Evaluation of Biofertilizer Application on the Physicochemical Characteristics of Peat Soil under Drought Stress

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Abstract

Peat soils are highly susceptible to drought stress because of their high organic matter content, low nutrient availability, and vulnerability to degradation under prolonged drying. This study evaluated the effects of biofertilizer application and irrigation interval on maize growth and selected physicochemical properties of hemic peat soil under drought stress. A factorial randomized block design with four biofertilizer rates (0, 10, 20, and 30 g polybag^{-1}) and four irrigation intervals (daily, every 3, 5, and 7 days) was used, with four replications, resulting in 64 experimental units. Measured variables included plant height, stem diameter, shoot dry weight, root length, soil organic carbon, total nitrogen, cation exchange capacity, soil porosity, and soil respiration. Analysis of variance indicated that biofertilizer application, irrigation interval, and their interaction did not significantly affect maize growth or the measured soil physicochemical properties ($P > 0.05$). Numerical variation among treatments was observed; however, the magnitude of these differences was insufficient to produce statistically significant responses. Peat soil exhibited a substantially higher respiration rate (2.76 µg CO_2–C g^{-1} soil h^{-1}) than mineral soil (0.44 µg CO_2–C g^{-1} soil h^{-1}), indicating greater carbon turnover under the experimental conditions. The results suggest that the inherent properties of hemic peat exerted a stronger influence on soil characteristics than short-term biofertilizer application or irrigation management during one cropping season. Further long-term studies are needed to evaluate the cumulative effects of biofertilizer on peat soil quality and crop productivity.

Keywords: *Biofertilizer, drought stress, emission, mycorrhiza, peat land*.

INTRODUCTION

The decline in productive agricultural land has encouraged the utilization of suboptimal lands for agricultural activities, one of which is peat soil. Peat soils have considerable potential for agricultural development; however, their utilization requires more intensive management compared to mineral soils. A fundamental difference between mineral soils and peat soils lies in their active components. In mineral soils, the active fraction is dominated by solid phases, whereas in peat soils, the active component is primarily in the liquid phase. This characteristic makes peat soils highly vulnerable to losing their function as a growing medium under drought stress, as their water retention capacity declines drastically.

Drought stress in peat soils can trigger an increase in carbon dioxide (CO_2) emissions. Peat soils are also susceptible to hydrophobicity, a condition of irreversible drying that prevents the soil from reabsorbing water effectively. This condition leads to increased soil respiration and CO_2 emissions into the atmosphere. Compared to mineral soils, peat soils can release up to six times more CO_2, indicating their substantial potential as a carbon emission source if not managed properly (Crnobrna *et al.,* 2022). Under drought conditions, the physicochemical properties of peat soils may change drastically, thereby inhibiting plant growth and increasing the risk of ecosystem degradation (Leifeld *et al.,* 2020).

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Global climate change is expected to further intensify the critical condition of peatlands. Based on their degree of decomposition, peat soils are classified into fibric, hemic, and sapric peat. Fibric peat represents the least decomposed stage, hemic peat has a moderate level of decomposition, and sapric peat is the most decomposed form. This degree of decomposition serves as an important indicator of peat soil quality, as more decomposed peat generally exhibits higher nutrient availability. Peat soils are characterized by high porosity, consisting of both macro- and micropores. Peat dominated by macropores typically indicates a lower degree of decomposition, whereas more decomposed peat is characterized by a greater proportion of micropores. Physically, peat soils have a low bulk density, ranging from 0.05 to 0.40 g cm^{-3}, resulting in low bearing capacity. When peatlands are drained and exposed to drying, peat soils are prone to subsidence or surface lowering. Chemically, peat soils are constrained by high acidity, high carbon-to-nitrogen (C/N) ratios, and high but less effective cation exchange capacity (CEC) (Delgado & Gómez, 2024). Biologically, a major limitation of peat soils is the loss of carbon and nitrogen through organic matter mineralization, which contributes to global warming and climate change.

Global climate change has increased both the frequency and intensity of drought events, significantly affecting agricultural productivity on peatlands. Although peat soils contain high levels of organic matter, they are generally poor in nutrients and have a low buffering capacity against extreme environmental conditions (Delgado and Gómez, 2024). Global temperature increases are projected to rise gradually by approximately 1.0–5.7°C (IPCC, 2013), further exacerbating the vulnerability of peat soils to drought stress. Prolonged drought stress can cause peat soils to undergo irreversible drying. Low soil moisture content leads to the deterioration of peat soil fertility due to the development of hydrophobic properties (Winarna *et al*., 2016). In addition, dry peat soils are highly susceptible to fire hazards.

The management of peat soils using inorganic fertilizers is considered less effective, as chemical fertilizer application may increase CO_2 emissions. Riyani *et al*., (2021) reported that the application of NPK fertilizers tends to produce higher CO_2 emissions compared to the use of biofertilizers. Drought stress in peat soils also results in a decline in groundwater levels, which accelerates peat degradation and increases the risk of land fires. This degradation promotes organic matter decomposition, leading to increased CO_2 emissions and a decline in soil cation exchange capacity.

Winarna *et al.,* (2016) stated that peat soil drying results in decreases in soil pH, CEC, and the concentration of functional groups such as COOH and OH, which play a crucial role in binding water and nutrients in peat soils. Drought stress also induces the accumulation of abscisic acid (ABA) in plants, leading to stomatal closure to reduce transpiration. This condition disrupts water and nutrient translocation, reduces turgor pressure, and ultimately causes plant wilting. Another challenge in utilizing peat soils for agriculture is their inherently low fertility, as reflected by acidic pH, high concentrations of organic acids, and low bulk density, resulting in lower nutrient availability per unit volume compared to mineral soils.

To address these challenges, sustainable management approaches through the application of biofertilizers have increasingly been developed. Biofertilizers contain functional microorganisms such as nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and mycorrhizae, which are capable of enhancing nutrient availability, improving soil structure, and increasing plant resistance to abiotic stress (Giri *et al*., 2025). The application of biofertilizers to drought-stressed peat soils has the potential not only to enhance plant growth but also to improve soil physicochemical properties, including pH, moisture content, nitrogen availability, and cation exchange capacity (Juhari *et al*., 2024).

Microbial activity associated with biofertilizers contributes to the improvement of soil physical properties, particularly soil structure, by enhancing aggregate stability. Well-structured soils promote better aeration, root penetration, and resistance to erosion. Stable soil aggregates indicate favorable root-zone conditions, thereby facilitating nutrient uptake for plant growth. The application of biofertilizers has been reported to positively affect maize growth on drought-stressed peat soils, as evidenced by increases in plant height, stem diameter, shoot dry weight, and root dry weight compared to treatments without biofertilizers (Lumbantoruan and Anggraini, 2021). The differences in peat decomposition levels influence soil organic carbon and bulk density, where hemic peat tends to have higher organic carbon content and lower bulk density than sapric peat (Rahmawati *et al.,* 2022). These characteristics indicate that peat soils with moderate decomposition still have better physical quality and nutrient retention capacity. The application of biofertilizers under drought stress conditions may help maintain soil structure and nutrient availability, thereby supporting peat soil fertility and sustainability under changing climate conditions.

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MATERIALS AND METHODS

Place and Time

The experiment was conducted in a greenhouse and soil laboratory of Universitas Sriwijaya, Indralaya, South Sumatra, Indonesia, for three months from May to July 2025.

Materials and Tools

The materials used included hemic peat soil, maize seeds, mycorrhizal biofertilizer, Petrobio biofertilizer, and distilled water. Laboratory equipment consisted of polybags, analytical balance, burettes, Erlenmeyer flasks, volumetric pipettes, graduated cylinders, and glassware for soil chemical analyses.

Experimental Design

The study was conducted using a factorial randomized block design (RBD) with two factors. The first factor was biofertilizer dosage, consisting of four levels: F0 = 0 g polybag^{-1} (control), F1 = 10 g polybag^{-1}, F2 = 20 g polybag^{-1}, and F3 = 30 g polybag^{-1}, comprising a combination of mycorrhizal inoculum and Petrobio. The second factor was irrigation interval, consisting of four levels: P1 = irrigation every day, P2 = irrigation every 3 days, P3 = irrigation every 5 days, and P4 = irrigation every 7 days. Each treatment combination was replicated four times. The experiment consisted of 16 treatment combinations (4 × 4) and 64 experimental units. Each treatment combination was replicated four times, resulting in 16 treatment combinations and 64 experimental units. Each polybag was filled with 10 kg of air-dried peat soil, and one maize plant was grown per polybag.

Soil and Plant Measurements

Observed variables included plant growth parameters (plant height, stem diameter, shoot dry weight, and root length) and soil physicochemical properties. Soil total nitrogen was measured using the Kjeldahl method, organic carbon using the Walkley and Black method, cation exchange capacity (CEC) using ammonium acetate extraction, and soil porosity using the gravimetric method. Soil respiration was determined by measuring CO_2 release through the acid–base titration method and expressed as μg CO_2–C g^{-1} soil h^{-1}.

Statistical Analysis

All data were subjected to two-way analysis of variance (ANOVA) to evaluate the effects of biofertilizer dosage, irrigation interval, and their interaction. When significant differences were detected, mean comparisons were performed using Duncan's Multiple Range Test (DMRT) at a 5% significance level.

RESULT AND DISCUSSION

Table 1 summarizes the results of the two-way analysis of variance (ANOVA) for plant height, stem diameter, shoot dry weight, and root length of maize grown in hemic peat soil under different biofertilizer application rates and irrigation intervals. The analysis showed that biofertilizer application, irrigation interval, and their interaction did not significantly affect any of the measured growth parameters ($P > 0.05$).

Table 1. Analysis of Variance (ANOVA) for Plant Height, Stem Diameter, Shoot Dry Weight, and Root Length of Maize as Affected by Biofertilizer and Irrigation Interval

Source of Variation	df	Plant Height (F-value)	Stem Diameter (F-value)	Shoot Dry Weight (F-value)	Root Length (F-value)	$F_{0.05}$	$F_{0.01}$
Block	3	0.89	0.44	0.81	0.84	2.81	4.25
Biofertilizer (F)	3	1.67	1.59	1.48	1.56	2.81	4.25
Irrigation Interval (P)	3	1.21	1.12	1.04	0.52	2.81	4.25
F × P Interaction	9	0.85	1.08	0.90	0.98	2.10	2.83
Error	45						
Total	63						

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The application of biofertilizer showed no statistically significant effect ($P > 0.05$) on plant height, stem diameter, shoot dry weight, or root length (Table 1). However, several growth parameters exhibited an increasing trend. The 20 g polybag^{-1} treatment (F2) produced the longest roots (66.91 cm) and higher shoot dry weight (9.5 g) compared to the control. Root elongation under biofertilizer application is commonly associated with mycorrhizal colonization, which enhances nutrient and water uptake efficiency through an expanded hyphal

Table 2. Growth Of Maize Plants in Peat Soil Under Drought Stress

Treatment	Growth Of Maize Plants			
	Plant Height (cm)	Stem Diameter (cm)	Shoot Dry Weight (g)	Root Length (cm)
Biofertilizer				
F0 = 0 g polybag^{-1}	133.90	4.20	9.30	60.07
F1 = 10 g polybag^{-1}	116.90	3.70	6.60	59.06
F2 = 20 g polybag^{-1}	123.30	3.90	9.50	66.09
F3 = 30 g polybag^{-1}	133.20	4.00	9.00	65.00
Irrigation				
P1 = irrigation every day	127	4.18	9.90	57.35
P2 = irrigation every 3 days	114	3.60	8.90	63.43
P3 = irrigation every 5 days	133	4.11	10.80	61.31
P4 = irrigation every 7 days	139	4.11	8.90	67.12

The application of biofertilizer at different rates did not significantly influence plant height, stem diameter, shoot dry weight, or root length of maize grown on hemic peat soil. This result indicates that the introduced microorganisms were not able to improve nutrient availability sufficiently to promote measurable changes in vegetative growth during the experimental period. One possible explanation is related to the inherent characteristics of hemic peat soil, which presents several constraints for both plant growth and microbial activity.

Hemic peat is characterized by an intermediate degree of decomposition, with approximately one-third to two-thirds of the original plant fibers still remaining in the peat matrix. This type of peat possesses high porosity, low bulk density, and an exceptionally high water-holding capacity (Page *et al*., 2011). Although these properties enable peat soils to retain substantial amounts of water, they also reduce soil aeration because most soil pores remain occupied by water. Under such conditions, oxygen diffusion into the rhizosphere becomes limited, restricting the activity of aerobic microorganisms responsible for decomposing organic matter and releasing nutrients required for plant growth (Ritzema *et al*., 2014).

In addition, tropical peat soils are generally acidic and characterized by low base saturation and limited concentrations of readily available nutrients despite their high organic matter content (Anda *et al*., 2021). Most nitrogen and phosphorus are stored in complex organic compounds and cannot be directly absorbed by plants. These nutrients must first undergo microbial mineralization before becoming available in inorganic forms (Brady & Weil, 2017). Consequently, the effectiveness of biofertilizer depends not only on the presence of beneficial microorganisms but also on their ability to survive, colonize the rhizosphere, and actively mineralize organic substrates. Under the acidic conditions of peat soil, these processes generally occur slowly, which may explain why biofertilizer application did not result in significant improvements in maize growth.

The establishment of inoculated microorganisms in peat soil may also have contributed to the absence of treatment effects. Following inoculation, beneficial microorganisms must compete with indigenous microbial communities that are already adapted to the peat ecosystem. Environmental factors such as low pH, limited oxygen availability, and high organic matter content strongly influence microbial survival and metabolic activity (Bashan *et al.,* 2014). Consequently, the inoculated microorganisms likely required a longer adaptation period before becoming sufficiently active to enhance nutrient cycling or produce plant growth-promoting compounds, such as phytohormones and organic acids. Since the experiment was conducted over a relatively short period, microbial populations may not have reached densities capable of producing measurable responses in plant growth.

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Similarly, irrigation interval did not significantly affect any of the measured growth parameters. This result is closely associated with the hydrological properties of hemic peat soil. Due to its fibrous organic structure, peat can retain water several times its dry weight, allowing moisture to remain available in the root zone even when irrigation frequency is reduced (Page *et al.*, 2011). As a result, the irrigation treatments evaluated in this study were likely insufficient to generate substantial differences in soil water availability among treatments. The relatively stable soil moisture conditions prevented maize plants from experiencing severe water stress, thereby producing similar vegetative growth across all irrigation intervals.

The lack of interaction between biofertilizer and irrigation interval further suggests that changes in irrigation frequency did not alter the effectiveness of the applied biofertilizer. The performance of beneficial microorganisms in peat soils is governed by multiple environmental factors rather than soil moisture alone. Soil acidity, oxygen availability, nutrient limitation, and competition with native microbial populations collectively regulate microbial activity and nutrient mineralization (Bashan *et al.*, 2014). Therefore, although irrigation frequency was modified, these fundamental constraints likely remained unchanged, resulting in similar microbial performance under all irrigation treatments.

The findings indicate that the intrinsic characteristics of hemic peat soil exerted a stronger influence on maize growth than either biofertilizer application or irrigation interval. The slow mineralization of organic nutrients, limited oxygen diffusion, acidic soil conditions, and gradual establishment of introduced microorganisms collectively reduced the effectiveness of biofertilizer during the experimental period. These results suggest that improving biofertilizer performance in peat soils may require complementary approaches, including pH amelioration through liming, the use of biochar as a microbial carrier to improve microbial survival, or a longer incubation period to allow microbial populations to become fully established before planting.

Table 3. Soil Respiration Rates of Peat and Mineral Soils

Soil Type	Soil Respiration (μg CO_2–C g^{-1} soil h^{-1})
Peat Soil	2.76
Mineral Soil	0.44

As presented in Table 3, peat soil exhibited a markedly higher soil respiration rate (2.76 μg CO_2–C g^{-1} soil h^{-1}) compared with mineral soil (0.44 μg CO_2–C g^{-1} soil h^{-1}), indicating that carbon release from peat was approximately six times greater. This difference reflects the intrinsic characteristics of peat soils, which contain abundant organic substrates that stimulate intensive microbial decomposition. Under drought conditions, reduced moisture and increased aeration enhance oxygen diffusion, thereby stimulating heterotrophic respiration and accelerating organic matter mineralization. Soil respiration represents the combined contribution of root (autotrophic) and microbial (heterotrophic) respiration, with the heterotrophic component closely related to peat decomposition processes. Higher respiration therefore indicates faster carbon turnover and potential peat degradation. Similar observations were reported by Addianto *et al*. (2020), who demonstrated that heterotrophic respiration increases under aerobic peat conditions, and by Sulistiana (2020), who found that peatland cultivation accelerates CO_2 emissions through enhanced decomposition. The elevated respiration measured in this study suggests that peat soils are highly susceptible to carbon loss when exposed to drying or disturbance. In contrast, mineral soils showed lower respiration due to reduced organic matter content and more stable carbon pools. These findings are consistent with reports by Feng *et al.* (2017) and Campbell *et al.* (2021), who emphasized the critical role of soil respiration in regulating ecosystem carbon fluxes. Although biofertilizer application did not significantly suppress respiration, improvements in soil nitrogen, cation exchange capacity, and porosity suggest better soil structural stability and nutrient retention. Such improvements may help moderate excessive carbon loss and maintain peat soil function as both a nutrient reservoir and a carbon sink.

Table 3 demonstrated that neither biofertilizer application nor irrigation interval significantly affected soil organic carbon (SOC), total nitrogen (TN), cation exchange capacity (CEC), or soil porosity in hemic peat soil. Although numerical variation among treatments was observed, the magnitude of these changes was insufficient to produce statistically significant differences. This finding suggests that the inherent physical and chemical characteristics of hemic peat soil played a more dominant role in regulating soil properties than the short-term application of biofertilizer or irrigation management.

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Table 4. Soil Physicochemical Properties of Peat Soil Under Different Irrigation Intervals and Biofertilizer Applications

Treatment	Soil Physicochemical Properties			
	Soil organic carbon (%)	Soil total nitrogen (%)	Cation exchange capacity (cmol(+)/kg)	Soil porosity (%)
Biofertilizer				
F0 = 0 g polybag^{-1}	37.50	0.52	53.25	79.50
F1 = 10 g polybag^{-1}	35.00	0.63	61.5	78.75
F2 = 20 g polybag^{-1}	35.75	0.96	65.00	78.75
F3 = 30 g polybag^{-1}	34.50	0.52	64.75	79.15
Irrigation				
P1 = irrigation every day	37.12	0.63	67.00	75.77
P2 = irrigation every 3 days	36.00	0.49	60.25	80.30
P3 = irrigation every 5 days	34.37	0.76	55.50	79.62
P4 = irrigation every 7 days	35.25	0.75	61.75	80.45

Note: The relatively stable SOC observed across treatments is closely related to the nature of hemic peat.

Hemic peat consists of partially decomposed plant residues with a high proportion of humified organic materials. Consequently, SOC in peat soils represents a large and relatively stable carbon pool that is not easily altered by short-term agronomic practices. Recent meta-analysis of tropical peatlands showed that carbon concentration generally remains relatively constant despite differences in land management because peat carbon is primarily controlled by peat maturity, hydrological conditions, and long-term decomposition processes rather than seasonal management interventions (Kunarso *et al*., 2022).

The absence of significant changes in SOC may also indicate that the duration of the experiment was insufficient to modify the balance between carbon inputs and carbon losses. Biofertilizers primarily influence SOC indirectly by stimulating plant growth, increasing root biomass, and enhancing microbial transformation of organic residues into stable soil organic matter. These mechanisms generally require repeated applications and several growing seasons before measurable increases in SOC become evident. A recent global meta-analysis involving 267 observations reported that microbial biofertilizers significantly increased SOC, but the magnitude of the response was strongly dependent on treatment duration, with medium- and long-term applications producing greater increases than short-term experiments. Therefore, the relatively constant SOC observed in this study is consistent with previous evidence indicating that changes in peat carbon storage occur gradually and cannot be expected within a single cropping cycle (T Singla Just et al. 2024).

Another important factor explaining the stable SOC content is the hydrological condition of hemic peat. The peat matrix possesses exceptionally high water-holding capacity and contains numerous water-filled micropores, which restrict oxygen diffusion into the soil profile. Limited oxygen availability suppresses aerobic decomposition and slows the mineralization of organic residues, thereby maintaining relatively constant carbon stocks (Kunarso *et al*., 2022). (Springer) Consequently, differences in irrigation interval were unlikely to substantially modify decomposition rates because the peat remained sufficiently moist throughout the experiment.

Total nitrogen also showed no significant response to either biofertilizer or irrigation interval. Although microbial inoculants are expected to enhance biological nitrogen fixation and nutrient cycling, the transformation of nitrogen in peat soils is governed by complex interactions among microorganisms, organic substrates, and environmental conditions. Most nitrogen in tropical peat remains incorporated within organic compounds and must undergo mineralization before becoming available to plants. Recent reviews have emphasized that microbial nitrogen cycling is strongly influenced by soil acidity, oxygen availability, and organic matter quality, all of which are major constraints in peat ecosystems (Soratur et al., 2024). Under these conditions, nitrogen mineralization proceeds slowly, limiting short-term improvements in total soil nitrogen.

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The establishment of inoculated microorganisms may also explain the limited response of total nitrogen. Following inoculation, microorganisms require sufficient time to adapt to acidic peat conditions, colonize the rhizosphere, compete with indigenous microbial populations, and synthesize extracellular enzymes involved in nitrogen transformation. These ecological processes develop progressively and are rarely completed within one growing season. Recent reviews on biofertilizer performance indicate that successful microbial colonization largely determines the effectiveness of microbial inoculants, whereas unfavorable soil conditions often delay their establishment and reduce their contribution to nutrient cycling. Therefore, although numerical increases in total nitrogen were observed in several treatments, these changes were insufficient to generate statistically significant differences.

The relatively unchanged CEC among treatments is also consistent with the chemical characteristics of peat soils. Unlike mineral soils, where CEC is largely determined by clay minerals, CEC in peat soils originates predominantly from negatively charged functional groups associated with humified organic matter. Carboxyl and phenolic groups provide numerous exchange sites capable of retaining nutrient cations. Because these functional groups are structural components of peat organic matter, their abundance is unlikely to change substantially following short-term biofertilizer application. The systematic review conducted by Kunarso et al. (2022) reported that peat chemical properties, including carbon content and several exchange-related characteristics, generally exhibit limited short-term variation and are more strongly influenced by peat maturity and land-use history than by seasonal management practices.

Furthermore, recent studies have shown that improvements in CEC generally occur through gradual modification of humic substances rather than through direct microbial inoculation. Humic substances regulate nutrient retention, water-holding capacity, and microbial habitat, while also interacting with microorganisms to regulate nutrient cycling. The development and transformation of these humic fractions require extended periods before measurable improvements in CEC become evident (Zhang et al., 2024). (ScienceDirect) Consequently, the numerical variation observed in this study most likely reflected natural heterogeneity of the peat material rather than treatment-induced changes.

Similarly, soil porosity remained statistically unchanged regardless of irrigation interval or biofertilizer application. This response is expected because porosity is fundamentally controlled by peat structure and fiber composition. Hemic peat contains abundant partially decomposed fibers that form interconnected pore networks, producing naturally high porosity and low bulk density. These structural characteristics develop over decades or centuries and therefore cannot be substantially modified through short-term agronomic treatments. Recent reviews on tropical peat soils similarly reported that physical properties such as porosity and hydraulic behavior exhibit relatively low sensitivity to short-term management because they are determined primarily by peat decomposition stage and hydrological history.

The absence of irrigation effects on porosity further indicates that the irrigation intervals imposed during the experiment did not induce sufficient drying to trigger peat shrinkage or structural collapse. Tropical peat possesses exceptional water retention capacity, enabling moisture to remain available within the peat matrix even under relatively long irrigation intervals. Consequently, pore continuity and soil structure remained largely unchanged throughout the experiment. This finding agrees with recent evaluations of tropical peat management, which emphasize that measurable changes in peat physical properties generally occur only following prolonged drainage, repeated wetting-drying cycles, or severe compaction rather than temporary irrigation treatments.

Although statistical analysis indicated no significant treatment effects, slight numerical variation among treatments should not be disregarded. Peat soils are among the most heterogeneous agricultural soils due to differences in botanical origin, decomposition stage, fiber content, ash content, nutrient distribution, and microbial diversity. Even within a single experimental site, considerable variability may occur over short distances. Such heterogeneity contributes substantially to experimental error and frequently masks relatively small treatment responses. The comprehensive meta-analysis by Kunarso et al. (2022) demonstrated that variability in tropical peat properties often exceeds the magnitude of short-term management effects, particularly for carbon concentration, nitrogen content, and porosity.

The results indicate that the physical, chemical, and biological characteristics of hemic peat remained relatively stable throughout the experimental period. The absence of significant differences does not necessarily imply that biofertilizer was ineffective, but rather suggests that improvements in peat soil quality require longer periods for microbial establishment, nutrient mineralization, and organic matter transformation. Previous studies have consistently shown that the benefits of microbial inoculants become more apparent under long-term application, particularly when integrated with soil ameliorants such as biochar, compost, or other organic amendments that improve microbial habitat and nutrient retention.

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This study therefore highlights that the response of hemic peat soil to biological inputs is governed primarily by intrinsic peat properties rather than by short-term agronomic interventions. Future research should evaluate longer incubation periods, repeated biofertilizer applications, and the integration of microbial inoculants with biochar-based carriers or other peat ameliorants to enhance microbial survival, accelerate nutrient cycling, and improve soil quality under tropical peatland conditions.

To further illustrate the effects of biofertilizer application and irrigation interval on soil chemical properties, the responses of soil total nitrogen (TN) and cation exchange capacity (CEC) under different treatment combinations are presented in Figure 1. Although the statistical analysis indicated no significant treatment effects ($P > 0.05$), the graphical presentation provides a clearer visualization of the numerical variation among treatments.

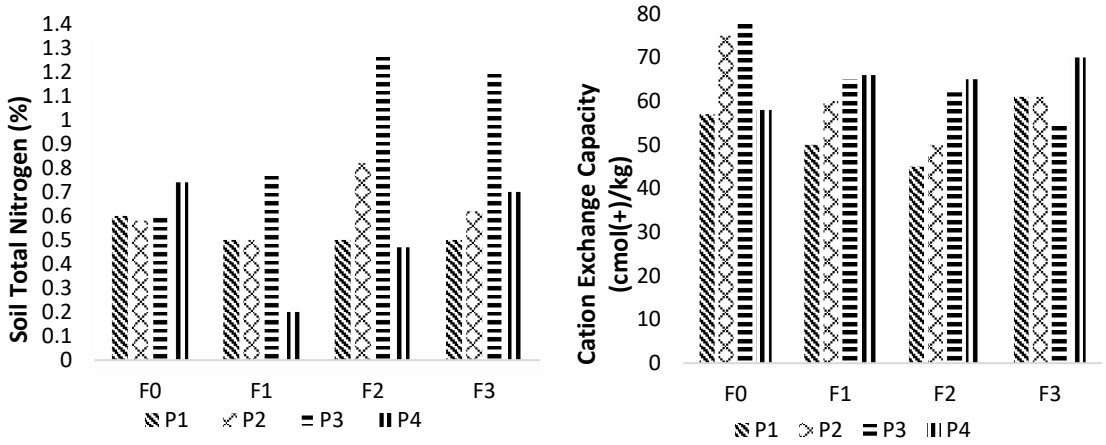


Figure 1. Effects of Biofertilizer Application and Irrigation Interval on (A) Soil Total Nitrogen and (B) Cation Exchange Capacity in Hemic Peat Soil.

Figure 1 (A–B) illustrates the responses of soil total nitrogen (TN) and cation exchange capacity (CEC) following the application of different biofertilizer rates under varying irrigation intervals in hemic peat soil. Statistical analysis showed that neither biofertilizer application, irrigation interval, nor their interaction significantly affected either soil property ($P > 0.05$). Nevertheless, numerical variation among treatment combinations indicates differences in the magnitude of soil response, although these variations were insufficient to produce statistically significant effects.

The concentration of soil total nitrogen remained relatively stable across all treatment combinations, with values fluctuating within a relatively narrow range. Under the control treatment (F0), soil total nitrogen showed moderate variation among irrigation intervals, indicating that differences in water availability alone were insufficient to substantially alter nitrogen accumulation in the peat soil. Similar responses were observed in F1, where nitrogen content remained relatively low and uniform regardless of irrigation interval, suggesting that microbial inoculation at this rate had not yet produced measurable improvements in nitrogen transformation during the experimental period.

A slightly different tendency was observed under F2 and F3, where the intermediate irrigation interval (P3) exhibited numerically higher total nitrogen than the other irrigation treatments. Although these differences were not statistically significant, this tendency may indicate that moderate soil moisture provided a more favorable environment for microbial metabolism and nitrogen transformation than either continuous irrigation or longer irrigation intervals. Soil microorganisms generally require adequate moisture for enzymatic activity and organic nitrogen mineralization; therefore, excessively wet or relatively dry conditions may reduce the efficiency of microbial processes (Soratur *et al*., 2024). However, because peat soils naturally maintain high moisture content, the irrigation treatments applied in this study were probably insufficient to create substantial differences in microbial activity.

The limited response of total nitrogen can also be explained by the characteristics of tropical peat soils. In peat ecosystems, most nitrogen exists in organic forms bound within partially decomposed plant residues rather than as readily available inorganic nitrogen. Consequently, increases in total nitrogen depend largely on gradual mineralization processes mediated by soil microorganisms. These processes generally occur slowly because the acidic environment, limited oxygen diffusion, and high moisture content typical of peat soils reduce microbial decomposition rates (Yuwati *et al*., 2021). Therefore, the absence of significant differences among treatments suggests that nitrogen transformation remained largely controlled by the inherent properties of the peat rather than by short-term management practices.

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Biofertilizer application also requires sufficient time before measurable improvements in soil nitrogen become evident. Following inoculation, beneficial microorganisms must adapt to soil acidity, establish populations in the rhizosphere, compete with indigenous microorganisms, and produce extracellular enzymes involved in nutrient cycling. These biological processes generally develop gradually and often require repeated applications before significant changes in soil nitrogen status can be detected (Aloo *et al*., 2022). Consequently, although F2 and F3 tended to maintain relatively higher nitrogen concentrations under certain irrigation intervals, these numerical differences should be interpreted as response tendencies rather than evidence of superior treatment performance.

Figure 1(B) shows that cation exchange capacity exhibited a response pattern comparable to that of total nitrogen, with relatively small variation among treatment combinations. The control treatment (F0) showed moderate variation in CEC across irrigation intervals, whereas biofertilizer treatments produced slight numerical increases under several irrigation regimes. Among the biofertilizer treatments, F3 tended to maintain relatively higher CEC under P4, while F2 exhibited relatively consistent values under P3 and P4. Nevertheless, these responses remained statistically similar, indicating that biofertilizer application did not substantially alter the exchange capacity of the peat soil during the study period.

The relatively stable CEC is consistent with the chemical characteristics of peat soils. Unlike mineral soils, where CEC is largely influenced by clay minerals, peat soils derive most of their exchange capacity from negatively charged functional groups associated with humified organic matter, particularly carboxyl and phenolic groups (Kunarso *et al*., 2022). Since these functional groups constitute the structural components of peat organic matter, their abundance is unlikely to change appreciably over a single growing season. Therefore, short-term biofertilizer application is more likely to influence nutrient cycling than to modify the intrinsic exchange capacity of the peat matrix.

The slight numerical increase in CEC observed under several biofertilizer treatments may be associated with enhanced microbial activity and gradual decomposition of organic substrates. Microbial metabolism contributes to the formation of humic substances through the transformation of plant residues, potentially increasing the number of functional groups capable of retaining nutrient cations. However, humification is a relatively slow process, and measurable changes in CEC generally require long-term organic matter transformation rather than a single cropping cycle (Singla Just *et al*., 2024). Therefore, the relatively small variation observed in this study is consistent with the expected temporal dynamics of peat organic matter.

When soil total nitrogen and CEC are considered together, both parameters exhibited similar response patterns. Treatments that tended to maintain relatively higher total nitrogen also generally showed relatively higher CEC, particularly under the intermediate irrigation intervals. Although this relationship was not statistically significant, it is consistent with the close association between nitrogen cycling and the abundance of soil organic matter. Organic matter serves not only as the principal reservoir of nitrogen but also as the primary source of negatively charged functional groups responsible for cation exchange. Consequently, gradual improvements in nitrogen mineralization may eventually contribute to improved nutrient retention through enhanced organic matter transformation (Aloo *et al.,* 2022).

The absence of significant interaction effects further indicates that irrigation management did not substantially modify the response of biofertilizer to either parameter. Because hemic peat possesses exceptionally high water-holding capacity, differences in irrigation interval probably resulted in only minor variation in soil water availability within the root zone. As a result, microbial activity, nitrogen transformation, and nutrient retention proceeded under relatively similar environmental conditions across all irrigation treatments. Yuwati *et al*. (2021) emphasized that the hydrological behavior of tropical peat tends to buffer short-term fluctuations in soil moisture, thereby reducing the influence of seasonal irrigation practices on peat chemical properties.

Another factor contributing to the observed variability is the natural heterogeneity of peat soils. Differences in peat maturity, botanical origin, fiber content, ash content, and indigenous microbial communities commonly occur within relatively small spatial scales, increasing experimental variability and reducing the statistical sensitivity to detect treatment effects. Kunarso et al. (2022) reported that such heterogeneity is a characteristic feature of tropical peatlands and frequently masks relatively small changes induced by agronomic management during short-term experiments.

In general, the results suggest that biofertilizer application under different irrigation intervals was able to maintain soil total nitrogen and cation exchange capacity within the normal range of hemic peat without causing deterioration of soil chemical quality. Although significant improvements were

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not detected during the experimental period, the numerical tendencies observed in several treatment combinations indicate that moderate soil moisture may provide a more favorable environment for microbial activity and nutrient cycling. These responses are likely to become more evident under longer experimental periods, repeated biofertilizer applications, or integration with soil amendments such as biochar that improve microbial habitat and nutrient retention.

The responses of soil organic carbon (SOC) and soil porosity to different biofertilizer application rates and irrigation intervals are presented in Figure 2. Similar to the other soil physicochemical properties, neither factor nor their interaction significantly affected SOC or soil porosity ($P > 0.05$). Nevertheless, the figure illustrates the numerical trends observed among treatment combinations and provides additional insight into the stability of hemic peat soil properties during the experimental period.

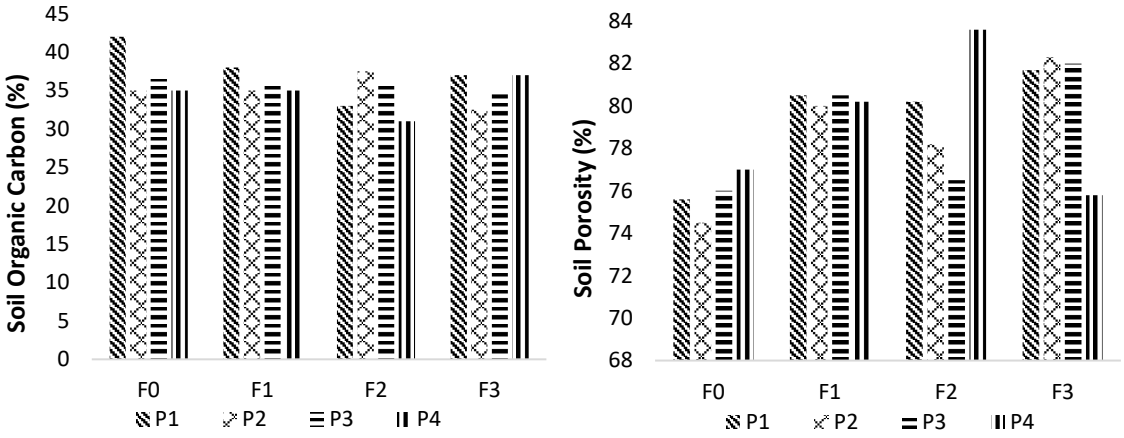


Figure 2. Response of (A) Peat Soil Organic Carbon Content and (B) Peat Soil Porosity to the Combined Effects of Biofertilizer Application and Drought Intensity in Peat Soil

Figure 2(C–D) shows the response of soil organic carbon (SOC) and soil porosity following biofertilizer application under different irrigation intervals in hemic peat soil. Statistical analysis indicated that neither biofertilizer application, irrigation interval, nor their interaction significantly affected SOC and soil porosity ($P > 0.05$). Nevertheless, the numerical variation among treatments illustrates the tendency of peat soil to respond differently to water management and microbial inoculation while maintaining relatively stable physical and chemical characteristics.

The SOC values remained within a relatively narrow range throughout the experiment regardless of biofertilizer dose or irrigation interval. Under the control treatment (F0), SOC showed only minor variation among irrigation regimes, suggesting that the native carbon reserve of the peat remained relatively stable during one growing season. Similar patterns were observed in F1, F2, and F3, where fluctuations in SOC were relatively small and did not follow a consistent increasing or decreasing trend across irrigation intervals. This finding indicates that the application of biofertilizer did not substantially alter the overall carbon stock of the hemic peat during the experimental period.

The relatively stable SOC content is consistent with the behavior of tropical peat ecosystems, where organic carbon is accumulated over long periods through incomplete decomposition of plant residues. Because hemic peat already contains abundant humified organic material, the contribution of newly added microbial biomass or root residues during a single cropping season represents only a small proportion of the total carbon pool. Consequently, measurable changes in SOC generally occur gradually and become evident only after prolonged management or repeated organic amendments (Leifeld & Menichetti, 2018). Furthermore, peat carbon dynamics are strongly regulated by groundwater conditions and decomposition intensity rather than short-term agronomic practices.

Although statistical differences were not detected, several numerical tendencies deserve consideration. Under F2, SOC appeared slightly higher at the intermediate irrigation interval than under the longest irrigation interval, whereas F3 showed relatively similar SOC values across all irrigation treatments. These observations may suggest that maintaining adequate soil moisture supported microbial activity without substantially accelerating organic matter decomposition. However, because the differences were small and statistically non-significant, these responses should be interpreted as normal variation rather than evidence of treatment superiority.

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Soil porosity exhibited a response pattern comparable to that of SOC. Overall porosity remained high under all treatment combinations, reflecting the naturally porous structure of hemic peat. Under F0, porosity fluctuated only slightly among irrigation intervals, indicating that differences in irrigation frequency were insufficient to modify the physical architecture of the peat matrix. Similar responses were also observed under biofertilizer treatments, where porosity remained relatively constant despite minor numerical differences among irrigation intervals.

The consistently high porosity observed throughout the experiment reflects the fibrous structure of hemic peat, which naturally contains abundant interconnected macro- and micropores. These pore systems allow peat soils to retain considerable amounts of water while simultaneously maintaining gaseous exchange within the root zone. Because the experimental irrigation intervals did not substantially alter peat moisture conditions, the overall pore structure remained relatively stable. Similar observations have been reported by Ahmad et al. (2020), who demonstrated that peat physical properties are largely governed by peat maturity and hydrological conditions rather than short-term cultivation practices.

The application of biofertilizer also did not significantly modify soil porosity. Nevertheless, F1 and F3 tended to maintain relatively high porosity under several irrigation intervals compared with the control. Although these numerical differences were not statistically significant, they suggest that microbial inoculation was able to maintain soil structural quality throughout the experiment. Plant growth-promoting microorganisms can produce extracellular polysaccharides and fungal hyphae that contribute to soil particle cohesion and pore continuity. However, these biological processes generally require repeated inoculation and longer incubation periods before measurable improvements in soil physical properties become apparent (Naylor & Coleman-Derr, 2018).

When SOC and porosity are considered together, both parameters exhibited closely related response patterns. Treatments showing relatively stable SOC also maintained relatively stable porosity, indicating that changes in peat organic matter were accompanied by minimal changes in soil structure. This relationship is expected because soil organic matter constitutes the principal framework of peat soils. Organic matter contributes directly to aggregate stability, pore formation, and water retention, while simultaneously serving as the primary energy source for soil microorganisms (Lehmann *et al*., 2020). Consequently, relatively constant SOC concentrations were associated with relatively unchanged porosity throughout the experiment.

The absence of significant interaction between biofertilizer and irrigation interval further suggests that soil moisture conditions remained within a range suitable for maintaining peat structural stability. Tropical peat possesses exceptionally high water-holding capacity, enabling the soil to buffer temporary fluctuations in irrigation frequency. Therefore, differences in irrigation interval were insufficient to induce peat shrinkage, excessive oxidation, or structural collapse during the experimental period (Evans *et al*., 2021).

The relatively small variation observed among treatments may also be attributed to the natural heterogeneity of peat soils. Variations in botanical composition, decomposition stage, fiber distribution, and organic matter quality commonly occur within short spatial distances, resulting in considerable variability among experimental units. Such heterogeneity frequently reduces the statistical sensitivity for detecting relatively small treatment responses during short-term experiments (Nichols & Peteet, 2019).

Collectively, the present results indicate that biofertilizer application under different irrigation intervals maintained soil organic carbon and soil porosity within the normal range of hemic peat without substantially altering either parameter. The absence of significant differences suggests that the intrinsic properties of peat exerted greater control over carbon storage and soil physical condition than the applied management treatments. Nevertheless, the numerical trends observed under several treatment combinations indicate that maintaining adequate soil moisture together with microbial inoculation may contribute to preserving peat quality over time. Future studies involving longer experimental periods and repeated biofertilizer application are therefore required to determine whether these early responses develop into measurable improvements in peat carbon dynamics and soil physical quality.

CONCLUSION

The present study demonstrated that biofertilizer application and irrigation interval, either individually or in combination, did not significantly affect maize growth, soil organic carbon, total nitrogen, cation exchange capacity, or soil porosity in hemic peat soil during a single growing season. These findings indicate that the intrinsic physicochemical characteristics of hemic peat, including high organic matter

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content, high water-holding capacity, acidic conditions, and slow nutrient mineralization, exerted a greater influence on soil properties than short-term agronomic interventions. Although statistical differences were not detected, several treatments receiving moderate to high biofertilizer rates showed consistent numerical trends toward improved soil quality indicators, suggesting potential long-term benefits. Furthermore, the substantially higher soil respiration observed in peat soil compared with mineral soil confirmed the high susceptibility of tropical peatlands to carbon loss under drought conditions. Therefore, improving peat soil productivity and sustainability is likely to require longer-term biofertilizer application, repeated microbial inoculation, and integration with suitable soil ameliorants such as biochar to enhance microbial establishment, nutrient cycling, and carbon retention. These findings provide valuable information for the development of sustainable peatland management strategies aimed at maintaining soil quality while minimizing carbon emissions under increasing drought stress.

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