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Effects of Organic and Mineral Fertilization, and Mycorrhizal Inoculation on the Growth and Agronomic Performance of Two Taro (*Colocasia esculenta* (L.) Schott) Varieties in Bamendjou, Western Highlands of Cameroon

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Abstract

Taro (*Colocasia esculenta* (L.) Schott) is an essential tuber crop contributing to food security and rural livelihoods in tropical regions, particularly in the Western Highlands of Cameroon. However, declining soil fertility severely restricts its agricultural productivity. This study evaluated the individual and synergistic effects of organic fertilization, mineral fertilization, and arbuscular mycorrhizal fungal (AMF) inoculation on the growth, morphological, and physiological parameters of two local taro varieties: ACHU (var. *esculenta*) and IGBO (var. *antiquorum*), grown in Bamendjou. The experiment followed a randomized complete block design (RCBD) featuring a 2 × 7 × 3 factorial arrangement: Variety × Treatment × Period with three replications. Treatments comprised: T0 (Control without inputs), T1 (100% NPK 20:10:10), T2 (100% Compost: *Tithonia diversifolia* + poultry manure), T3 (100% Mycorrhizal Inoculum: *Rhizophagus irregularis*, *R. hoi*, *Gigaspora margarita*), T4 (50% Compost + 50% NPK), T5 (50% Compost + 50% Mycorrhizae), and T6 (50% NPK + 50% Mycorrhizae). Key parameters measured included plant height, collar diameter, leaf count, leaf area expansion, chlorophyll content, proline accumulation, flavonoids, and soluble sugars. The results demonstrated that soil fertility management practices significantly ($p < 0.05$) enhanced vegetative growth and physiological status across both varieties compared to unfertilized control

plots. Integrated nutrient management regimes, specifically T2 (100% compost), T4 (50% compost + 50% NPK), and T6 (50% NPK + 50% mycorrhizae), produced the most outstanding vegetative growth, maximum collar diameter expansion, and accelerated leaf area development. Furthermore, physiological traits exhibited pronounced treatment responses; total chlorophyll, free proline, and soluble sugars were significantly upregulated under T2, T4 and T6, signaling enhanced photosynthetic capacity and osmoprotective adjustments. Varietal differences were evident, with IGBO displaying higher baseline chlorophyll levels and distinct biochemical plasticity under stress-adapting combinations. These findings highlight the significant agronomic value of organic compost and integrated management approaches that combine organic amendments, reduced synthetic fertilizer doses, and mycorrhizal symbiosis for sustainable taro production in the Western Highlands of Cameroon.

Keywords

Taro, Compost, NPK, Mycorrhizae, Growth, Chlorophyll, Proline, Sustainable Agriculture

1. Introduction

Taro (*Colocasia esculenta* (L.) Schott) is an essential tuberous crop belonging to the Araceae family, widely cultivated across tropical and subtropical regions for its starch-rich corms and nutritious culinary leaves [1] [2]. Beyond its central role in dietary diversification, taro serves as a crucial driver for household food security and rural income generation. Recent agronomic advances demonstrate that organic management practices can significantly boost taro growth and yield, underscoring its growing importance in sustainable farming systems [3] [4]. To optimize crop performance, integrating biological amendments such as arbuscular mycorrhizal fungi (AMF) alongside organic inputs has shown remarkable synergistic effects on plant nutrient uptake, soil structure preservation, and stress tolerance across various root and tuber crops [5] [6]. Organic amendments enhance physical soil attributes, such as soil aggregation, porosity, and water-holding capacity, while creating a favorable rhizosphere environment that stimulates beneficial soil biodiversity and mycorrhizal proliferation [7] [8]. In turn, this symbiotic network accelerates nutrient delivery to the plant root system, with a particularly vital impact on phosphorus (P) acquisition. Furthermore, this integrated approach mitigates abiotic stressors by modulating key biochemical responses, including osmotic adjustment and antioxidant defense activity. Consequently, it offers a robust framework for improving taro productivity while reducing reliance on synthetic agrochemicals, aligning with broader evidence that AMF symbiosis promotes disease suppression and overall physiological vigor in *C. esculenta* [5] [9].

In the Western Highlands of Cameroon, agricultural productivity is severely

constrained by declining soil fertility, accelerated topsoil erosion, and organic matter depletion [10] [11]. The region's tropical ferrallitic soils are characteristically highly leached, clay-rich, and strongly acidic, resulting in low general mineral availability and severe phosphorus immobilization through structural fixation with iron (Fe^{3+}) and aluminum (Al^{3+}) oxides [12] [13]. Although synthetic mineral fertilizers provide rapid, short-term improvements in crop growth, their high cost, low agronomic use efficiency, and long-term soil degradation risks, such as secondary acidification and loss of biological diversity, highlight the urgent need for sustainable alternatives [14] [15]. Organic inputs, particularly quality-controlled composts derived from plant biomass and animal manures like *Tithonia diversifolia* and poultry manure respectively, offer a viable strategy for restoring physical, chemical, and biological soil properties while replenishing soil organic carbon pools in tropical agrosystems [16] [17]. However, because organic sources often exhibit slow mineral release dynamics and variable P contents, pairing organic inputs with biological biofertilizers, notably native AMF strains, presents an optimal pathway for ecological intensification [9] [18].

The physical and biochemical mechanisms driving AMF-mediated crop enhancement are rooted in the expansion of an extra-radical hyphal network that extends beyond the root depletion zone, fundamentally altering the surrounding hyphosphere micro-environment [19]. Mycorrhizal colonization directly improves root hydraulic conductivity, phosphorus solubilization, and seedling establishment under stress [20] [21]. Importantly, the effectiveness of mycorrhizal symbiosis is heavily modulated by local phosphorus management. Moderate or low phosphorus additions combined with AMF inoculation enhance root colonization efficiency and leaf nutrient accumulation, whereas excessive mineral P inputs significantly suppress root colonization intensity, spore density, and functional mycorrhizal efficiency [12] [13]. Field surveys and trapping studies across diverse agroecological zones in Cameroon have isolated rich native AMF assemblages spanning multiple genera, including *Glomus*, *Acaulospora*, *Gigaspora*, *Funneliformis*, *Rhizophagus*, *Septoglomus*, and *Scutellospora* [12] [22]. Utilizing these indigenous AMF populations offers a distinct physiological advantage, as locally adapted strains exhibit superior resilience and functional compatibility under regional pedoclimatic conditions compared to exotic formulations [18] [22].

Combining organic, mineral, and biological inputs thus represents a highly effective agronomic strategy to optimize vegetative and physiological performance in *C. esculenta*. This integrated nutrient management approach restructures rhizosphere ecology by encouraging beneficial microbial populations, such as phosphate-solubilizing and plant-growth-promoting rhizobacteria, and boosting substrate-induced enzymatic activity [23] [24]. Furthermore, AMF symbiosis triggers key physiological protections, stimulating chlorophyll biosynthesis, osmotic regulation, and free proline accumulation to buffer the photosynthetic apparatus against environmental stress [25] [26]. Investigating these multi-input synergies is essential for identifying fertilizer combinations capable of stabilizing crop yields

while conserving long-term soil health [8].

This study aims to evaluate the interactive effects of organic fertilization (compost), mineral fertilization (NPK), and native mycorrhizal inoculation on the growth, yield, and physiological parameters of two contrasting taro varieties (ACHU and IGBO) grown in Bamendjou, located in the Western Highlands of Cameroon. By assessing the agronomic efficacy of single-source versus integrated inputs, this research seeks to establish a replicable, rate-sensitive nutrient management framework that enhances crop vigor and metabolic resilience in resource-constrained smallholder farming systems. Additionally, systematic evaluation of these practices provides vital empirical data for optimizing nutrient use efficiency in acidic ferrallitic soils, where sole reliance on chemical inputs fails to sustain long-term fertility. Finally, utilizing indigenous AMF strains is prioritized to leverage their evolutionary adaptation to regional soil environments, offering a scalable, nature-based solution for sustainable food production in Central Africa.

2. Materials and Methods

2.1. Experimental Site

The field trial was conducted during the rainy season, spanning from late July 2024 to mid-February 2025, in the Bamendjou Sub-division within the Hauts-Plateaux Division, West Region of Cameroon (5˚22'N, 10˚18'E; altitude ~1350 m a.s.l.). The site experiences a high-altitude equatorial monsoon climate characterized by an average annual rainfall ranging from 1500 to 1800 mm, mean annual temperatures between 20˚C and 22˚C, and consistently elevated relative humidity throughout the year.

2.2. Soil and Compost Sampling and Analysis

Soil samples were collected from the experimental site following the sampling procedure described by Wamba *et al.* [27]. The collected soil samples were properly labelled, transported to the laboratory, and analyzed for their physicochemical properties. A representative sample of the compost used in the experiment was also collected separately and submitted for physicochemical analysis. Both soil and compost samples were analyzed at the Laboratory of Soil Analysis and Environmental Chemistry, Faculty of Agronomy and Agricultural Sciences, University of Dschang, Cameroon (**Table 1**).

The compost was considered mature and well stabilized, as indicated by its near-neutral pH (6.5) within the pH 6 - 8 window reported for mature composts [28]. Its low C/N ratio (10.33), which sits squarely within the standard 10 - 15 maturity range [28] and closely matches the optimal C/N of ≈ 10:1 - 12:1 reported for high-quality chimato composts produced by blending *Tithonia diversifolia* with maize stalks or grass in 50:50 or 60:40 volumetric ratios [29]; the absence of unpleasant odor, since the disappearance of ammonia and reduced-sulphur volatiles is a classical indicator of stabilized organic matter [28] [30] and fully mature compost.

Table 1. Physico-chemical characteristics of the experimental soil and compost.

Sample	Soil	Compost
Clay %	25.50	
Sand %	41.50	
Silt %	33.00	
Organic Carbon (OC) %	4.42	31
Total Nitrogen (N) %	0.12	3.0
C/N ratio%	36.8	10.33
Organic matter % (OM)	7.62	58
Available Phosphorus (P) (mg/kg)	5.49	8.880
Exchangeable Potassium (k) ($mg{\cdot}kg^{-1}$)	0.59	1800
Exchangeable Sodium (Na) ($mg{\cdot}kg^{-1}$)	0.03	123
Exchangeable calcium (Ca) ($mg{\cdot}kg^{-1}$)	2.16	14,720
Exchangeable Magnesium(Mg) ($mg{\cdot}kg^{-1}$)	1.84	8546.4
pH (H_2O)	6.30	6.5
Cation exchange capacity CEC ($Cmol_c{\cdot}kg^{-1}$)	15.7	

2.3. Plant Material

Two locally cultivated varieties of taro (*Colocasia esculenta* (L.) Schott) were evaluated:

- *Eddoes* (*ACHU*): *Colocasia esculenta* var. *antiquorum*, a triploid (3n = 3x = 42) variety of Asian origin, characterized morphologically by a small central corm and numerous prominent cormels.
- *Dasheen* (*IGBO*): *Colocasia esculenta* var. *esculenta*, a diploid (2n = 2x = 28) variety of Pacific origin, characterized by a large central corm with minimal to no cormel formation.

2.4. Fertilizers and Mycorrhizal Inoculum

Three fertilizer sources were utilized, either individually or in combination:

- *Compost:* Prepared locally using equal mass ratio of fresh *Tithonia diversifolia* biomass (75kg of chopped leaves and tender stems) and laying hen manure (75kg) obtained from local poultry farms. The mixture underwent aerobic composting for three months, with bi-weekly turnings to facilitate uniform aeration and decomposition.
- *Mineral Fertilizer:* Commercial NPK 20:10:10 formulation (20% N, 10% P_2O_5, 10% K_2O), representing the standard recommended compound fertilizer for food crop production in Cameroon.
- *Arbuscular Mycorrhizal Inoculum:* The inoculum consisted of two arbuscular mycorrhizal fungal species supplied as root- and soil-based cultures: *Gigaspora margarita*, containing 5 - 10 $spores{\cdot}g^{-1}$ with 85% infective spores, and *Rhizoph-*

agus hoi, containing 15 - 20 spores·g^{-1} with 90% propagated and sourced from the Soil Laboratory at the University of Yaounde I.

2.5. Experimental Design and Sampling Structure

The experiment was arranged in a randomized complete block design (RCBD) comprising seven treatments and three replications for each variety (Figure 1). Each experimental unit consisted of a plot containing three plants spaced at 0.50 m × 0.50 m. For each variety, a total of 21 experimental units (7 treatments × 3 replications) were established, resulting in 42 experimental units for the entire experiment. All three plants within each plot were measured, and the mean value was used as the experimental observation for statistical analysis. Treatments consisted of seven distinct soil amendment regimes applied at the vegetative stage (the seedlings were raised in the nursery for 30 days and upon transplantation to the field, the various treatments were applied immediately and thereafter no other application was made) replicated three times across both taro varieties. The codification and details of the experimental treatments are summarized in Table 2.

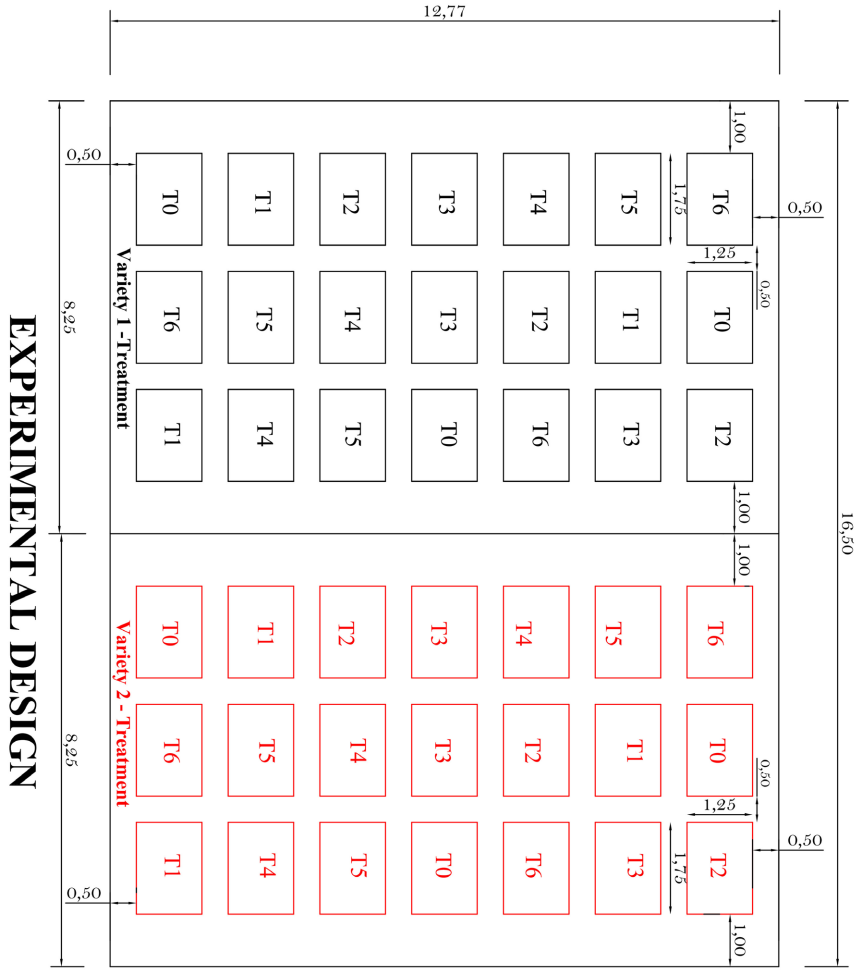

Figure 1. Experimental design and sampling structure.

Table 2. Codification and description of experimental treatments.

Code	Treatment Description
T0	Control (no fertilizer application or mycorrhizal inoculation)
T1	20 g (100%) Mineral Fertilizer (NPK 20:10:10)
T2	600 g (100%) Compost (*T. diversifolia* + poultry manure)
T3	100 g (100%) Arbuscular Mycorrhizal Inoculum
T4	300 g (50%) Compost +10 g (50%) Mineral Fertilizer (NPK)
T5	300 g (50%) Compost + 50 g (50%) Arbuscular Mycorrhizal Inoculum
T6	10 g (50%) Mineral Fertilizer (NPK) + 50 g (50%) Arbuscular Mycorrhizal Inoculum

2.6. Data Collection and Parameter Measurements

2.6.1. Morphological Growth Parameters

Morphological development was monitored non-destructively *in situ* across five primary growth parameters:

- *Plant Height* (cm): Measured using a flexible graduated measuring tape from the soil surface to the insertion point of the petiole on the youngest fully expanded leaf.
- *Collar Diameter* (mm): Measured at ground level using a precision digital caliper.
- *Number of Functional Leaves:* Determined by an exhaustive count of all fully green, functional leaves displaying > 50% active photosynthetic surface area.
- *Leaf Length* (L, cm): Measured along the midrib from the petiole insertion point to the leaf apex.
- *Leaf Width* (W, cm): Measured at the widest portion of the lamina perpendicular to the primary vein.

2.6.2. Physiological and Biochemical Analyses

Biochemical assays were performed using fresh foliage excised from the third fully expanded leaf from the plant apex. Samples were kept stored at 4˚C during transport and processed within 24 hours of collection:

- *Total Chlorophyll Content* (mg/g·FW): Quantified spectrophotometrically following extraction in acetone according to Arnon, D.I. [31] method.
- *Free Proline Content* (µmol/g·FW): Extracted and determined colorimetrically using acid-ninhydrin reagent as described by Bates *et al.* [32], Cha *et al.* [33].
- *Total Flavonoid Content* (mg QE/g·FW): Assayed via the aluminum chloride ($AlCl_3$) colorimetric method and expressed as quercetin equivalents (QE).
- *Total Soluble Sugars* (mg/g·FW): Determined colorimetrically using the phenol-sulfuric acid method established by Dubois *et al.* [34], Kultur *et al.* [35].

2.7. Statistical Analysis

Repeated growth data were subjected to a three-way Analysis of Variance (ANOVA):

Variety × Treatment × Period at a significance threshold of alpha = 0.05 using RStudio software. Block effects were modeled as random factors within a linear mixed-effects model framework. Where main effects or interaction terms V × T, V × P, T × P, and V × T × P were statistically significant, post-hoc multiple mean comparisons were carried out using Tukey's Honestly Significant Difference (HSD) test. Meanwhile Biochemical and physiological Data were subjected to two-way analysis of variance (ANOVA) to evaluate the effects of treatment, variety, and their interaction. When significant differences were detected, treatment means were compared using Tukey's multiple comparison test at the 5% significance level ($p < 0.05$) and graphs were plotted using GraphPad Prism (Version 8.0.1 (244); San Diego, CA, USA).

3. Results

3.1. Overview of Statistical Significance

The three-way ANOVA revealed strong significant main effects and interaction terms across both vegetative and biochemical attributes (Table 3 and Table 4).

Table 3. Summary ANOVA of main vegetative growth parameters.

Parameter	Significant Effects	Main Interpretation
Plant height	Variety, treatment, period, and main interactions significant ($p < 0.001$)	Growth heavily depends on treatment, variety, and time.
Collar diameter	Treatment and period significant ($p < 0.001$); variety non-significant	Diameter depends mainly on nutrient supply and growth stage.
Leaf width	Variety, treatment, and period significant ($p < 0.001$)	Treatments strongly modify leaf development.
Leaf area	Variety, treatment, period, and triple interaction significant ($p = 0.023$)	Leaf area depends simultaneously on treatment, variety, and time.

Table 4. Summary ANOVA of physiological and biochemical parameters.

Parameter	Variety Effect	Treatment Effect	Interaction (V × T)	Conclusion
Total Chlorophyll	$p = 2.87 \times 10^{-9}$ (***)	$p = 0.0013$ (**)	$p = 0.1456$ (ns)	Content depends mostly on variety and treatment.
Soluble Sugars	$p = 3.32 \times 10^{-5}$ (***)	$p = 2.99 \times 10^{-11}$ (***)	$p = 8.45 \times 10^{-7}$ (***)	Strong metabolic response to applied treatments.
Proline	$p = 0.2796$ (ns)	$p = 0.1274$ (ns)	$p = 0.00524$ (**)	Response depends mainly on variety-treatment combination.
Flavonoids	$p = 0.320$ (ns)	$p = 0.490$ (ns)	$p = 0.639$ (ns)	Variations observed but statistically non-significant.

(***) and (**) represent the degree of statistical significance. (ns) = non-significant variations.

3.2. Plant Height Response

ANOVA revealed a highly significant effect of variety, treatment, and sampling period on plant height (Figure 2). Interactive effects V × T, V × P, and T × P were also significant. Overall, treatments T2, T4, and T6 exhibited the highest growth rates

across the evaluation period. Treatment T4 (50% Compost + 50% NPK) recorded the highest overall plant heights at the end of the vegetative cycle, whereas the unfertilized control (T0) remained consistently among the lowest performers.

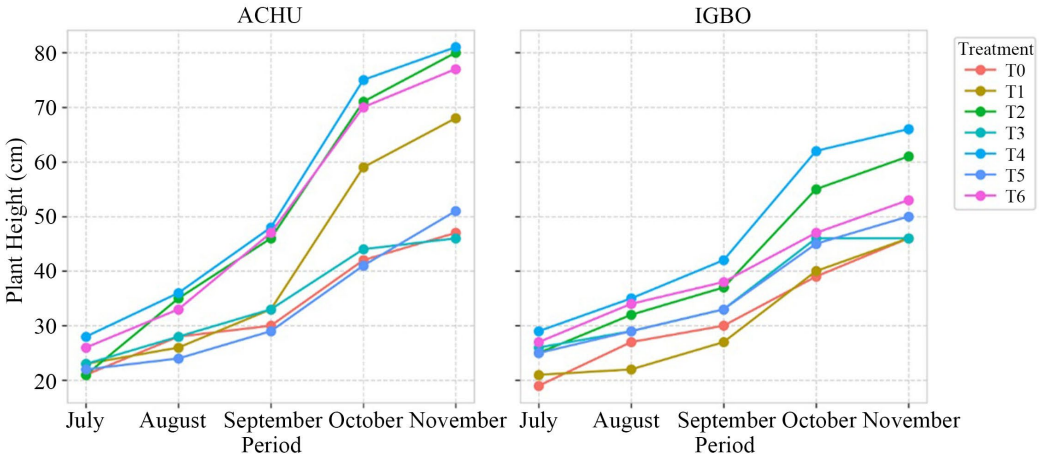

Figure 2. Effect of variety, treatment, and period on plant height.

3.3. Collar Diameter Dynamics

Collar diameter increased progressively throughout the growing cycle across all treatments (**Figure 3**). Treatments T2, T4, and T6 yielded the largest collar diameters, reflecting superior vegetative vigor. Treatment and period effects were highly significant ($p < 0.001$), whereas varietal differences were less pronounced for this structural parameter.

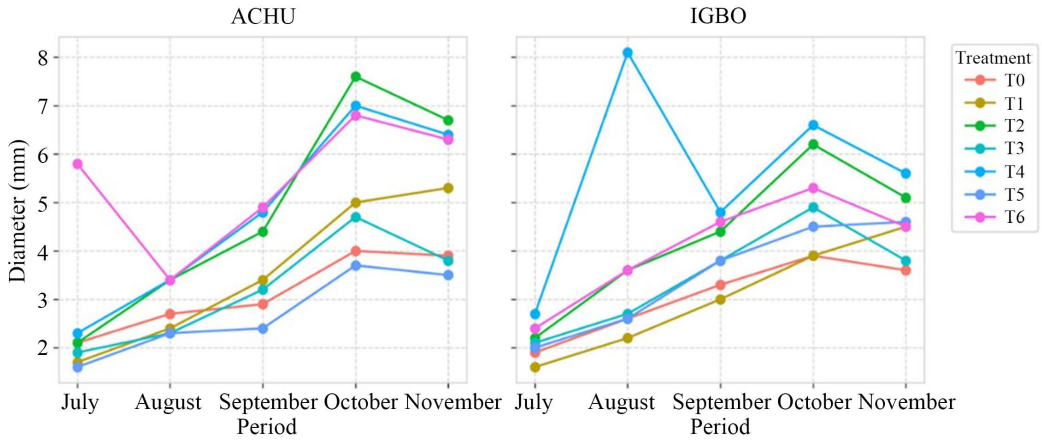

Figure 3. Treatment and period effects on collar diameter.

3.4. Leaf Number Dynamics

Functional leaf count varied according to variety, treatment, and growth period (**Figure 4**). Combined fertilization and biological treatments (T4 and T6) generally favored the retention of a larger photosynthetic canopy prior to the expected physiological leaf senescence observed near crop harvest.

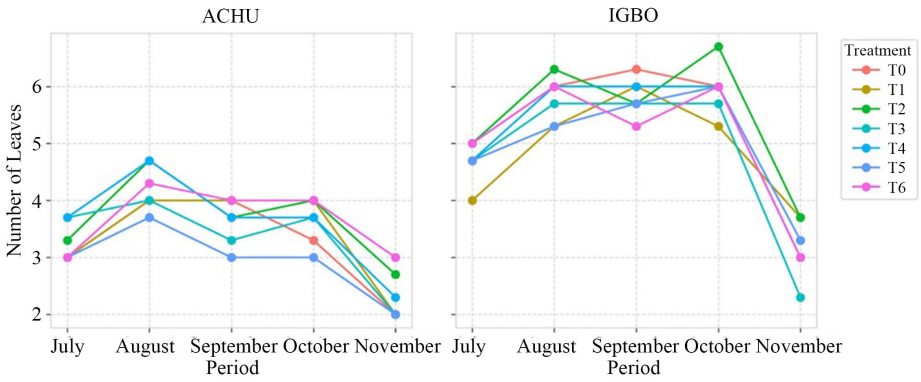

Figure 4. Variation of functional leaf count according to variety, treatment, and time.

3.5. Leaf Area Expansion

Leaf area varied significantly across treatments, varieties, and sampling periods V × T × P, p = 0.023. In variety ACHU, treatments T4 and T6 induced a sharp increase in total leaf area during November. In variety IGBO, treatments T4, T2, and T6 also produced markedly higher photosynthetic leaf surface areas compared to unfertilized control plants (Figure 5).

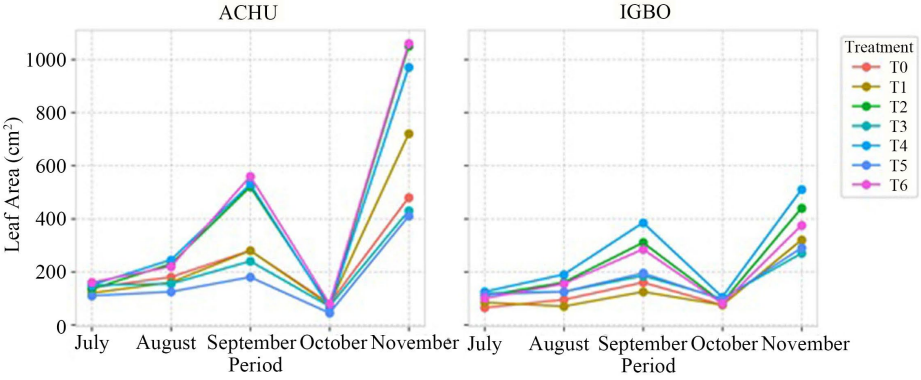

Figure 5. Variation of leaf area across treatments, varieties, and sampling periods.

3.6. Total Chlorophyll Content

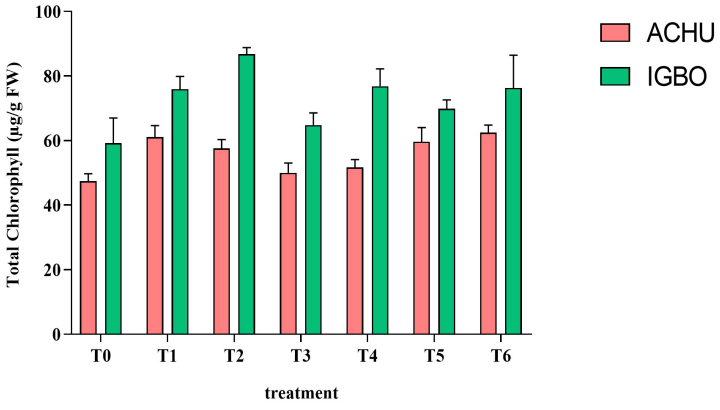

Figure 6. Total chlorophyll content by variety and treatment.

Total chlorophyll content was strongly influenced by main factors variety ($p = 2.87 \times 10^{-9}$) and treatment ($p = 0.0013$). Baseline chlorophyll concentrations were generally higher in IGBO than in ACHU (Figure 6). Sole compost (T2), and combined regimes (T4 and T6) significantly promoted chlorophyll accumulation, signaling enhanced photosynthetic potential.

3.7. Proline Accumulation

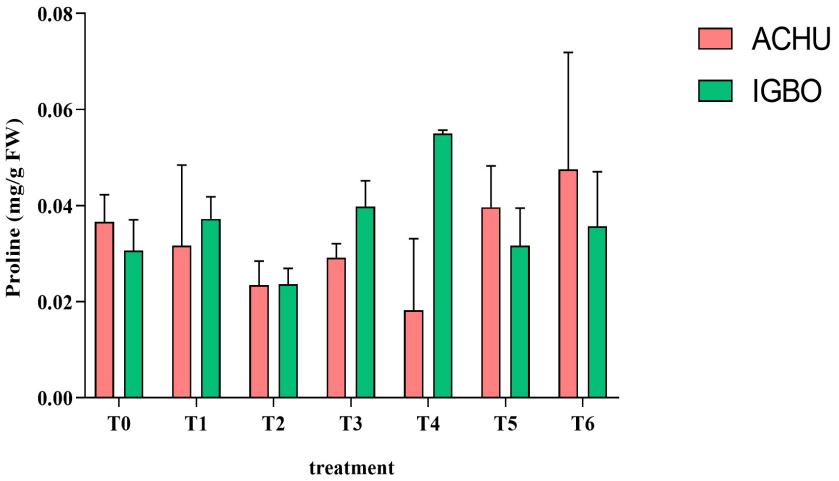

Figure 7. Proline accumulation with respect to variety and treatment interactions.

Free proline accumulation exhibited a highly significant variety-by-treatment interaction V × T, $p = 0.00524$. In ACHU, maximum proline levels were observed under T6 (50% NPK + 50% Mycorrhizae), whereas in IGBO, T4 (50% Compost + 50% NPK) induced the strongest proline accumulation (Figure 7). This response indicates a variety-specific osmotic adjustment and stress adaptation mechanism under distinct nutrient amendment regimes.

3.8. Total Flavonoids

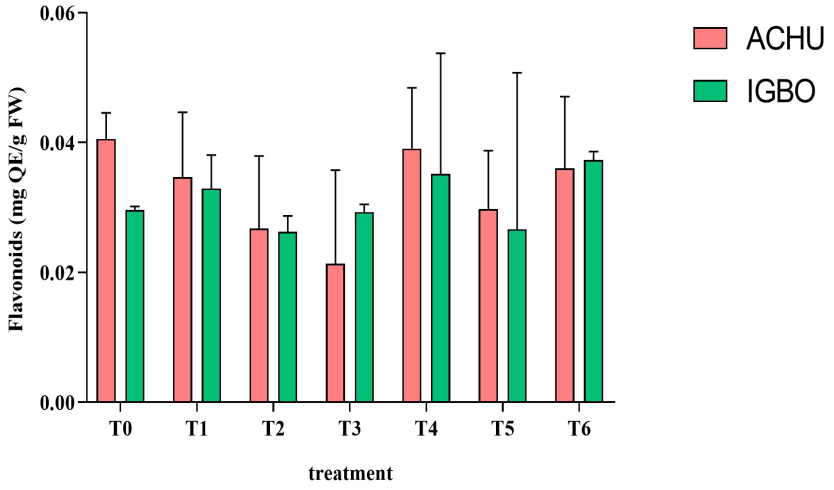

Figure 8. Flavonoid contents variation across treatments and varieties.

Flavonoid contents varied visually across treatments and varieties, though global main effects and interactions were statistically non-significant ($p > 0.05$; Figure 8). Nevertheless, observable trends suggest a variable stimulation of secondary polyphenol metabolism under combined nutrient inputs.

3.9. Total Soluble Sugars

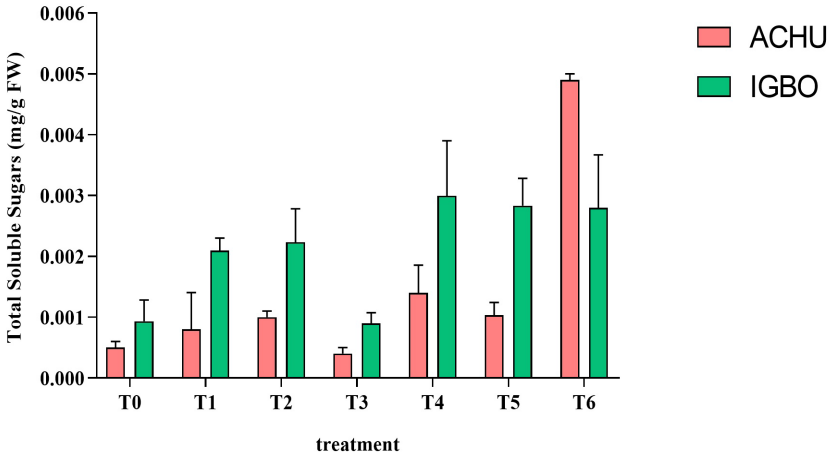

Figure 9. Soluble sugar levels by variety, treatment, and their interaction.

Total soluble sugar levels were heavily governed by variety ($p = 3.32 \times 10^{-5}$), treatment ($p = 2.99 \times 10^{-11}$), and their interaction ($p = 8.45 \times 10^{-7}$). The highest soluble sugar concentrations were registered under integrated treatments T4 and T6, pointing to elevated carbohydrate synthesis and active photo assimilate translocation (Figure 9).

4. Discussion

The results of this study demonstrate that integrated soil fertility management practices significantly enhance both the vegetative growth and physiological status of taro (*Colocasia esculenta*) in the Western Highlands of Cameroon. The observed variations across treatments reflect fundamental differences in nutrient availability, rhizosphere microbial dynamics, and variety-specific physiological mechanisms.

4.1. Nutrient Limitations and Control Performance

The poor vegetative growth and physiological performance observed in the unfertilized control plots (T0) across both taro varieties underscore the severe soil fertility constraints inherent to the highly weathered, highly leached ferrallitic soils of the Western Highlands of Cameroon. In these low-input environments, unamended soils fail to supply adequate macronutrients to meet the crop's demand during critical growth stages, severely restricting canopy development, collar diameter expansion, and leaf area accumulation. These findings align with the paradigm established by Agegnehu & Amede [36], who demonstrated that tropical

agro-ecosystems suffer widespread land degradation, intense nutrient mining, and organic matter depletion when crops are managed without external nutrient inputs. Without targeted amendments, the natural supply capacity of tropical soils is insufficient to sustain optimal crop development. Conversely, the significantly enhanced vegetative vigor, leaf area expansion, and physiological performance recorded under integrated nutrient management regimes (T4: 50% Compost + 50% NPK and T6: 50% NPK + 50% Mycorrhizae) highlight a powerful synergistic mechanism. The integrated use of organic, inorganic, and biological inputs optimizes both soil nutrient availability and plant uptake efficiency.

With regards to Physico-Chemical & Biological Complementarity, Agegnehu & Amede [36] emphasized that Integrated Soil Fertility Management (ISFM) bridges the gap between fast-acting synthetic inputs and long-term soil health. Mineral fertilizers provide an immediate, readily available pool of essential macronutrients (N, P, K) during early crop establishment, while recycled organic amendments (compost) build soil organic matter, improve moisture retention, minimize nutrient leaching, and gradually release mineralized nutrients over time.

Concerning Tuber Crop Responsiveness to Integrated Inputs, similar synergistic yield and growth benefits have been documented in other tropical root and tuber crops. For instance, Biratu *et al.* [37] demonstrated that combining organic poultry manure with mineral NPK fertilizers significantly increased cassava stem girth, canopy development, and root yields by up to 29% compared to sole mineral fertilization, while simultaneously optimizing the agronomic efficiency of N, P, and K. In the present study, a similar response was observed in taro, where partial substitution of chemical fertilizers with compost (T4) promoted biomass production and leaf retention without causing nutrient stress.

Considering Symbiotic Efficiency and Suboptimal Fertilizer Rates, the strong performance of mycorrhizal combinations (T6) reflects the mechanisms detailed by Espinosa *et al.* [38], who established that arbuscular mycorrhizal inoculants reach peak functional efficiency under *suboptimal* or reduced mineral fertilizer inputs. Because excessive chemical phosphorus application can suppress mycorrhizal colonization, applying a reduced (50%) NPK dose creates the ideal rhizosphere condition for the *Rhizophagus* and *Gigaspora* consortium to expand its extra-radical hyphae. This expanded hyphal network increases active soil exploration, mobilizes bound phosphorus, and improves nutrient delivery to the roots. Furthermore, Espinosa *et al.* [38] demonstrated that integrating mycorrhizal inoculation with organic amendments or green manures enhances nutrient balances across successional and vegetatively propagated crops, offering a sustainable pathway to lower chemical input dependency while preserving high crop yields.

Together, these multi-input synergies confirm that combining organic amendments, mycorrhizal bio-inoculants, and reduced doses of synthetic fertilizer is a superior agronomic strategy for overcoming tropical soil fertility barriers, improving nutrient use efficiency, and promoting sustainable taro production in the

Western Highlands of Cameroon.

4.2. Agronomic Efficacy of Local Organic Compost

The sole application of locally produced compost (T2: *Tithonia diversifolia* + poultry manure) significantly enhanced key morphological and growth parameters - including plant height, collar diameter, and total leaf area expansion - compared to unfertilized control plots. This positive response is directly attributable to the functional duality of quality organic amendments: delivering a balanced, readily available macronutrient supply while simultaneously enhancing physical, chemical, and biological soil properties.

4.2.1. Rapid Mineralization and Green Manure Potential of *Tithonia diversifolia*

Tithonia diversifolia is widely celebrated as an exceptionally high-quality green manure due to its elevated tissue concentrations of nitrogen (N) and potassium (K) and its narrow carbon-to-nitrogen (C:N) ratio. As demonstrated by Ogunwole [39], formulations derived from green *Tithonia* biomass (such as leaf blends and teas) exhibit rapid nutrient mineralization in tropical soils. This rapid release rate allows organic treatments to match or even exceed synthetic NPK fertilizers and pure poultry manure in promoting vegetative expansion, leaf area index, and photosynthetic pigment accumulation. Similarly, Nkongolo *et al.* [40] observed that applying *T. diversifolia* biomass on nutrient-depleted tropical Oxisols significantly improved crop height and yield components, proving that *Tithonia*-based amendments provide an effective, closed-loop on-farm organic solution to overcome extreme soil fertility constraints.

4.2.2. Synergistic Multi-Organic Formulations

The strong agronomic performance of treatment T2 in this study also highlights the advantages of blending plant biomass with animal manure. Aboyeji [41] reported that combining composted *T. diversifolia* leaves with organo-biodegradable fertilizers produced significant synergistic effects on vegetative growth, early flowering, and yield performance in horticultural crops compared to unamended controls. Co-composting high-N poultry manure with K-rich *Tithonia* biomass balances the nutrient profile, accelerates organic matter decomposition, and supplies crucial biochemical compounds required for rapid tissue development.

4.2.3. Microbial Dynamics, Rhizosphere Enzymes, and Taro Performance

In taro (*Colocasia esculenta*) specifically, the growth-promoting action of organic composts is strongly mediated by soil microbial activity and biological health. Désiré *et al.* [42] demonstrated that microbial-enriched organic manures (utilizing effective or indigenous microorganisms) significantly increased taro plant height, functional leaf production, and corm/cormel yields (+47.5% over control) in Bambili, Cameroon. Désiré *et al.* [42] attributed these yield gains to enhanced rhizosphere microbial diversity, which upregulated key defense- and nutrient-mobilizing enzymes, such as peroxidase (Pox) and polyphenoloxidase (PPO). However,

while organic amendments substantially boost soil quality, physiological vigor, and crop yield, Désiré *et al.* [42] also noted that compost manures alone were insufficient to control severe foliar outbreaks such as taro leaf blight. This underscores that while *T. diversifolia* and poultry manure compost (T2) serve as powerful drivers of structural growth, photosynthetic capacity, and overall agronomic productivity in Cameroonian soils, they achieve their maximum potential when integrated into comprehensive management strategies.

4.3. Synergies in Integrated Nutrient Management

The superior vegetative vigor and physiological performance recorded under integrated treatments—specifically T4 (50% Compost + 50% NPK) and T6 (50% NPK + 50% Mycorrhizae)—demonstrate that synchronizing inorganic inputs with biological and organic amendments yields benefits greater than the sum of their individual components. Rather than acting as mere partial substitutes for synthetic fertilizers, compost and arbuscular mycorrhizal fungi (AMF) fundamentally re-engineer soil physical, chemical, and biological environments to enhance overall nutrient use efficiency.

The success of T4 relies on dual-action nutrient delivery and structural soil conditioning. While mineral NPK supplies an immediate pool of readily available macronutrients vital for early crop establishment, the organic compost component provides sustained, multi-phase nutrient mineralization over time [43]. Beyond simple nutrient release, mature compost introduces stable soil organic carbon and humic substances that significantly boost the soil's cation exchange capacity, providing reactive functional groups that bind ammonium and potassium to reduce leaching losses [43]. Furthermore, compost application at targeted agronomic rates improves macroaggregation, soil porosity, and water-holding capacity, which optimizes root penetration and maintains the soil moisture tension required for efficient dissolved nutrient mass flow toward root surfaces. Crucially, as emphasized by Manono [43], the success of organic-mineral integration depends strictly on compost maturity and quality. Mature composts characterized by moderate C:N ratios and low phytotoxicity avoid the severe risks associated with immature organic inputs—such as temporary nitrogen immobilization, ammonia toxicity, and high electrical conductivity—while pairing compost at common agronomic rates (5 - 20 $Mg \cdot ha^{-1}$) with reduced NPK prevents excess phosphorus accumulation and salinity risks.

Concurrently, the enhanced physiological performance observed under T6 is driven by the physical and biochemical functions of the hyphosphere—the distinct soil zone surrounding the extraradical hyphae of AMF that extends far beyond the root depletion zone [19]. In highly weathered, acidic ferrallitic soils where inorganic phosphorus is rapidly immobilized through fixation with iron and aluminum oxides, the extraradical hyphal network overcomes spatial constraints by dramatically increasing the effective absorptive surface area of the root system for water and nutrient acquisition [25]. Biochemically, AMF hyphae alter

the local hyphosphere micro-environment by exuding organic acids, protons, and phosphatases that solubilize fixed inorganic phosphorus and mineralize organic phosphorus pools [19]. When combined with reduced mineral NPK, the initial inorganic fertilizer application supports rapid early root growth and mycorrhizal colonization without reaching the threshold concentrations that suppress AMF symbiosis, allowing the established hyphal network to maximize the recovery efficiency of applied mineral nutrients [19] [25].

The physiological vigor observed across both integrated treatments extends beyond baseline nutrition into systemic plant stress resilience. Symbiotic AMF associations modulate key physiological pathways, improving stomatal conductance, photosynthetic water-use efficiency, and osmotic adjustment [25]. Furthermore, AMF colonization upregulates host antioxidant enzyme defense systems—including superoxide dismutase, peroxidase, and ascorbate peroxidase, which detoxify reactive oxygen species and prevent lipid peroxidation (indicated by reduced malondialdehyde levels) during periods of environmental stress [25]. Concurrently, the hyphosphere promotes aggregate stabilization via glomalin secretion and fosters beneficial plant-growth-promoting rhizobacteria, creating a self-reinforcing soil-plant feedback loop that optimizes biomass production under integrated management regimes [19].

4.4. Physiological and Biochemical Adaptations

The marked increases in leaf area and total chlorophyll content observed in treatments T2, T4, and T6 directly drive canopy structural expansion, light interception, and photoassimilate production. However, as demonstrated by Zhang *et al.* [44], expanding canopy architecture alone does not automatically translate into yield improvements unless individual leaf photosynthetic competence and metabolic integrity are maintained. In dense or highly invigorated canopies, trade-offs often emerge where excessive light capture leads to severe non-stomatal photosynthetic limitations, characterized by reduced net photosynthetic rates (P_n) and elevated intercellular CO_2 concentrations (C_i). In the present study, integrated nutrient treatments (T4 and T6) successfully reconciled this trade-off by expanding source capacity (higher leaf area) while simultaneously preserving functional photosynthetic performance (chlorophyll accumulation and metabolic efficiency). This structural-metabolic coordination prevents resource-dilution penalties and ensures that enhanced light capture is effectively converted into chemical energy for dry matter accumulation [44].

This enhanced photosynthetic capacity directly reinforces source strength, which must be tightly coordinated with sink demand to drive corm development. As detailed by Liu [45], plant productivity relies on the dynamic interplay and signal-regulated transport between source organs (mature leaves) and sink organs (developing corms). Elevated concentrations of soluble sugars in treatments T2, T4, and T6 reflect not only active carbohydrate synthesis via enhanced P_n, but also efficient vascular loading, long-distance phloem transport, and sink-source trans-

location [45]. Rather than accumulating statically in source leaves, these soluble sugars act both as osmotic substrates and primary signaling molecules that upregulate sugar transporters and enzymes responsible for starch synthesis in the underground corms, ensuring robust assimilate partition toward yield formation [45].

Concurrently, significant treatment- and variety-dependent shifts in free proline and soluble sugar concentrations highlight essential metabolic protective mechanisms under fluctuating environmental conditions. Proline accumulation functions as a major compatible osmolyte, stabilizing cellular membranes, preserving protein tertiary structures, and scavenging reactive oxygen species during transient osmotic stress [46]. The physiological and biochemical variations observed between ACHU (diploid, var. *esculenta*) and IGBO (triploid, var. *antiquorum*) underscore distinct phenotypic plasticity and stress-adaptation strategies between the two cultivars. As demonstrated by Sahoo *et al.* [46] in taro (*Colocasia esculenta*), genotypes with superior stress tolerance maintain stable net photosynthetic rates, stomatal conductance, and carboxylation efficiency under osmotic stress by triggering higher endogenous accumulation of proline, total phenols, and protective antioxidative enzymes (such as superoxide dismutase and guaiacol peroxidase). The triploid variety IGBO exhibited higher biochemical plasticity, manifested through pronounced proline accumulation and osmotic adjustment, which buffers the photosynthetic apparatus against metabolic strain, whereas ACHU relied more heavily on structural source expansion (leaf area expansion). These contrasting mechanisms highlight how ploidy and varietal background dictate the allocation of photoassimilates between vegetative growth, metabolic protection, and storage organ sink strength [45] [46].

4.5. Economic and Ecological Implications for Local Farming Systems

Crucially, reducing the mineral fertilizer application rate by 50% under integrated treatments (T4 and T6) maintained or even surpassed the agronomic performance achieved with 100% mineral fertilization (T1). This concept of ecological intensification is of paramount practical importance for resource-constrained smallholders in sub-Saharan Africa, where historical adoption of high mineral fertilizer regimes is severely restricted by high input costs, low purchasing power, and inefficient supply chains [15].

In sub-Saharan agricultural systems, smallholder food security is frequently bottlenecked by widespread phosphorus (P) deficiencies, stemming either from inherently low soil P reserves or extreme P-fixation capacity in highly weathered soils [47]. While continuous application of fully soluble inorganic P fertilizers remains financially out of reach for most farmers, relying exclusively on organic inputs is equally unfeasible due to their low inherent P concentration and limited bulk availability on small farms [47]. In this context, integrated soil management acts as a crucial economic bridge. By strategic co-application of 50% inorganic

NPK with organic compost (T4) or mycorrhizal inoculants (T6), farmers optimize fertilizer use efficiency and maximize the recovery of both applied and residual phosphorus, effectively overcoming P-fixation barriers without incurring the prohibitive costs of full mineral inputs [15] [47].

From an agronomic efficiency standpoint, sole reliance on high rates of synthetic NPK creates significant environmental and economic trade-offs. Unbalanced, high-dose mineral fertilization in sub-Saharan soils often yields low agronomic nitrogen efficiency, with up to 70% of applied N lost via ammonia volatilization, nitrate leaching, and nitrous oxide emissions, alongside phosphorus runoff into aquatic systems [15]. Conversely, as demonstrated by Droppelmann *et al.* [48], integrated nutrient management and biological diversification dramatically improve resource use efficiency, delivering substantial incremental yield gains at lower fertilizer input rates (<50 kg·N·ha^{-1}). Partial substitution of mineral fertilizers with organic or biological amendments prevents resource dilution penalties, buffers soil against acidification, and enhances the agronomic efficiency of applied nutrients per unit cost invested [23] [48].

At the soil-ecosystem level, replacing 20% - 50% of synthetic inputs with mature organic amendments or biological inoculants serves as a multi-target driver for long-term soil health and functional resilience [23]. The incorporation of compost and mycorrhizal fungi stimulates crucial soil enzyme activities (e.g., β-glucosidase and urease) and boosts microbial biomass by 20% - 30%, fostering a diverse soil microbiome capable of enhanced nutrient cycling, organic matter decomposition, and pathogen suppression [23]. Furthermore, this integrated regime builds stable soil organic carbon, improves soil physical structure and water-holding capacity, and mitigates environmental risks such as GHG emissions and nutrient leaching [15] [23]. Halving expensive synthetic fertilizer requirements through integrated management provides smallholders with a financially viable, self-reinforcing, and ecologically resilient strategy to secure high crop yields while safeguarding regional soil quality.

5. Conclusions

This study evaluated the single and interactive effects of organic fertilization (*Tithonia diversifolia* + poultry manure compost), synthetic mineral fertilization (NPK 20:10:10), and biological inoculation with arbuscular mycorrhizal fungi (a consortium including *Rhizophagus irregularis*) on the growth, physiological performance, and metabolic resilience of two taro (*Colocasia esculenta*) varieties (ACHU and IGBO) in the Western Highlands of Cameroon.

The empirical findings clearly demonstrate that unamended soil conditions (T0) severely restrict taro canopy development and biochemical status, reinforcing the critical necessity of nutrient replenishment in low-organic-matter ferrallitic soils. Among the applied amendment regimes, integrated soil management practices yielded the most outstanding agronomic outcomes. Specifically, treatments T2 (100% compost), T4 (50% compost + 50% NPK), and T6 (50% NPK +

50% mycorrhizae) consistently promoted superior performance across structural growth markers (plant height, collar diameter, and leaf area expansion) as well as primary and secondary physiological metabolites (total chlorophyll, free proline, and soluble sugars). The observed varietal variations between ACHU (*var. esculenta*) and IGBO (*var. antiquorum*) further highlight distinct phenotypic and biochemical plasticity in response to combined nutrient inputs.

Implications for Sustainable Agriculture

From a practical and ecological standpoint, these results demonstrate that halving the conventional dose of synthetic mineral fertilizer, when complemented by locally produced organic compost or native mycorrhizal inoculants, maintains or surpasses the crop growth and metabolic performance achieved through full mineral fertilization. This has significant implications for sustainable agricultural systems:

Economic Viability for Smallholders: Reducing reliance on expensive synthetic fertilizers by 50% lowers cash outlay barriers for resource-constrained smallholder farmers in sub-Saharan Africa, offering a cost-effective pathway to bridge the gap between actual field yields and potential crop productivity.

Soil Health & Ecological Intensification: Substituting synthetic inputs with organic compost improves soil physical structure, biological activity, and long-term organic matter retention, mitigating the acidification and degradation risks associated with exclusive, long-term chemical input use.

Rhizosphere Efficiency: Leveraging indigenous mycorrhizal fungi enhances nutrient use efficiency, particularly for immobile elements like phosphorus, and bolsters plant metabolic resilience against environmental fluctuations through increased osmoprotectant (proline) accumulation and active carbohydrate translocation.

In conclusion, the integration of compost and mycorrhizal inoculants alongside optimized mineral fertilizer doses represents a robust, scalable, and environmentally sound strategy for ecological intensification. Adopting this holistic nutrient management framework can stabilize taro productivity, enhance farmer livelihoods, and safeguard long-term agro ecological health in the Western Highlands of Cameroon and similar tropical environments.

Author Contributions

Conceptualization, T. V. D. and T. M. C.; methodology, T. V. D., G. N. N., and T. M. C.; validation, T. V. D., G. N. N., and T. M. C.; investigation, T. M. C. and T. V. D.; data curation, T. M. C., D. T. C., P. H. N.; writing—original draft preparation, T. M. C.; writing—review and editing, T. V. D., T. M. C. D. T. C., P. H. N. and G. N. N.; supervision, T. V. D.; project administration, T. V. D., G. N. N., D. T. C. and P. H. N. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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