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Application of mycorrhiza biofertilizer and bio-ameliorants in improving growth of tomato under water saturation

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ABSTRACT

The transition period in tropical riparian wetland areas involves alternating drought and flooding. During this period, the land can be used for vegetable cultivation, such as tomato, but unpredictable rhizosphere water saturation often induces transient anaerobic conditions that limit root function and nutrient uptake. Therefore, this study aims to evaluate the growth of tomato plants in tropical riparian wetland areas using mycorrhizal biofertilizers and bio-ameliorants at various levels of water-saturated rhizosphere. A factorial design was used with 2 factors, namely levels of water-saturated rhizosphere as well as the doses of mycorrhizal biofertilizers and bio-ameliorants. The results showed that tomato plants exposed to water saturation experienced more favourable growth when treated with 15 g of mycorrhizal biofertilizers per plant, 120 g of goat manure, and 80 g of rice husk charcoal per plant. The impact of the treatment on tomato plant growth was observed for 4 days after stress and 2 weeks after recovery. Increases were observed in plant height (approximately 30–40%), leaf number (60–70%), and root length (30–35%) compared to the control. The effect of a water-saturated rhizosphere was reflected in the reduction in dry matter accumulation of all plant organs. Meanwhile, the application of biofertilizers and bio-ameliorants under water-saturated conditions increased total dry matter relative to untreated plants. The results showed that tomato cultivation in tropical conditions was optimally supported under field capacity, and to a lesser extent in partial waterlogging. This was achieved by the combined application of 15 g plant^{-1} mycorrhizal biofertilizer and 200 g plant^{-1} bio-ameliorant, which resulted in the greatest improvements in growth and biomass.

Keywords: Dry matter, Rice husk, *Solanum lycopersicum*, Tropical wetland, Waterlogging.

Aplicação de biofertilizante micorrizário e bioameliorantes em tomates em solo saturado de água

RESUMO

Num ambiente de zona húmida ribeirinha tropical, o período de transição é caraterizado pela alternância entre períodos de seca e inundações. Durante este período, a terra pode ser utilizada para o cultivo de vegetais, como tomates. Contudo, a saturação imprevisível da água na rizosfera pode induzir condições anaeróbicas transitórias que limitam a função das raízes e a absorção de nutrientes. Portanto, o presente estudo avaliou o crescimento de plantas de tomate em ambiente húmido, com características tropicais, utilizando biofertilizantes micorrízicos e bioameliorantes em diversos níveis de rizosfera saturada hídricamente. O estudo adotou um delineamento fatorial com dois fatores: níveis de rizosfera saturada de água como primeiro fator e doses de biofertilizantes micorrízicos e bioameliorantes como segundo fator. Os resultados obtidos demonstraram que as plantas de tomate expostas à saturação hídrica apresentaram um crescimento mais favorável quando sujeitas a 15 g de biofertilizantes micorrízicos por planta, bem como a 120 g de estrume de cabra e 80 g de carvão de casca de arroz por planta. O impacto dos biofertilizantes micorrízicos e bio-ameliorantes no crescimento das plantas de tomate foi observado quatro dias após o stress e duas semanas após a recuperação, conforme indicado pelos aumentos na altura das plantas (aproximadamente 30-40%), número de folhas (60-70%) e comprimento das raízes (30-35%) em comparação com o controle. O efeito de uma rizosfera com elevado teor de água resultou numa redução da acumulação de matéria seca em todos os órgãos da planta. Em contrapartida, a aplicação de biofertilizantes e bioameliorantes em condições de saturação hídrica promoveu um aumento da matéria seca total em comparação com as plantas não sujeitas a tratamento. Consequentemente, o cultivo de tomate em regiões tropicais é otimizado sob capacidade de campo e, em menor grau, sob alagamento parcial, pela aplicação combinada de

15 g por planta de biofertilizante micorrízico e 200 g por planta de bio-ameliorante, o que resultou nas maiores melhorias no crescimento e na biomassa.

Palavras-chave: Casca de arroz, Inundações, Matéria seca, *Solanum lycopersicum*, Zona húmida tropical.

1. Introduction

The rapid increase in population has led to a rise in food demand in Indonesia. However, this increase has not been accompanied by a corresponding increment in the amount of land available for food production. A potential avenue for expansion involves the exploitation of riparian wetland areas that are currently underutilized. Several studies have shown that these areas exhibit a range of characteristics and potential uses. Therefore, the development strategy must be demand-driven (Lakitan et al., 2018; 2019), prioritizing technological innovations that are technically relevant, economically affordable, and expected to be in line with the local culture, as well as based on the principles of sustainable agriculture (Lakitan et al., 2019).

In the majority of riparian wetland areas, particularly in South Sumatra, management practices remain disorganized and fragmented (Lakitan et al., 2019), with interventions being implemented in a piecemeal and sectoral manner, often with a centralized approach. Consequently, agricultural activities in this landscape are strongly constrained by land topography, specifically variations in water table depth, which determine the feasibility of crop cultivation (Qurani and Lakitan, 2021). The utilization of these areas for agricultural purposes remains constrained at present, with cultivation being predominantly focused on the primary crop, rice. A previous study showed that vegetable cultivation remains comparatively restricted, including tomato, which is a significant horticultural commodity. Tomato (*Solanum lycopersicum* L.) is one of the most important horticultural commodities globally due to its high production value, significant economic role in providing year-round income for farmers (Bhandari and Adhikari, 2024). In addition, it contributes substantially to human nutrition as a rich source of vitamins, phytochemicals, and antioxidants (Giri et al., 2025).

The current low production of vegetable crops is primarily attributable to the absence of an appropriate cultivation system, particularly in conditions of waterlogging. During the transition period, the water dynamics begin with dry soil conditions, progress to field capacity, then total saturation, and ultimately result in flooding. The most effective solution to this challenge is the implementation of cultivation strategies that enhance the tolerance of vegetable crops to waterlogged conditions (Zhang et al., 2025). The primary factor contributing to the decline in cultivation on tropical wetland areas is the high risk of crop loss due to waterlogging during the transition period (Siaga et al., 2019b).

The enhancement of the tolerance of vegetable crops to conditions of waterlogged soil can be achieved through the implementation of mycorrhizal biofertilizers. In addition to playing a pivotal role in the efficient uptake of mineral nutrients and water through colonization and hyphal spread, mycorrhizae also help to protect roots from abiotic stress factors (Muis et al., 2016). The inoculation of vegetable plants with Arbuscula mycorrhizal fungi (AMF) has been showed to serve as a protective measure (Malhi et al., 2021). In conditions of hydric stress, the mycorrhizal fungal activity has been documented as a bioindicator of plant tolerance. This phenomenon occurs through the process of water absorption, facilitated by aquaporin (APQ) expression in plant roots (Cheng et al., 2021) and regulated by osmotic pressure and the modulation of plant physiology (Wei et al., 2024).

The cultivation of plants in waterlogged conditions through the application of mycorrhiza has also been proven effective in soybeans (Malhi et al., 2021), citrus fruits (Cheng et al., 2021), and tomato. Mycorrhizal inoculation with *Rhizophagus irregularis* enhanced root water transport and increased physiological tolerance to flooded or waterlogged conditions compared to non-inoculated plants (Calvo-Polanco et al., 2014). The use of soil amendments as soil improvers is imperative to facilitate the cultivation of vegetable crops. The addition of soil amendments to waterlogged soils has been shown to have a significant impact on the pore structure, leading to an increase in porosity and connectivity for facilitating the movement of air and water (Xuan et al., 2023; Wang et al., 2023).

The integration of mycorrhizal biofertilizer and soil amendment holds considerable promise as an effective technology for vegetable cultivation in waterlogged conditions during the transition period in riparian wetland areas. Therefore, this study aims to examine the growth response of tomato plants, which are frequently cultivated in riparian wetland areas, to waterlogged rhizosphere conditions through the application of mycorrhiza and bio-ameliorant.

2. Material and Methods

This study was carried out in the screen house and laboratory of plant physiology at Universitas Bina Insan in Lubuklinggau, South Sumatra, Indonesia 3.273888° S and 102.964784° E), from July to October 2024. The experiment began by preparing the growing medium and tomato seedlings over the course of 4 weeks. The Indonesian tomato variety (*Solanum lycopersicum*) used in this study was Gustavi F1, a hybrid type with good adaptation to low, medium, and high altitudes, released in 2019.

The preparation of seedlings entailed an initial soaking of the seeds in warm water for a duration of 1 hour. Subsequently, the seeds were germinated on a wet cloth until sprouts became visible. Seeds that had sprouted were planted in tray pots with planting media consisting of a mixture of topsoil and compost in a ratio of 3:1 (v/v) (Siaga et al., 2019b). Seeds with 4 leaves or approximately 4 weeks of development were transplanted into polybag planting media. Healthy tomato seedlings that had developed 4 leaves were used as the planting materials. The seedlings were subsequently transplanted into polybags, with a diameter of 17.5 centimetres and a height of 35 centimetres, which contained the designated growing medium.

This study was established under a Factorial Randomized Design (FRD) with 2 (two) factors. The first factor examined various levels of a water-saturated rhizosphere (WSR), while the second factor examined the doses of mycorrhizal biofertilizers + bio-ameliorants. The treatment required a water-saturated rhizosphere at 3 levels, namely field capacity/control (S0), partial waterlogging (S1), and full waterlogging (S2) (Figure 1).

Furthermore, 5 different doses of the designated mycorrhizal biofertilizers + bio-ameliorants (M) were observed, which consisted of mycorrhizal biofertilizers + bio-ameliorants as control (M0), and mycorrhizal biofertilizer at a dose of 10 g plant^{-1} (M1). Others included mycorrhizal biofertilizer at a dose of 15 g plant^{-1} (M2), bio- ameliorants at a dose of 200 g plant^{-1} (B), mycorrhizal biofertilizer at a dose of 10 g plant^{-1} + bio-ameliorants at a dose of 200 g plant^{-1} (M1+B), and mycorrhizal biofertilizer at a dose of 15 g plant^{-1} + bio-ameliorants at a dose of 200 g plant^{-1} (M2+B).

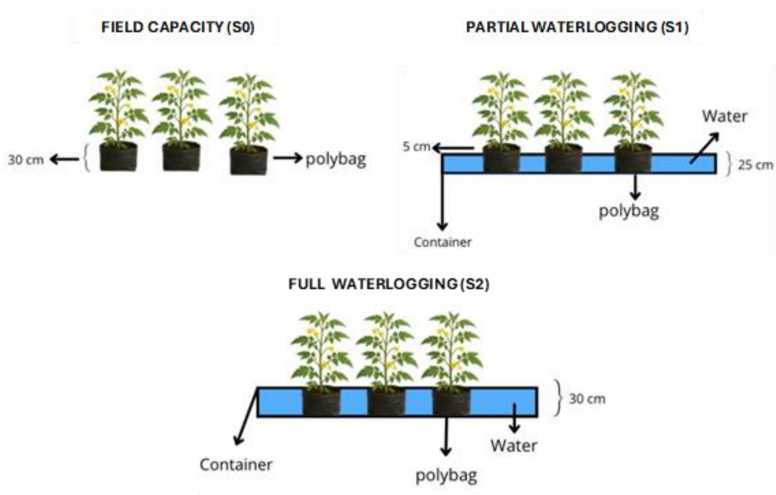

Figure 1. A simulation of water-saturated rhizosphere treatment.

The biofertilizer used in this study was a mycorrhizal product known as MZ2000, which was developed by the Indonesian company INAGRO. The bio-ameliorant used was 120 g of goat manure + 80 g of rice husk biochar per plant.

The water-saturated treatments were imposed 6 weeks after transplanting, corresponding to the early generative growth stage, under simulated conditions in a tropical riparian wetland. The treatments were maintained throughout the stress period and followed by a 2-week recovery phase. Plants under the field capacity (control) treatment were irrigated daily at approximately 08:00 h to maintain optimal soil moisture. Measurements of water pH, electrical conductivity (EC), and total dissolved solids (TDS) in the partial and full waterlogging treatments were recorded 4 days after treatment initiation, as shown in Figure 2.

The treatment with mycorrhizal biofertilizers commenced 1 week after transplanting, while the bio-ameliorants were administered 1 week before transplanting. A total of 18 treatment combinations were used, with 5 replicates each, resulting in a total of 90 tomato plants. The initiation of plant treatments was implemented at 6 weeks post-transplanting (DAT) (before WSR), with the termination of treatments occurring after 4 days of exposure (after WSR). Subsequently, a recovery period of 7 (recovery 1) and 14 days was allowed (recovery 2). On the final day of the recovery period (14 days), tomato plants from all treatments were harvested and observed.

The data collection covered tomato plant morphology, and the obtained growth data were categorized into 2 types of measurements, namely non-destructive and destructive.

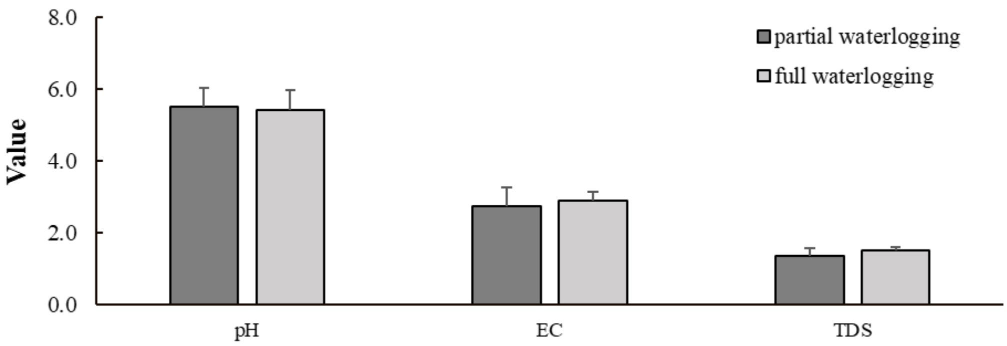

Figure 2. Value of pH, EC, and TDS of water in a container of partial and full waterlogging after 4 (four) days.

The non-destructive growth measurement dataset included several variables, such as plant height (PH), stem diameter (ST), and number of leaves (NoL). Meanwhile, the destructive measurements included root length (RL), root dry matter (RDM), stem dry matter (SDM), leaf dry matter (LDM), flower dry matter (FDM), and total dry matter (TDM). The collected data for the analysis of tomato plant growth covered several parameters, including the root weight ratio (RWR), stem weight ratio (SWR), leaf weight ratio (LWR), flower weight ratio (FWR), and shoot-to-root ratio (SRR). The dry weight of each plant organ was determined by drying it in an oven at 90 °C for 24 hours. The plant organs were trimmed to a reduced thickness before being placed in the oven to accelerate the drying process.

To determine when there were significant differences between the treatments, an analysis of variance (ANOVA) was performed. When the ANOVA showed significant differences ($p < 0.05$), the least squares difference (LSD) test was applied at a 5% probability to identify which treatments differed from each other in the water-saturated rhizosphere (first factor). Subsequently, Duncan's multiple range test (DMRT) was applied to compare the means of the mycorrhizal biofertilizers + bio-ameliorants application (second factor). All other analyses were performed using the SAS Academic Software, developed by SAS Institute Inc.

3. Results and Discussion

The early vegetative growth of tomato plants was analyzed by considering their morphological characteristics. This approach used non-destructive observation techniques, thereby facilitating the natural growth of plants. Water saturated rhizosphere (WSR) condition significantly reduced plant height, stem diameter, and leaf number of tomato plant field capacity (Figure 3). Across waterlogging treatments, plant height, stem diameter, and leaf number declined by approximately 20% under partial waterlogging and by up to 40 to 80% under full waterlogging relative to field capacity at the recovery stage (Table 2). These results showed that optimal soil moisture at field capacity promoted vegetative growth, while excess water strongly suppressed tomato development. Similar responses were reported previously, where tomato plants grown at field capacity (80-100% FC) enhanced the plant height, stem diameter, and leaf number compared to those under water stress or excess water conditions (Li et al., 2023).

The observed reduction in morphological characteristics under WSR was primarily associated with oxygen deficiency in the root zone, which hindered root respiration and nutrient uptake (Mohanty et al., 2020; Zhu et al., 2020). In this study, this stress was reflected in reduced shoot growth and leaf production (Figure 3).

Physiologically, waterlogging stress was known to decrease photosynthetic rates, increase foliar temperature, and alter leaf expansion dynamics, as well as induce aerenchyma formation in roots and reduce specific leaf fresh weight and water content (Meihana et al., 2023). These mechanisms were consistent with the growth suppression observed in our experiment.

During waterlogging, oxygen deficiency in the rhizosphere caused root hypoxia, decreased respiration, limited nutrient absorption, and oxidative stress (Pan et al., 2021; Alordzinu et al., 2024; Siaga et al., 2024). In this study, these physiological constraints translated into significant declines in plant height, stem diameter, and leaf number under both partial and full WSR (Table 2; Figure 3).

Application of mycorrhizal biofertilizers and bio-ameliorants significantly affected tomato growth under WSR conditions (Figure 3; Tables 1 and 2). Under partial waterlogging, mycorrhizal biofertilizer applied alone (M1 and M2) produced the greatest improvement in plant height, increasing height by approximately 15 to 20% compared with the untreated control at the recovery stage (Table 2). This showed that mycorrhizal colonization partially mitigated moderate waterlogging stress.

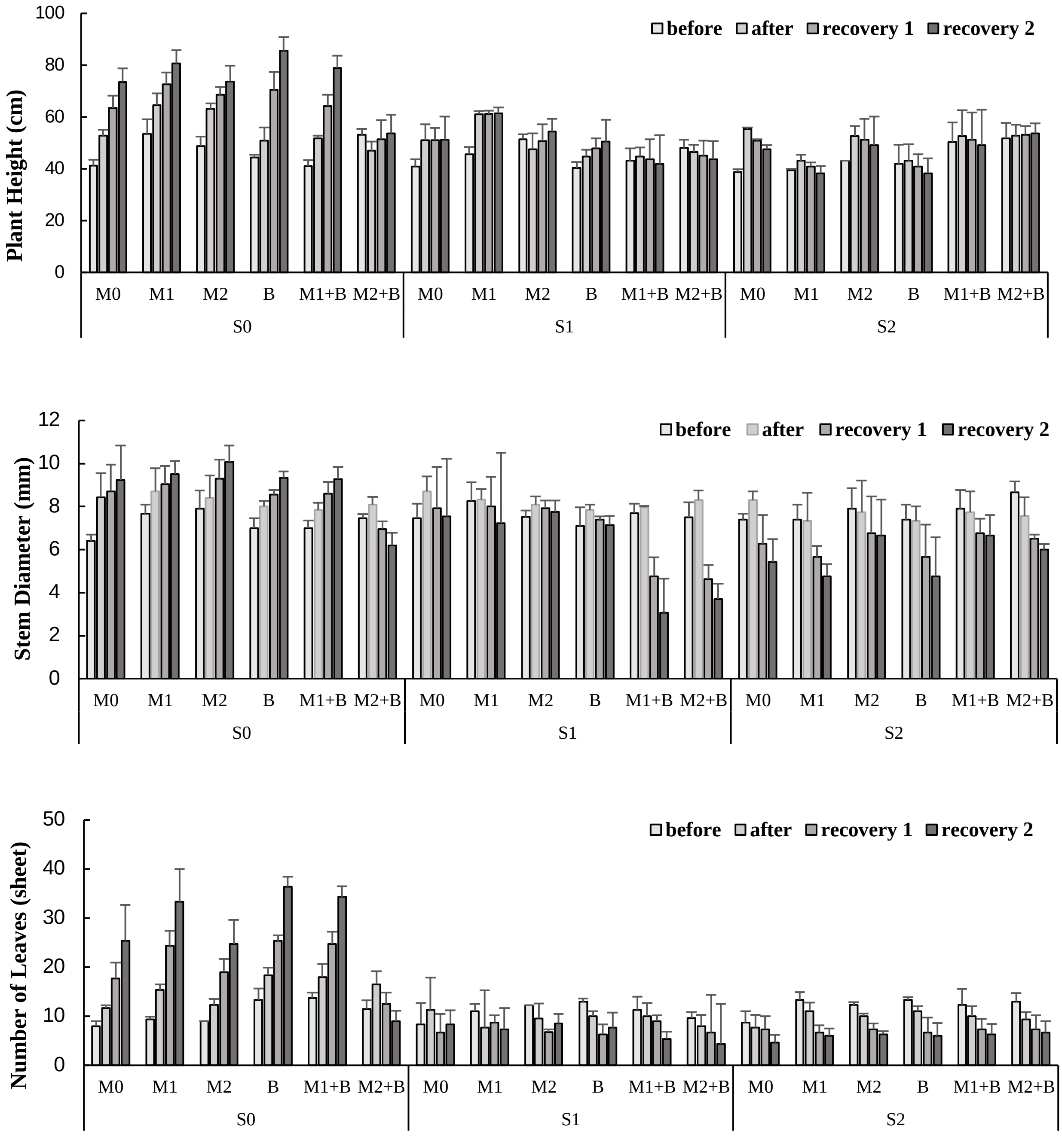

Figure 3. Effect of 3 levels of water-saturated rhizosphere (WSR) and mycorrhizal biofertilizer + bio-ameliorant application on plant height, stem diameter, and number of leaves of the tomato plant. S0 = field capacity; S1 = partial waterlogging; S2 = full waterlogging. M0= control, M1= mycorrhizal biofertilizer 10 g plant^{-1}, M2= mycorrhizal biofertilizer 15 g plant^{-1}, and B = bio-ameliorant 200 g plant^{-1}.

Table 1. Statistical calculation of the growth non-destructive parameters of the tomato plant treated with mycorrhizal biofertilizers + bio-ameliorant applications before and after exposure to water-saturated rhizosphere.

Traits	Water Saturated Rhizosphere (S)	Mycorrhizal Biofertilizers + Bio-ameliorant (MB)	S X MB
	Mean Square Value		
Before treatments			
Plant height	37.851^{ns}	133.446^{**}	54.925^{**}
Stem diameter	1.069^{ns}	0.530^{*}	0.531^{ns}
Number of leaves	0.463^{ns}	37.941^{**}	3.552^{ns}
After treatments			
Plant height	368.927^{**}	248.444^{**}	40.710^{ns}
Stem diameter	0.703^{ns}	1.183^{ns}	0.103^{ns}
Number of leaves	228.129^{**}	27.218^{*}	15.818^{ns}
After recovery			
Plant height	5728.258^{**}	180.831^{*}	67.549^{ns}
Stem diameter	90.659^{**}	5.834^{*}	2.398^{ns}
Number of leaves	3430.907^{**}	47.885^{*}	25.707^{ns}

**significantly different at $p \leq 0.01$; *significantly different at $p \leq 0.05$; ^{ns}: not significantly different at $p < 0.05$.

Under partial WSR, mycorrhizal biofertilizers – colonized plants were stimulated by enhanced nutrient uptake through the roots with more open membranes, shown to have enhanced root hydraulic conductance (Chowdhary and Songachan, 2025). In this experiment, these benefits were reflected in higher plant height and leaf number relative to non-inoculated plants (Figure 3). Mycorrhizal biofertilizers enhanced nutrient absorption and soil health to reduce the impact of suboptimal water condition stress (Xiao et al., 2023). However, under full waterlogging, mycorrhizal biofertilizers alone were insufficient to sustain vegetative growth. In this condition, the addition of bio-ameliorants improved soil aeration, nutrient balance, and soil aggregation, resulting in greater plant height compared with mycorrhizal application alone (Figure 3).

Table 2. Comparison of plant height, stem diameter, and number of leaves of tomato plants treated with mycorrhizal biofertilizers + bio-ameliorant applications before, after, and recovery time after exposure to water-saturated rhizosphere.

Treatments	Plant height (cm)			Stem diameter (mm)			Number of leaves (sheet)		
	Before	*After*	*Recovery*	*Before*	*After*	*Recovery*	*Before*	*After*	*Recovery*
Water saturated									
Field capacity	46.5 a^{z}	57.1 a	79.40 a	7.3	8.2	9.4 a	11.4	16.1 a	31.1 a
Partial waterlogging	44.9 ab	50.4 b	55.8 b	7.6	8.2	7.4 b	11.7	10.8 b	9.3 b
Fully waterlogging	44.3 b	49.3 b	45.7 c	7.8	7.8	4.9 c	11.4	9.3 b	5.6 c
Mycorrhizal Biofertilizers + Bio-ameliorant									
Control	40.3 d	48.0c	55. b	7.1 c	8.1	5.8 b	9.8 b	11.6 ab	12.7 b
Mycorrhizal 10 g plant^{-1} (M1)	46.2 b	55.5 b	60.0 b	7.8 ab	8.6	7.0 ab	9.6 b	11.9 ab	15.6 ab
Mycorrhizal 15 g plant^{-1} (M2)	47.8 ab	59.9 a	61.4 b	7.8 ab	8.4	8.1 a	9.6 b	9.1 b	12.4 b
Bio-ameliorant 200 g plant^{-1} (B)	42.3 cd	46.3 c	58.9 b	7.2 bc	7.7	7.1 ab	13.1 a	13.1 a	17.0 a
M1 + B	44.9 bc	49.7 c	59.5 b	7.3 bc	7.8	7.7 a	13.0 a	12.7 a	16.1 ab
M2 + B	51.0 a	55.3 b	68.7 a	8.1 a	7.9	7.7 a	13.9 a	14.2 a	18.1 a

^{z} Means followed with the same letters within columns are not significantly different based on the LSD at $p \leq 0.05$.
^{y} Means followed with the same letters within columns are not significantly different based on the Duncan test at $p \leq 0.05$.

This suggested that under severe rhizosphere saturation, combined biological and organic amendments were required to alleviate growth limitations (Shao et al., 2024).

The combined application of mycorrhizal biofertilizers and bio-ameliorants decreased the stem diameter and number of leaves approximately 50% under WSR compared to the treatment of mycorrhizal biofertilizers alone (Figure 3). This decline suggested a potential shift in resource allocation under severe stress, where plants prioritized survival and vertical growth rather than lateral expansion. Statistical analysis confirmed significant effects ($p \leq 0.05$) of WSR and amendment treatments on all non-destructive growth parameters, while their interaction was generally non-significant, except for plant height before WSR exposure (Table 1).

This result showed that the WSR decreased the non-destructive growth parameters during the experiment (Table 2). Compared with field capacity, partial and full waterlogging resulted in marked declines in plant height, stem diameter, and leaf number, particularly after exposure to WSR and during the recovery phase. At the recovery stage, full waterlogging reduced plant height by 42%, stem diameter by 48%, and leaf number by 82% relative to field capacity, while partial waterlogging caused intermediate reductions (Table 2).

These results showed that increasing rhizosphere saturation progressively constrained vegetative growth.

The observed reductions were consistent with previous results. Yin et al. (2023) reported that 6-genotype tomato showed substantial decreases in plant height, stem diameter, and fruit-related traits after treatment with waterlogging compared to controls. Similarly, waterlogged tomato plants experienced reduced stem growth, leaf area, and biomass production (Hao et al., 2019). In this study, statistical analysis confirmed significant effects ($p \leq 0.05$) of WSR on morphological traits across 3 observation periods (before WSR, after WSR, and after recovery), showing that both the intensity and duration of saturation influenced growth responses (Table 1).

An exception was observed for stem diameter, which showed significant differences only after WSR exposure, showing a delayed sensitivity of radial growth to waterlogging stress. Furthermore, the interaction between WSR and mycorrhizal biofertilizer + bio-ameliorant treatments was not significant for most non-destructive growth parameters, except for plant height before WSR application (Table 1).

This suggested that the water regime was the dominant factor controlling early vegetative growth, while amendment effects were secondary under severe saturation.

Table 3. Statistical calculation of the growth destructive parameters of the tomato plant treated with mycorrhizal biofertilizers + bio-ameliorant applications at 2 weeks/ end of recovery after exposure to water-saturated rhizosphere.

Traits	**Water Saturated Rhizosphere (S)**	**Mycorrhizal Biofertilizers + Bio-ameliorant (MB)**	**S X MB**
		Mean Square Value	
Root length	4485.745^{**}	58.272^{ns}	20.380^{ns}
Dry weight			
Root	120.838^{**}	2.979^{*}	1.832^{ns}
Stem	118.536^{**}	29.369^{**}	11.755^{**}
Leaves	765.756^{**}	20.888^{**}	12.657^{**}
Flower	1.554^{**}	0.061^{*}	0.030^{ns}
Total	5561.669^{**}	113.469^{**}	52.881^{**}

**significantly different at $p \leq 0.01$; *significantly different at $p \leq 0.05$; ^{ns}: not significantly different at $p < 0.05$.

Non-destructive growth parameters continued to show an increase at the end of the WSR time period. However, these parameters decreased at the end of the recovery process, which spanned 2 weeks (Table 2). This pattern showed that tomato plants maintained limited growth during waterlogging but experienced post-stress growth inhibition following re-aeration. Such responses reflected a physiological adjustment phase, during which plants transition from hypoxic or anoxic conditions back to aerobic soil environments, resulting in temporary growth suppression.

This result shows that water saturated rhizosphere (WSR) and mycorrhizal biofertilizers and bio-ameliorant applications also significantly influenced the growth destructive parameters of tomato during the experiment (Table 3). WSR significantly reduced the dry matter of roots, stems, leaves, flowers, and total biomass ($p \leq 0.05$) 2 weeks after recovery. Total dry matter under full waterlogging (6.23 g plant^{-1}) was 84% lower than under field capacity (38.07 g plant^{-1}) (Table 4). These reductions reflected the strong inhibitory effect of oxygen deficiency on carbon assimilation and biomass formation. Under partial and full waterlogging conditions, no significant differences were observed among individual plant organs' dry weight accumulation, showing uniform growth suppression across organs.

Oxygen deficiency under waterlogged conditions restricted root respiration and energy production and thereby reduced their ability to take up water and nutrients required for their growth and development, including the dry matter of the plant (Anee et al., 2025; Li et al., 2025; Zhang et al., 2025). However, amendment treatments significantly affected total dry matter. The combined application of mycorrhizal biofertilizer at 15 g plant^{-1} and bio-ameliorant at 200 g plant^{-1} produced the highest total dry matter (23.35 g plant^{-1}), representing an 83% increase compared with the untreated control (Table 4). The interaction between WSR and mycorrhizal biofertilizer + bio-ameliorant significantly influenced stem dry matter (SDM), leaf dry matter (LDM), and total dry matter (TDM) (Figure 4).

Table 4. Root, stem, leaves, flower, and total dry matter of tomato plant treated with mycorrhizal biofertilizers + bio-ameliorant applications at 2 weeks/ end of recovery after exposure to water-saturated rhizosphere.

Treatments	Dry matter (g plant^{-1})				
	Root	Stem	Leaves	Flower	Total
Water saturated					
Field capacity	5.157 a[z]	17.735 a	14.647 a	0.536 a	38.074 a
Partial waterlogging	1.039 b	4.316 b	3.829 b	0.062 b	9.246 b
Fully waterlogging	0.373 b	3.087 b	2.886 b	0.000 b	6.234 c
Mycorrhizal Biofertilizers + Bio-ameliorant					
Control	1.712 b[y]	5.922 d	4.974 c	0.134 b	12.743 c
Mycorrhizal 10 g plant^{-1} (M1)	1.792 b	8.101 bc	6.540 bc	0.156 b	16.587 bc
Mycorrhizal 15 g plant^{-1} (M2)	3.104 a	6.808 cd	6.551 bc	0.131 b	16.371 bc
Bio-ameliorant 200 g plant^{-1} (B)	2.061 ab	9.597 ab	7.347 b	0.251 ab	19.258 b
M1 + B	1.780 b	9.066 ab	7.770 b	0.182 b	18.796 b
M2 + B	2.688 ab	10.78 a	9.542 a	0.341 a	23.354 a

[z] Means followed with the same letters within columns are not significantly different based on the LSD at $p \leq 0.05$.
[y] Means followed with the same letters within columns are not significantly different based on the Duncan test at $p \leq 0.05$.

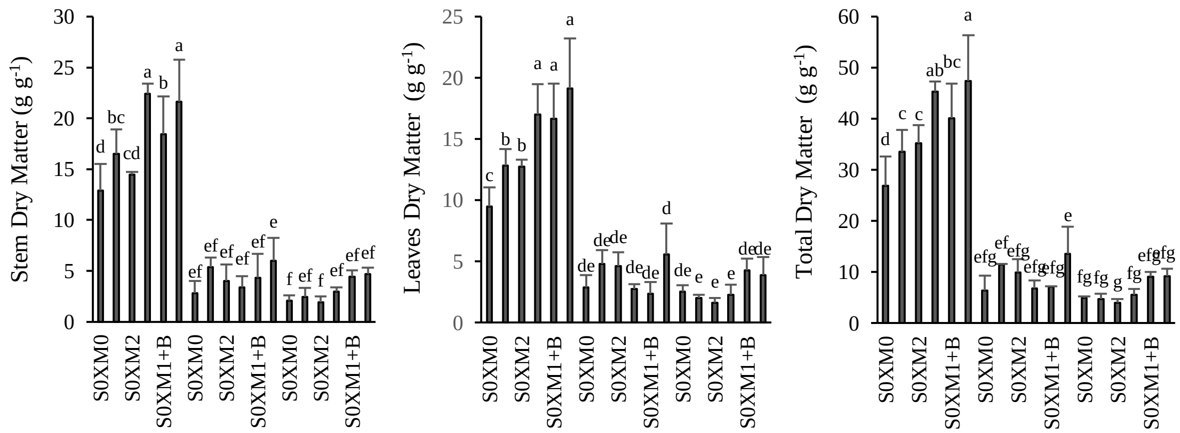

Figure 4. Interaction of water-saturated rhizosphere and the mycorrhizal biofertilizer + bio-ameliorant in stem dry matter, leaf dry matter, and total dry matter of the tomato plant. S0 = field capacity; S1 = partial waterlogging; S2 = full waterlogging. M0= control, M1= mycorrhizal biofertilizer 10 g plant^{-1}, M2= mycorrhizal biofertilizer 10 g plant^{-1}, and B = bio-ameliorant 200 g plant^{-1}.

The most favorable outcomes were consistently observed under field capacity combined with 15 g plant^{-1} mycorrhizal biofertilizer and 200 g plant^{-1} bio-ameliorant. These results were consistent with the results of a previous study showing that the application of mycorrhizal and bio-ameliorant significantly increased fresh and dry weight matter and of plants (Lumbantoruan et al., 2023; Mulyadi and Jiang, 2023b; Wangiyana et al., 2024). Furthermore, this resulted from an improved soil structure and the availability of nutrients provided by the ameliorants, which balanced out the nutrient cycling role of mycorrhizal fungi (Az-Azahra et al., 2024; Astiko et al., 2024).

Growth analysis further showed that WSR significantly affected root weight ratio (RWR), leaf weight ratio (LWR), flower weight ratio (FWR), and shoot-to-root ratio (SRR), whereas stem weight ratio (SWR) remained unaffected (Tables 5 and 6). Under full waterlogging, RWR declined by 54%, while SRR increased by 153% compared with field capacity, showing a shift toward shoot dominance under hypoxic stress. This response suggested that tomato roots were particularly sensitive to oxygen deprivation, which restricted root growth and nutrient uptake, leading plants to preferentially allocate resources to aboveground organs to enhance survival (Niu et al., 2012). Similar allocation patterns under saturated soil conditions were also reported in other crops (Lizaso and Ritchie, 1997; Siaga et al., 2019b).

Amendment treatments significantly increased RWR and FWR but did not affect SWR, LWR, or SRR. The highest RWR and FWR values were obtained with mycorrhizal biofertilizer at 15 g plant^{-1} alone and in combination with bio-ameliorant (Table 6).

Table 5. Statistical calculation of the growth analysis parameters of the tomato plant treated with mycorrhizal biofertilizers + bio-ameliorant applications at 2 weeks/ end of recovery after exposure to water-saturated rhizosphere.

Parameters	Water Saturated Rhizosphere (S)	Mycorrhizal Biofertilizers + Bio-ameliorant (MB)	S X MB
		Mean Square Value	
RWR	0.0186^{**}	0.0086^{*}	0.0012^{ns}
SWR	0.0013^{ns}	0.0113^{ns}	0.0044^{ns}
LWR	0.0158^{*}	0.0027^{ns}	0.0062^{ns}
FWR	0.00086^{**}	0.0000057^{*}	0.00003^{ns}
SRR	533.898^{**}	54.834^{ns}	14.533^{ns}

**significantly different at $p \leq 0.01$; *significantly different at $p \leq 0.05$; ^{ns}: not significantly different at $p < 0.05$. RWR = root weight ratio, SWR = stem weight ratio (SWR), LWR = leaf weight ratio, FWR = flower weight ratio, and SRR= shoot root ratio.

Table 6. Root weight ratio (RWR), stem weight ratio (SWR), leaf weight ratio (LWR), flower weight ratio (FWR), and shoot root ratio (SRR) of tomato plant treated with mycorrhizal biofertilizers + bio-ameliorant applications at 2 weeks/ end of recovery after exposure to water-saturated rhizosphere.

Treatments	RWR ($g\ g^{-1}$)	SWR ($g\ g^{-1}$)	LWR ($g\ g^{-1}$)	FWR ($g\ g^{-1}$)	SRR ($g\ g^{-1}$)
Water saturated					
Field capacity	0.138 a^{z}	0.467	0.383 b	0.0137 a	6.926 b
Partial waterlogging	0.106 ab	0.473	0.416 ab	0.0049 b	10.224 b
Fully waterlogging	0.063 b	0.485	0.447 a	0.0000 c	17.565 a
Mycorrhizal Biofertilizers + Bio-ameliorant					
Control	0.099 b^{y}	0.448	0.447	0.0053 b	11.904
Mycorrhizal 10 g plant^{-1} (M1)	0.095 b	0.487	0.412	0.0053 b	12.152
Mycorrhizal 15 g plant^{-1} (M2)	0.145 a	0.417	0.421	0.0041 b	8.055
Bio-ameliorant 200 g plant^{-1} (B)	0.094 b	0.505	0.395	0.0057 b	11.091
M1 + B	0.078 b	0.510	0.406	0.0056 b	15.63
M2 + B	0.100 b	0.480	0.408	0.0112 a	10.598

^{z} Means followed with the same letters within columns are not significantly different based on the LSD at $p \leq 0.05$.
^{y} Means followed with the same letters within columns are not significantly different based on the Duncan test at $p \leq 0.05$.

These results supported previous results that combined mycorrhizal and organic amendments enhanced nutrient uptake, soil conditions, and microbial activity, thereby improving plant growth and reproductive allocation (Apu et al., 2023; Ahmadabadi et al., 2018; Soussani et al., 2023; Wei et al., 2024).

Overall, the simultaneous application of mycorrhizal biofertilizers and bio-ameliorants provided a comprehensive approach to improving tomato growth and resilience under water-saturated rhizosphere conditions. This strategy offered a significant opportunity for developing agronomic practices for tomato production in tropical wetland areas that frequently experience WSR issues. However, further studies were needed, particularly those focusing on more appropriate application methods and analyses of physiological characteristics.

4. Conclusions

In conclusion, the concurrent utilization of mycorrhizal biofertilizer + bio-ameliorant (goat manure mixed rice husk biochar) has been showed to exert a favourable influence on tomato plant growth in conditions of water-saturated rhizosphere during the early generative stage. The utilization of mycorrhizal biofertilizer + bio-ameliorant has been showed to exert a favourable influence on the enhancement of tomato plants' resilience to water-saturated rhizosphere conditions. This study shows that the use of 15 g plant^{-1} of mycorrhizal biofertilizer + 200 g plant^{-1} of bio-ameliorant can be recommended as a cultivation method to enhance tomato growth, particularly in water-saturated rhizosphere conditions. The application of mycorrhizal biofertilizer in the absence of a bio-ameliorant has been showed to enhance growth under conditions of field capacity and partial water-saturated rhizosphere, but not to the same extent under full water-saturated rhizosphere. However, the morpho-agronomic adaptation response of tomato plants remains contingent on the severity of water stress experienced by the plants.

Authors' Contribution

Erna Siaga was responsible to conceptualization, methodology, formal analysis, data curation, resources, visualization, writing – original draft, writing – review and editing, and funding acquisition. Mei Meihana contributed to writing – original draft and writing – review and editing. Santa Maria Lumbantoruan was responsible for software and writing – original draft. Mulyadi contributed to writing – original draft and writing – review and editing. Dheo Rimbano carried out project administration. Kartika Kartika performed the data curation, writing – original draft, and writing – review and editing. All authors have read and approved the final manuscript.

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