\text{Highest value } \times \text{Total number of plants}} \times 100$$

Fruit yield was calculated by multiplying the harvest weight of each variety in the elementary plot by the harvest weight of the 1 ha area divided by the area of the elementary plot.

$$\boldsymbol{Yield} = \frac{\boldsymbol{harvest\ weight\ of\ each\ variety}}{\boldsymbol{area\ of\ the\ elementary\ plot}}\ \textbf{X 1 ha}$$

Data analysis

SAS software was used for analysis and graphing. The means and standard errors were performed to compare seedlings sizes, to visualized differences between Fusarium disease severity according to the treatments and to implement yield variability from a treatment to another through the graphic. The means variances of the different treatments were compared using the Tukey test at a confidence level of 95%.

Results

Effects of the tested factors on the different tomato parameters measured

The analysis of variance showed that fertilization had a significant effect on yield ($P < 0.0001$), disease aggressiveness at 60 days after transplanting (DAT) ($P < 0.0001$) and 80 DAT ($P < 0.0001$), as well as plant height at 40 DAT ($P < 0.0085$), 60 DAT ($P < 0.0069$), and 75 DAT ($P < 0.0015$) (Table 1).

Concerning fertilization effect on yield, T1(10.84 t/ha) and T4 (10.54 t/ha) had the highest values, and the control T0 (1.94 t/ha) got the lowest value (Figure 4). T3 (9.95 t/ha) and T2 (8.56 t/ha) had intermediate values. For the fertilization effect on disease aggressiveness at 60 days, T0 (2.62) had the highest disease score mean, and T4 (0.68) had the lowest disease score. T3 (1.18), T2 (1.00) and T1 (0.75) had intermediate disease score means. Fertilization effect on disease aggressiveness at 80 days showed that T0 (4.00) had the highest disease score mean, T4 (2.00) and T3 (0.75) had the lowest disease score means (Figure 3). T2 (2.25) and T1 (2.06) had intermediate disease score means. Fertilization effect on plant height at 40 DAT showed that T4 (43.68 cm) got the highest height mean, T0 (31.87 cm) and T3 (31.57 cm) had the lowest height values (Figure 2). T1 (38.29 cm) and T2 (36.87 cm) had intermediate heights. At 60 DAT, T4 (63.20 cm) had the highest mean height, while T0 (52.36 cm) and T3 (50.26 cm) had the lowest. T1 (59.36 cm) and T2 (56.63 cm) had intermediate heights. Finally, at 75 DAT, T4 (66.45 cm) got the highest height mean while application of T0 (52.13 cm) had the lowest height values. T1 (63.11 cm), T2 (61.58 cm) and T3 (57.38 cm) had intermediate heights.

Only yield ($P < 0.0004$), plant height at 60 DAT ($P < 0.0001$), and 75 DAT ($P < 0.0001$) were significantly affected by the variety (Table 1). For the variety effect on yield, V3 (10.89 t/ha) had the biggest values and V1 (6.34 t/ha) got the lowest value (Figure 6). V2 (9.95 t/ha) and V4 (10.54 t/ha) had intermediate values. Additionally, at 60 DAT, V3 (66.20 cm) had the highest mean height compared with V4 (54.67 cm), V1 (54.42 cm), and V2 (50.62 cm). Yet, at 75 DAT, V3 (71.02 cm) got the highest height mean compared with V1 (59.06 cm), V4 (56.41 cm) and V2 (54.03 cm).

Table I: Probabilities of significance for the factors tested on different tomato parameters measured

Factor	Evaluated parameters	P-value	Significance
Fertilizer (T)	Yield	P < 0.0001	Significant
Fertilizer (T)	Plant height at 40 DAT	P < 0.0085	Significant
Fertilizer (T)	Plant height at 60 DAT	P < 0.0069	Significant
Fertilizer (T)	Plant height at 75 DAT	P < 0.0015	Significant
Fertilizer (T)	Disease rating at 40 DAT	P < 0.5006	Not significant
Fertilizer (T)	Disease rating at 60 DAT	P < 0.0001	Significant
Fertilizer (T)	Disease rating at 80 DAT	P < 0.0001	Significant
Variety (V)	Yield	P < 0.0004	Significant
Variety (V)	Plant height at 40 DAT	P < 0.1256	Not significant
Variety (V)	Plant height at 60 DAT	P < 0.0001	Significant
Variety (V)	Plant height at 75 DAT	P < 0.0001	Significant
Variety (V)	Disease rating at 40 DAT	P < 0.1256	Not Significant
Variety (V)	Disease rating at 60 DAT	P < 0.7556	Not Significant
Variety (V)	Disease rating at 80 DAT	P < 0.3361	Not Significant

Effect of biofertilizers on tomato growth

The height of the tomato plants in the different treatments changed over time. In the trial (Figure 2), the effect of fertilizers was significant in plant height at 40^{th} , 60^{th} and at 80^{th} days after transplanting. Fertilization effect on plant height at 40 DAT showed that T4(Compost with 43.68 cm) got the highest height mean, T0 (Control with 31.87 cm) and T3 (Manure with 31.57 cm) had the lowest height values. T1 (38.29 cm) and T2 (36.87 cm) had intermediate heights. At 60 DAT, T4 (63.20 cm) got the highest height mean, T0 (52.36 cm) and T3 (50.26 cm) had the lowest height values. T1 (59.36 cm) and T2 (56.63 cm) had intermediate heights. Finally, at 75 DAT, T4 (66.45 cm) got the highest height mean while application of T0 (52.13 cm) had the lowest height values. T1 (63.11 cm), T2 (61.58 cm) and T3 (57.38 cm) had intermediate heights.

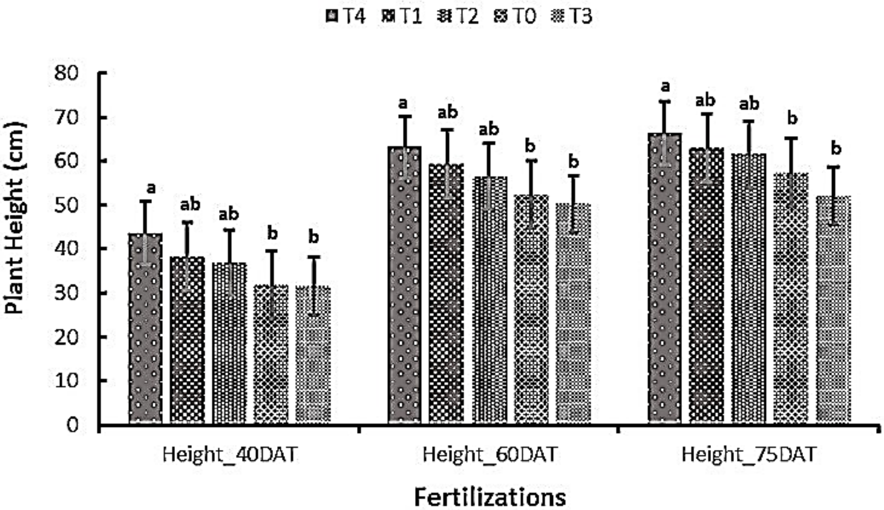


Figure 2: Effect of fertilization treatments (T0 to T4) on tomato plant height at 40; 60 and 75 days after transplanting (DAT). Error bars represent standard deviation.

T0=Control, T1=Compost, T2=Bokashi, T3=Organic manure, T4=NPK, V1=Petomech, V2=UC82, V3=Cobra, V4=Mongal, DAT= Days After Replanting, the bagplots with the same letter are not significantly different at the 5% threshold according to the Student-Newman-Keuls test and the Tukey and Fisher pairwise comparison at 95%.

Effect of fertilizers on Fusarium disease in tomatoes

Figure 3 shows the evolution of Fusarium disease in the trial. There was significant difference between plants that received fertilizers associated with oil formulations and the control 60th and 80th days after transplanting ($p \leq 0.0001$). For fertilization effect on disease aggressiveness at 60 days, the Control T0 (2.62) had the highest disease score mean and Compost T4 (0.68) had the lowest disease score. T3 (1.18), T2 (1.00) and T1 (0.75) had intermediate disease score means. Fertilization effect on disease aggressiveness at 80 days showed that Control T0 (4.00) had the highest disease score mean, Compost T4 (2.00) and Manure T3 (0.75) had the lowest disease score means. T2 (2.25) and T1 (2.06) had intermediate disease score means.

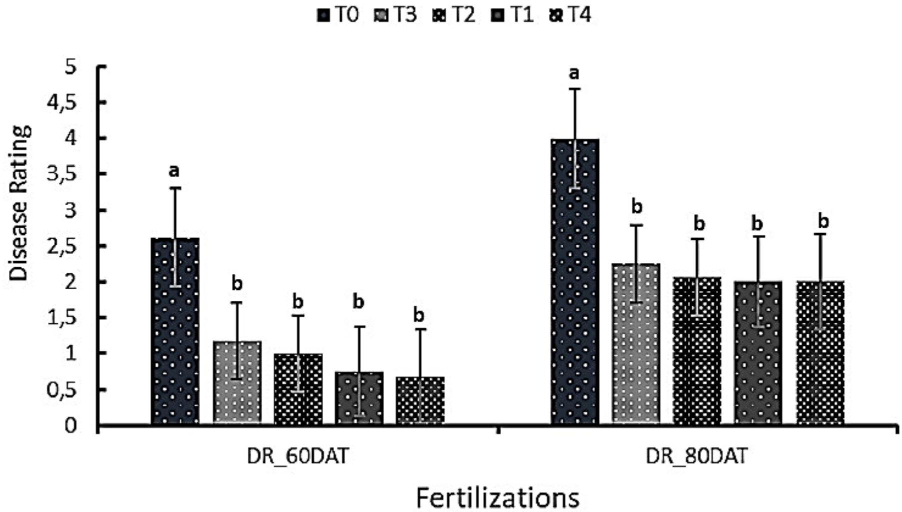


Figure 3: Effect of fertilization treatments (T0 to T4) on disease aggressiveness (DA) at 60 and 75 days after transplanting (DAT).

Error bars represent standard deviation ; T0=Control, T1=Compost, T2=Bokashi, T3=Organic manure, T4=NPK, V1=Petomech, V2=UC82, V3=Cobra, V4=Mongal, DR= Disease Rating, DAT= Days After Transplanting, the means followed by the same letter are not significantly different at the 5% threshold according to the Student-Newman-Keuls test and the Tukey pairwise comparison at 95%.

Effect of fertilizers on tomato fruit yield

The difference between tomato fruit yields of the treatments and the control was highly significant ($p \leq 0.0001$) due to fertilizers (Figure 4). Concerning fertilization effect on yield, T1(10.84 t/ha) and T4 (10.54 t/ha) had the highest values, and the control T0 (1.94 t/ha) got the lowest value. T3 (9.95 t/ha) and T2 (8.56 t/ha) had intermediate values.

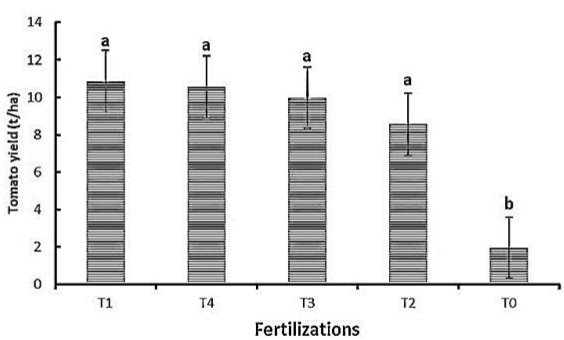


Figure 4: Effect of fertilization treatments (T0 to T4) on tomato yield.
Error bars represent standard deviations

Error bars represent standard deviation ; T0=Control, T1=Compost, T2=Bokashi, T3=Organic manure, T4=NPK, V1=Petomech, V2=UC82, V3=Cobra, V4=Mongal, DR= Disease Rating, DAT= Days After Transplanting, the means followed by the same letter are not significantly different at the 5% threshold according to the Student-Newman-Keuls test and the Tukey pairwise comparison at 95%.

Effect of varieties on tomato growth

The different tomato varieties had significant effect on tomato plants height during the experimentation (Figure 5). In fact, there was significant variability in height between tomato varieties at 60th and 80th days after transplanting ($p \leq 0.0001$). About plant height at 60 DAT, V3 (66.20 cm) got the highest height mean compared with V4 (54.67 cm), V1 (54.42 cm) and V2 (50.62 cm). Yet, at 75 DAT, V3 (71.02 cm) got the highest height mean compared with V1 (59.06 cm), V4 (56.41 cm) and V2 (54.03 cm).

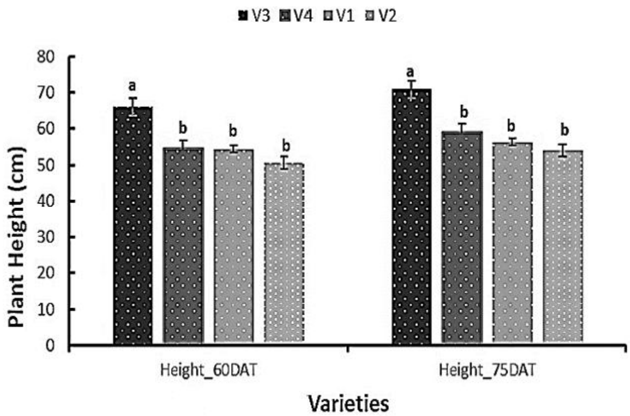


Figure 5: Effect of varieties (V1 to V4) on tomato plant height at 60 and 75 days after transplanting (DAT). Error bars represent standard deviations

Error bars represent standard deviation ; T0=Control, T1=Compost, T2=Bokashi, T3=Organic manure, T4=NPK, V1=Petomech, V2=UC82, V3=Cobra, V4=Mongal, DR= Disease Rating, DAT= Days After Transplanting, the means followed by the same letter are not significantly different at the 5% threshold according to the Student-Newman-Keuls test and the Tukey pairwise comparison at 95%.

Effect of varieties on tomato fruit yield

According to tomato varieties, the difference between tomato fruit yields was highly significant ($p \leq 0.0001$). The fruit yield varied from one variety to another (Figure 6). For the variety effect on yield, V3 (10.89 t/ha) had the biggest values and V1 (6.34 t/ha) got the lowest value. V2 (9.95 t/ha) and V4 (10.54 t/ha) had intermediate values.

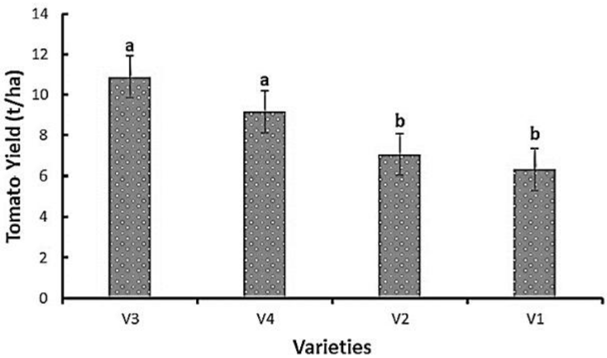


Figure 6: Effect of varieties (V1 to V4) on tomato yield. Error bars represent standard deviations.

T0=Control, T1=Compost, T2=Bokashi, T3=Organic manure, T4=NPK, V1=Petomech, V2=UC82, V3=Cobra, V4=Mongal, DR= Disease Rating, DAT= Days After Transplanting, the means followed by the same letter are not significantly different at the 5% threshold according to the Student-Newman-Keuls test and the Tukey pairwise comparison at 95%.

Discussion

The study showed that biofertilizers combined with essential oil-based formulations reduced the pathogen's impact on tomatoes. In fact, the growth of plants treated with biofertilizers was higher than that of control plants throughout the trial. The variation in plant height, pathogen control, and yield across the treatments can be attributed to the synergistic effects of biofertilizers and essential oil-based formulations. Biofertilizers provide sustained nutrient release, enhance rhizosphere microbial diversity, and stimulate plant physiological processes (MĄCIK *et al*., 2020). This supports robust vegetative growth and improves plant resilience against stress factors, explaining the superior growth and yield in treated plants compared to the control. Our results are in line with those of (GARANE *et al*., 2019), (SAWADOGO *et al*., 2021), and (WALSH, 2024), who argued that biofertilizers promote good growth in tomato. The work of (KOTAIX *et al*., 2019) also showed that T4 promotes tomato growth. Regarding the effect of formulations on *Fusarium*, the effectiveness of essential oil-based formulations against *Fusarium* is linked to their bioactive compounds, such as terpenes and phenolics, which disrupt fungal cell membranes and inhibit pathogen proliferation (DERAVEL *et al*., 2014). These antifungal properties likely complemented the nutrient-enhancing effects of biofertilizers, resulting in lower pathogen aggressiveness scores. Differences among treatments may also reflect variations in formulation concentration, application methods, or plant variety responses. Authors such as (SON *et al*., 2018), (KOTAIX *et al*., 2019), and (ALVES *et al*., 2018) have also demonstrated the efficacy of essential oils against Fusarium. (SIRIMA *et al*., 2020) showed in their work the inhibitory activity of these essential oils against tomato arternariosis. Similarly, (SOGOBA *et al*., 2024) observed the antifungal activity of the same essential oil-based formulations against Fusarium on onion. The tomato fruit yield analysis revealed that all treatments produced higher yields than the control. The enhanced post-harvest quality of biofertilizer-treated tomatoes highlights the role of balanced soil nutrition in influencing cell wall strength and metabolic stability. Unlike synthetic fertilizers, which may cause rapid but unsustainable growth, biofertilizers support gradual nutrient uptake, promoting healthier, more durable fruits. The extended shelf life of biofertilizer-treated fruits aligns with these effects, while the faster deterioration of NPK-treated fruits likely reflects nutrient imbalances that favour rapid senescence (JURADO *et al*., 2019; SHARMA *et al*., 2017). (GARANE *et al*., 2019) have also shown that biofertilizers such as Compost and Bokashi contribute to higher tomato yields. (ADEDEJI *et al*., 2020) carried out studies on tomato fruit firmness and showed that fruit quality varies according to certain factors such as soil fertilization. The study also confirms the tomato variety significantly influences both plant height and fruit yield. Variations in plant height among varieties likely reflect genetic differences in growth vigour, internode length, and hormonal regulation (SANCHEZ *et al*., 2014). Taller plants may exhibit enhanced light interception, though height alone does not guarantee higher yield. Yield differences among varieties were also statistically significant. These disparities can be attributed to factors such as flower production, fruit set efficiency, and biomass partitioning. Some shorter varieties still achieved high yields, indicating that reproductive efficiency plays a more crucial role than vegetative growth alone. These results align with earlier findings that emphasize the importance of variety selection in tomato production systems (ADEDEJI *et al*., 2020). Site-specific evaluation remains essential for selecting high-performing varieties under local agro-ecological conditions. Furthermore, the coefficients of determination (R2) obtained from the analysis of variance of the trial data mainly were greater than 0.7 and closer to 1. This high coefficient indicates that the observed differences are not random but instead result from the systematic influence of the treatments. These differences underscore the efficacy of integrating biofertilizers and essential oils into agricultural practices, with each treatment's success dependent on its ability to balance nutrient delivery, pathogen suppression, and overall plant health.

Conclusion

The aim of our work was to implement an agro-ecological method, using biofertilizers and biopesticides, to overcome the damage and economic losses associated with the spread of *Fusarium*. The results highlight the significant potential of combining biofertilizers with essential oil-based formulations to mitigate Fusarium's impact on tomato plants while enhancing growth, yield, and post-harvest quality. Biofertilizers improved plant growth and yield by promoting nutrient availability and microbial diversity in the rhizosphere, whereas essential oils effectively suppressed pathogen aggressiveness through their antifungal properties. As for NPK, although it accelerates tomato growth, its impact on fruit shelf life and soil sensitivity makes it a last resort. To complete and strengthen the present study, the active components of the formulations could be isolated, registered, and made available to market gardeners. The use of biofertilizers and essential oil-based biopesticides presents a viable alternative to chemical inputs, promoting agricultural sustainability and environmental health. Future studies should focus on optimizing application methods and exploring their broader applicability across different crops and environments to maximize benefits.

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Author Contribution

MS collected the data; MS, KHS and HS managed laboratory works; SP and MK helps to analyze the data; SP drafted and corrected the manuscript; KK supervised all the work.

Conflict of Interest

All authors declare no conflict of interest.

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