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Enhancing acclimatization of *Coffea arabica* F1 hybrids through poultry manure biochar amendment

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ABSTRACT

Coffea arabica F1 hybrids offer elite agronomic traits (high yield potential and disease resistance), but they remain difficult to propagate at scale due to high mortality during the acclimatization phase. This study investigated the potential of poultry manure biochar (PMB) to improve substrate properties and enhance the survival and physiological vigour of Starmaya mini-cuttings. Using a Randomized Complete Block Design (RCBD), rooted cuttings were grown in substrates amended with PMB at 0%, 2.5%, 5%, and 10% v/v. Survival rate, root and shoot biomass, root-to-shoot ratio (RSR), and chlorophyll content (SPAD) were assessed over 12 weeks, with an extension phase to monitor post-acclimatization resilience. Results indicated that PMB significantly altered substrate pH and nutrient retention. A 5% PMB amendment was identified as the optimal dose, increasing survival rates to 92.1% compared to 68.9% in the control. This treatment also maximized root biomass (0.87 g/plant) and maintained a balanced RSR (0.6). While higher application rates (10%) induced phytotoxicity linked to elevated salinity, the 5% treatment demonstrated sustained benefits without mineral fertilization. These findings suggest that PMB at a modest rate offers a sustainable, waste-derived solution to the critical bottleneck of nursery acclimatization for elite coffee hybrids.

Key words: Circular economy, mini-cuttings, nursery management, seedling vigor, starmaya, substrate amendment, waste valorization

INTRODUCTION

The rapid development of resilient *Coffea arabica* varieties in the 21st century is essential to counter the threats of shifting climate patterns, rising temperatures, and escalating pest and disease pressures (Marie et al., 2020; World Coffee Research, 2024). Recent advancements in genome editing, such as the clustered regularly interspaced short palindromic repeats CRISPR-Cas9 genome engineering technology (CRISPR/Cas) are revolutionizing crop improvement by enabling the development of varieties that are more productive and resilient to these very stresses (Das et al., 2025). With the land suitable for Arabica coffee cultivation projected to decline sharply, enhancing tree productivity is critical to meeting global demand (Marie et al., 2020). To address these urgent challenges, researchers and international organizations are prioritizing F1 hybrids, a high-performing class of varieties designed to ensure long-term crop stability and farmer prosperity (Georget et al., 2019; Bertrand et al., 2021; World Coffee Research, 2024).

While F1 hybrids are relatively a recent introduction to the coffee sector, they are increasingly viewed as a cornerstone of the future of the coffee industry (World Coffee Research, 2024). These varieties are characterized by hybrid vigor, which manifests as higher yields, broader climate adaptability and enhanced resilience against stressors such as frost, coffee leaf rust and drought (Bertrand et al., 2011; Georget et al., 2019).

The economic advantages of adopting high-performing hybrid varieties over traditional cultivars have been consistently demonstrated across various crops; for instance, front-line demonstrations in sweet corn recorded a 238% yield increase by adopting hybrid varieties (Priyadarshini and Nath, 2025).

Additionally, F1 hybrids offer a significant strategic advantage by accelerating the breeding cycle, reducing the timeline from initial development to commercial release to just 10-20 years, compared to the 25–30 years required for traditional pure line varieties (Mc Cook and Montero-Mora, 2024). Looking forward, the integration of precision breeding tools such as CRISPR- Cas9 genome engineering technology with conventional methods offers further potential to enhance these traits rapidly and sustainably (Das et al., 2024).While F1 hybrids offer high performance, they present risks for farmers accustomed to saving seeds, as F1 offspring do not breed true (Georget et al., 2019). Furthermore, large-scale production is constrained by the high cost of elite germplasm production, driven largely by significant losses during the acclimatization phase (Mondal et al., 2023).

The transition of rooted cuttings from a controlled greenhouse to an external (*ex vitro*) environment, known as acclimatization, represents a primary limiting factor in the successful micropropagation of many plant species (Hazarika, 2003; Jagiełło-Kubiec et al., 2021). During this phase, the micropropagated plants with under developed root systems and stomatal control often struggle to survive after transfer because they are accustomed to high humidity, low light, and a sterile, sugar-rich, autotrophic environment, making them vulnerable to environmental stress (Hazarika, 2003; Grossnickle, 2012). Mortality rates during this stage can reach 30-40%, rendering large-scale deployment financially prohibitive for many nurseries (Politud and Avako, 2016). Therefore, a successful acclimatization ensures high survival rates of the rooted mini-cuttings through environmental regulation by gradually reducing humidity and increasing light intensity in the tunnel to stimulate stomatal function, the selection of optimized substrates such as soil-sand-organic mixtures to promote robust root development (Nogueira et al., 2022), and the implementation of in vitro preconditioning such as adjusting sucrose levels or improving container ventilation to physiologically prepare the plantlet for weaning (Pires et al., 2023).

Concurrently, the rapid expansion of poultry farming in tropical regions generates vast quantities of manure. Direct application of raw manure to sensitive nursery substrates often leads to phytotoxicity due to high ammonia content and low carbon-to-nitrogen (C/N) ratios (Kumari et al., 2024). However, thermochemical conversion via slow pyrolysis will produce P-enriched biochar with surface-bound calcium phosphates, available P from <0.1% to 1.5-2.5%, reduced NH_3 loss, and surfaces for lactic acid bacteria (Bruun et al., 2012; Hadroug et al., 2019). Raw biochar produced from crop wastes via an Elsa barrel pyrolyser (300-500 °C) has high porosity and stability but low concentrations of readily available N, P, and K. Its negative surface charge binds cations well but does not supply them initially (Domingues et al., 2017). Loading raw poultry manure into a specialized container (such as the Elsa barrel, a pyrolysis metal container) for slow pyrolysis keeps the process efficient while producing high-quality biochar (Cantrell et al., 2012; Chen et al., 2017; Hadroug et al., 2019). This method allows for the thermal decomposition of manure into a porous carbonaceous material, which enhances nutrient management and increases the Cation Exchange Capacity (CEC) by 20-35% compared to raw poultry manure (Cantrell et al., 2012; Hadroug et al., 2019).

Poultry Manure Biochar (PMB) is characterized by high nutrient density (specifically P and K) and an alkaline pH, making it a potentially ideal bio-fertilizer or recycled organic residual amendment for the acidic substrates typical of tropical coffee nurseries (Dasgan et al., 2023; Côté and Khiari, 2026). However, while the general benefits of biochar are documented, the specific application of PMB to mitigate transplant shock in F1 coffee hybrids remains underexplored. Additionally, the optimal dosages required to avoid toxicity are not well established.

This study investigates the potential of PMB as a strategic substrate amendment to facilitate the bio-acclimatization of rooted *Coffea arabica* mini-cuttings. The study hypothesizes that: (1) An optimal dose of PMB will stabilize substrate pH and enhance nutrient bioavailability without inducing salinity stress; and (2) improvements in the rhizosphere will promote robust root architecture, maximizing the survival rate (SR) of F1 hybrid mini-cuttings.

MATERIALS AND METHODS

Site and plant material

The study was carried out at the IRAD Foumbot multipurpose research station located in Cameroon's Western Highland agroecological zone III (1014 m asl.; 5°51'41" N, 10°34'13" E). Characterized by a humid subtropical equatorial climate and rugged volcanic topography, the region receives an average annual rainfall of 2,400 mm distributed through a distinct bimodal pattern. The year is divided into a lengthy rainy season from mid-March to mid-November and a subsequent dry season, during which northeasterly Harmattan winds introduce dusty air and reduced humidity. Throughout these shifts, the environmental conditions remain consistently tropical, with temperatures fluctuating between 15°C and 32°C. The study utilized uniform six-week-old rooted mini-cuttings of the Starmaya F1 hybrid, which were obtained from a specialized clonal propagation facility.

Production and characterization of poultry manure biochar (PMB)

Poultry manure was pyrolyzed in an Elsar barrel retort under slow pyrolysis conditions at 500°C for 40-50 minutes (Billa et al., 2017). The resulting biochar was ground and sieved (<2 mm). Physicochemical analyses included pH (1:10 w/v), electrical conductivity (EC), cation exchange capacity (CEC), and total macronutrient content (C, N, P and K) using standardized protocols.

Experimental design and treatments

A randomized complete block design (RCBD) with four PMB treatments (0%, 2.5%, 5%, 10% v/v) and four replications was implemented. Each plot contained 25 mini-cuttings (total n = 400). The substrate comprised topsoil and sand (2:1 v/v). To eliminate soil-borne pathogens that could confound mortality results, the topsoil was sterilized by autoclaving at 121°C for 1 hour prior to mixing. The substrate was then amended with PMB at specified concentrations. Treatment details with concentration of PMB indicating T_0,T_1,T_2 and T_3 are presented for better clarity.

Acclimatization of F1 coffee hybrids

Plants were transplanted into polybags (10 ×20cm) containing respective treatment substrates. They were maintained under 70% relative humidity and 50% shade for 4 weeks, gradually acclimatized to 25% shade over 8 weeks. Substrate moisture was manually maintained at ~60% field capacity. No external mineral fertilizers were applied during the initial 12-week trial.

Longitudinal assessment (weeks 13-24)

The second phase evaluated sustained resilience by comparing the optimal 5% PMB dose (T_2) to a control (T_0) and a high-input treatment (T_4). Although the 10% PMB treatment (T_3) exhibited a survival rate of 80.5% at 12 weeks, it was excluded from the longitudinal growth assessment. This exclusion was based on qualitative observations of severe phytotoxicity and root system dysfunction; surviving T_3 plants displayed stunted orthotropic growth, leaf chlorosis, and brittle root systems that lacked the capacity for future nutrient uptake. These symptoms indicated that the high salinity of the substrate would inevitably lead to failure during the extended nursery cycle. Consequently, T_3 was deemed unsuitable for the long-term study, which focused on viable production protocols. Phase two focused on sustained resilience, comparing three specific treatments:

T_0: Control

T_2: Optimal 5% PMB dose

T_4: High - input regime (Optimal PMB + Fertilization): Plants from T_2 receiving liquid NPK (20-10-10) at 2 g/l starting Week 13.

Data collection

At 12 and 24 weeks, survival rate (SR), root dry weight (RDW), shoot dry weight (SDW), and root-to-shoot ratio (RSR) were measured.

Survival rate (SR)

The number of green and turgid cuttings showing signs of viability (whether rooted or not) were counted and used to determine the survival rate (SR) of the cuttings using the following equation

$$SR\ (\%) = \frac{Ns}{Nt} \times 100$$

- Ns = Number of surviving cuttings at the end of the assessment period.
- Nt = Total number of cuttings planted at the start of the experiment.

Shoot dry weight (SDW) **and** ***root dry weight (RDW)***

On the day of harvest, five plants were randomly selected from each treatment and carefully separated into shoot (stem + leaves) and root samples. The roots were gently washed under running water to remove all substrate particles. The shoot and root samples were then placed into labelled paper bags and dried in a forced-air oven at 60°C until a constant weight was achieved. The dried samples were immediately weighed using a precision Sartorius analytical balance (0.0001 g) to obtain the shoot dry weight (SDW) and root dry weight (RDW), respectively.

Root-to-shoot ratio

The root-to-shoot ratio (RSR) indicates biomass partitioning between the root and the shoot and is often used as an indicator of plant vigor and ability to survive transplanting. To ensure statistical validity, the dry weights of the five sub-samples were averaged to represent a single value per plot. These plot means (n = 4 replications per treatment) were then used for the Analysis of Variance (ANOVA) and mean separation tests.

SPAD value

The chlorophyll content was determined by measuring the third pair of fully expanded leaves from the top of the orthotropic branch using a Minolta SPAD-502.

Field readiness (FR)

To assess the suitability of plants for out-planting, field readiness (FR) was determined at 24 weeks. FR was defined as the percentage of plants in each treatment meeting specific morphological criteria: having a lignified stem (brown coloration), at least five pairs of mature leaves, and a root system capable of holding the substrate ball intact without disintegrating upon removal from the polybag.

Data analysis

Quadratic regression models were employed to describe the response curves to PMB dosage; this approach was specifically chosen to test for an optimal dosage threshold beyond which benefits might decline. Data normality was verified, and means were compared via Tukey's HSD ($p < 0.05$) using IBM SPSS Statistics version 20. The data for survival rate (SR), root dry weight (RDW), and shoot dry weight (SDW) were all best fit by a second-order polynomial equation ($y=a + bx + cx^2$). The resulting models and high coefficients of determination (R^2) were summarized below:

Survival Rate (SR): $SR = 68.5 + 9.1x - 0.85x^2$ ($R^2 = 0.95$).

Root Dry Weight (RDW): $RDW = 0.63 + 0.15x - 0.012x^2$ ($R^2 = 0.91$).

Shoot Dry Weight (SDW): $SDW = 1.17 + 0.20x - 0.019x^2$ ($R^2 = 0.93$).

RESULTS AND DISCUSSION

Physico-chemical properties of the growth substrates

The chemical properties of the base components (soil, sand, and PMB) used to formulate the treatments are presented in Table 1. Based on the volumetric incorporation rates, the calculated substrate pH for the optimal treatment (T_2, 5% PMB) was approximately 6.0, representing a slight liming effect from the alkaline biochar (pH 9.3). This adjusted pH, combined with the elevated CEC, created the physicochemical environment responsible for the significant improvements in nutrient uptake observed in the subsequent growth analysis.

Table 1. Physico-chemical properties of the base substrates (soil, sand, and poultry manure biochar) used in the study

Parameter	Unit	Soil: sand media (2:1 by volume)	Poultry manure	PMB
Pyrolysis temperature	^oC	-	-	500
Yield	%	-	-	45.2
pH (1:10 w/v H_2O)	-	5.9	8.77	9.3
EC	dS m^{-1}	0.34	0.4	2.56
Total carbon (C)	%	22.34	30.17	48.7
Total nitrogen (N)	%	0.43	2.37	2.1
Available phosphorus (P)	g kg^{-1}	0.31	25.3	28.0
Total potassium (K)	%	0.13	3.22	4.1
CEC	cmolc kg^{-1}	20.08	19.74	45.8
Sand	%	50.43	-	-
Silt	%	20.32	-	-
Clay	%	29.25	-	-

PMB: Poultry manure biochar; EC: Electrical Conductivity; dS: deciSiemens; CEC: Cation Exchange Capacity; cmolc: centimoles of positive charge.

Influence of biochar on substrate pH and salinity

Pyrolysis increases pH by concentrating basic cations and forming carbonates, creating a nutrient-dense carbon skeleton essential for neutralizing the acidic soils of the Western Highlands. This process occurs as volatile components like hydrogen and oxygen are lost, leaving behind concentrated mineral nutrients such as phosphorus, potassium, calcium, and magnesium. This chemical transformation makes Poultry Manure Biochar an effective amendment for stabilizing soil acidity and improving nutrient availability in tropical highland environments. The control substrate (pH 5.9) was slightly acidic. PMB addition linearly increased substrate pH, reaching 6.4 at 10% PMB (Fig. 1). The 5% PMB treatment adjusted the substrate to pH 6, the recognized physiological optimum for Arabica coffee nutrient uptake. Electrical Conductivity (EC) increased with PMB but remained below salinity stress thresholds in the 0-5% treatments.

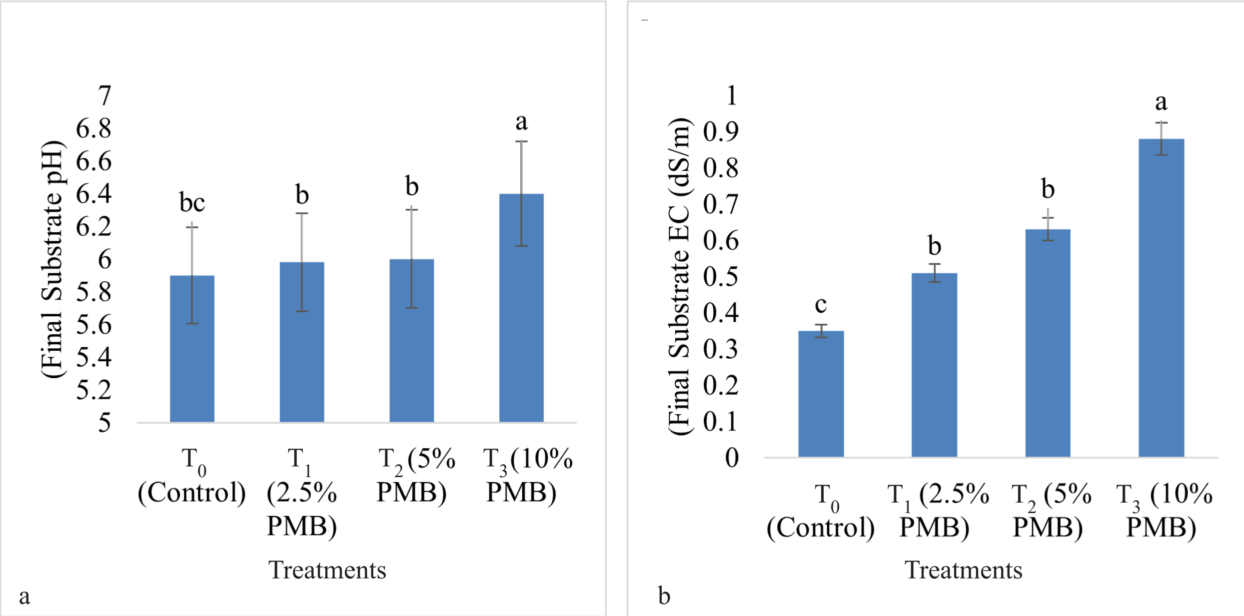

Fig. 1 (a and b). Changes in substrate pH and electrical conductivity (EC) following amendment with varying levels of poultry manure biochar (PMB). Means followed by the same letter in a column are not significantly different (p<0.05).

Survival rate, root morphological attributes and acclimatization success

PMB significantly enhanced survival rates (Table 2). The 5% PMB treatment (T_2) achieved the highest survival rate (92.1%), a 34% increase over the control (68.9%). The 10% treatment (T_3) resulted in significantly lower survival (80.5%) and reduced root length, indicating a toxicity threshold at higher PMB concentrations.

Table 2. Influence of poultry manure biochar (PMB) amendment on survival rate and root morphological traits of *Coffea arabica* F1 hybrid mini-cuttings at 12 weeks after transplanting

Treatment	Survival rate (SR %)	Root length (mm)	Number of roots
T_0 (Control)	68.9^c	115^c	7.5^d
T_1 (2.5% PMB)	90.1^b	145^b	10.2^b
T_2 (5% PMB)	92.1^a	159^a	12.8^a
T_3 (10% PMB)	80.5^d	140^b	8.9^c
SEm (±)	1.25	4.30	0.55
CD5%	3.82	13.20	1.69

Note: Means followed by the same letter in a column are not significantly different ($p < 0.05$). SEm **(±)** = Standard Error of Mean; CD5% = Critical Difference at 5% level

Biomass production and allocation patterns

The 5% PMB amendment promoted greater biomass accumulation (Table 3). T_2 yielded a 35% increase in root dry weight (RDW) compared to the control. Furthermore, T_2 achieved an optimal root-to-shoot ratio (RSR) of 0.6, suggesting a balanced allocation of resources to water-absorbing roots versus transpiring shoots.

Table 3. Effect of different levels of poultry manure biochar (PMB) on biomass accumulation and root-to-shoot ratio of *Coffea arabica* F1 hybrid mini-cuttings at 12 weeks after transplanting

Treatment	Root dry weight (RDW, g/plant)	Shoot dry weight (SDW, g/plant)	Root-to-shoot ratio (RSR)
T_0 (Control)	0.64^c	1.18^c	0.54^c
T_1 (2.5% PMB)	0.75^b	1.30^b	0.58^b
T_2 (5% PMB)	0.87^a	1.45^a	0.60^a
T_3 (10% PMB)	0.71^{bc}	1.22^{bc}	0.58^b
SEm (±)	0.025	0.041	0.012
CD5%	0.077	0.126	0.037

Note: Means followed by the same letter in a column are not significantly different ($p < 0.05$). SEm (±) = Standard Error of Mean; CD5% = Critical Difference at 5% level

Chlorophyll content and photosynthetic efficiency

The physiological health of the plantlets, as measured by SPAD values in the T_2 treatments (45.2), was significantly higher than the control (38.5), reflecting enhanced nitrogen (N) assimilation mediated by the biochar's CEC (Fig. 2). The lower SPAD values in T_3 (10%) suggest that excessive PMB may inhibit nutrient uptake through osmotic stress.

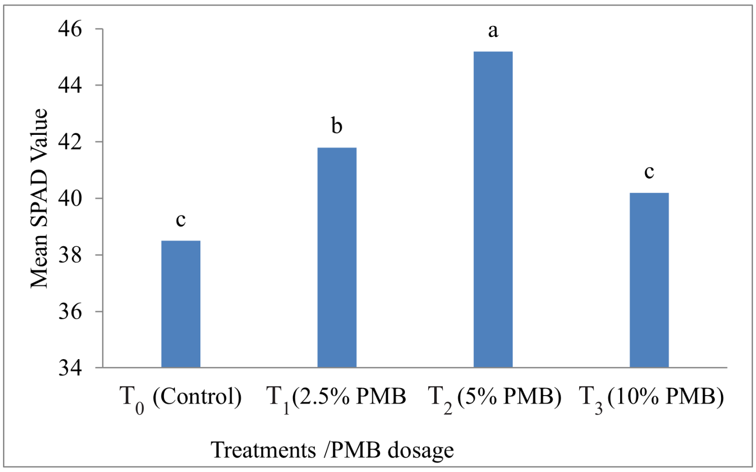

Fig. 2. Effect of poultry manure biochar (PMB) application on chlorophyll content (SPAD values) of *Coffea arabica* F1 hybrid mini-cuttings. Means followed by the same letter are not significantly different ($p < 0.05$). Higher values indicate photosynthetic efficiency and nitrogen assimilation.

Long-term growth resilience and field readiness

By week 24, the survival advantage of the 5% PMB treatment (T_2) persisted (~90.5%), while the control (T_0) experienced a further decline to 65.1% due to nutrient exhaustion (Fig. 3). Although T4 (PMB + fertilizer) treatment achieved the highest total biomass, the T_2 plants exhibited survival rates comparable to T_4 and a balanced RSR, demonstrating that PMB alone can sustain seedling vigor through a standard nursery cycle. The exclusion of the 10% PMB treatment (T_3) from this phase was confirmed as prudent by the observed quality decline in T_3 plants during the interim period; despite initial numerical survival, these plants failed to develop the lignified stems and robust root systems necessary for field readiness (FR).

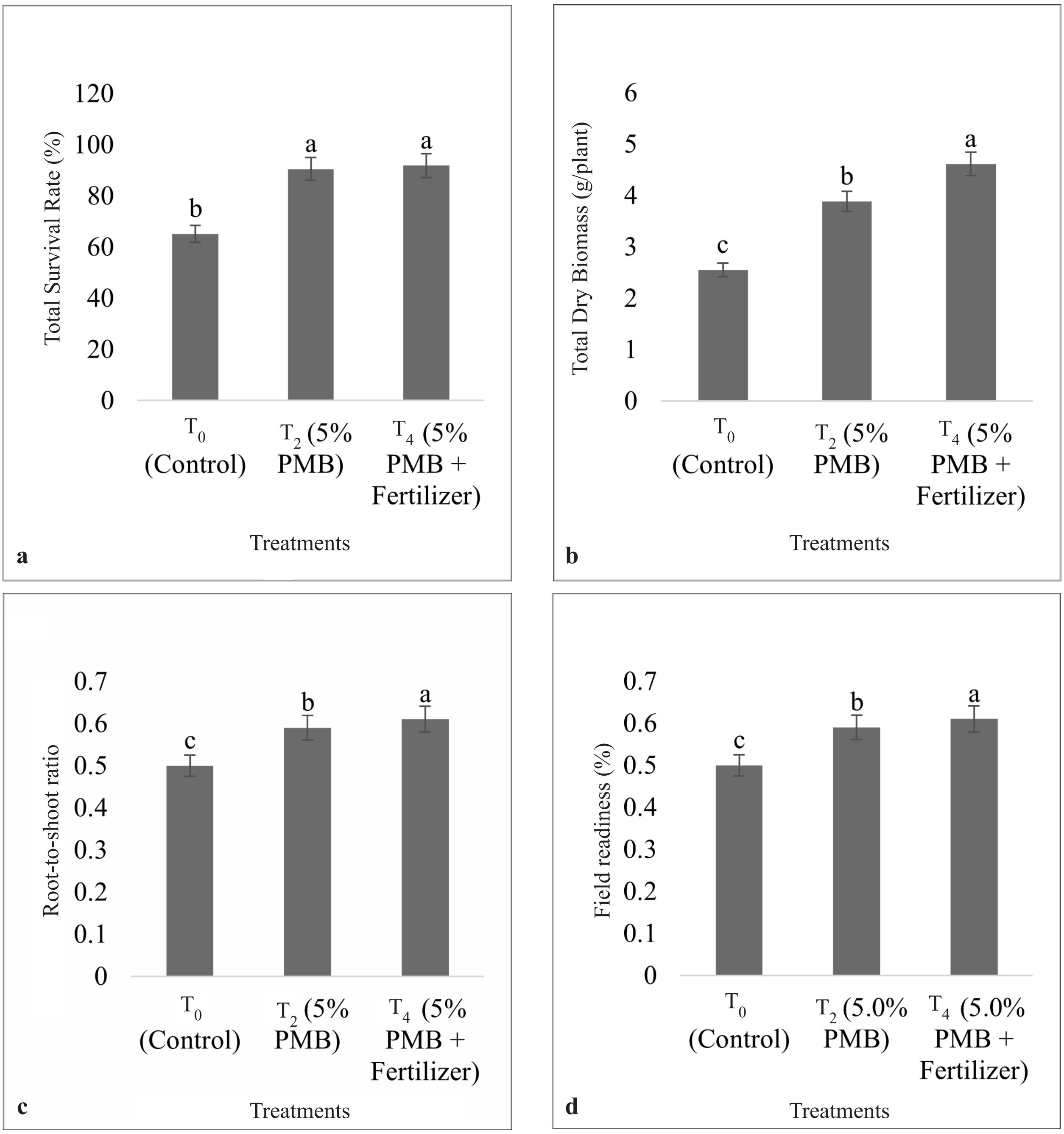

Fig. 3. Performance metrics of *Coffea arabica* F1 hybrid mini-cuttings at 24 weeks: (a) Survival rate (SR, %), (b) Total dry biomass (g/plant), (c) Root-to-shoot ratio, and (d) Field readiness percentage. Means followed by the same letter in a column are not significantly different ($p < 0.05$)

Pearson correlation analysis of growth and physiological interrelationships

To further confirm interrelationship among the key agronomic and physiological variables, a Pearson correlation analysis was conducted (Table 4). This analysis confirmed strong, positive, and significant linear relationships between survival, biomass, and physiological vigour.

Table 4. Pearson's correlation coefficients (r) illustrating relationships among survival, biomass, and physiological parameters in *Coffea arabica* F1 hybrid mini-cuttings

Variable	RDW	SDW	RSR	SPAD
SR (Survival rate)	0.88**	0.90**	0.55*	0.79**
RDW (Root dry weight)		0.92**	0.65**	0.85**
SDW (Shoot dry weight)			0.35	0.88**
RSR (Root-to-shoot ratio)				0.51*
SPAD (Chlorophyll content)				

Note: ** Correlation is significant at the p<0.01 level (2-tailed). * Correlation is significant at the p<0.05 level (2-tailed).

Pearson correlation analysis confirmed a strong positive correlation between RDW and SR ($r = 0.88$, $p < 0.01$) and between RDW and SDW ($r = 0.92$), identifying root development as the primary driver of acclimatization success. The SPAD values showed a highly significant correlation with all three biomass components, indicating that improved physiological health (chlorophyll content) is associated with higher dry matter production.

The findings strongly support the hypothesis that poultry manure biochar (PMB) effectively ameliorates nursery substrates and enhances the bio-acclimatization of arabica coffee mini-cuttings. Historically, raw animal manure has been valued for increasing soil organic carbon (SOC) and cation exchange capacity (CEC) via carboxyl and phenolic group enrichment (Kumari et al., 2024). However, the raw manure management faces logistical constraints, including high moisture and low C/N ratios that complicate composting and transport. Pyrolysis offers a better valorization pathway, destroying pathogens while transforming labile carbon into a stable, long-term sink that maintains nutrient balance (Bruun et al., 2011; Hadroug et al., 2019).

Amendment of substrate properties and mitigation of transplant stress

The performance of Starmaya cuttings in the 5% PMB substrate (T_2) underscores the role of substrate quality in overcoming transition mortality, primarily caused by water stress and nutrient deficiency (Nogueira et al., 2022; Lopez-Merino et al., 2026). PMB addressed these challenges by increasing Water Holding Capacity (WHC) to 65% and decreasing bulk density, which improved aeration essential for aerobic root respiration (Alma and Altikat, 2021; Hadroug et al., 2019).The substrate's high porosity and expansive surface area act as a functional sponge, significantly enhancing water-holding capacity while reducing nutrient leaching (Alma and Altikat, 2021). This physical retention ensures that essential resources remain available within the root zone for extended periods.

Regulation of rhizosphere pH and nutrient dynamics

The acidity (pH 5.1) of the control substrate likely restricted nutrient availability (Table 1). The alkaline nature of the PMB (pH 9.3) served as an effective liming agent, adjusting the T_2 substrate to pH 6.0, which was optimal for the Arabica F1 Hybrid coffee (Hadroug et al., 2019). This stabilization in pH, combined with high P and K content, maximized nutrient uptake, as evidenced by high SPAD values of 45.2 (Nogueira et al., 2022). The high surface area, CEC and porous structure of the biochar enhanced the capacity of the PMB substrate to hold cations and moisture during critical periods of stress (Bruun et al., 2012; Silva et al., 2022). With an annual rainfall averaging 2400 mm, traditional nursery substrates are highly susceptible to nutrient leaching, whereby valuable cations (K^+, Ca^{2+}, Mg^{2+}, and NH_4^+) are washed away before they could be absorbed by the roots. Subsequently, through desorption kinetics, the biochar releases these nutrients back into the soil solution in response to root demand.

This slow-release mechanism effectively explains why the 5% PMB treatment (T_2) sustained vigorous growth for 24 weeks without mineral fertilization, whereas the control (T_0) suffered from nutrient exhaustion. The high nutrient density of the PMB (specifically P and K), coupled with this retention mechanism, creates a consistent nutrient supply that matches the uptake capacity of the developing cuttings. Conversely, the 10% dose (T_3) exceeded the cuttings' tolerance due to high Electrical Conductivity (0.88 dS/m) and excessive pH, leading to salinity-induced growth reduction (Chen et al., 2021).

Effect of biochar on biomass accumulation and partitioning

Superior performance in T_2 was reflected in both above-ground and below-ground biomass. A higher shoot dry weight (SDW) correlates with improved photosynthetic efficiency fueled by PMB-mediated nutrient availability (Evans, 1983). This chemical support translated into significantly higher root dry weight (RDW) and an optimized root-to-shoot ratio (RSR) of 0.60. A balanced RSR is a primary index of nursery stock quality, ensuring absorptive organs can meet the transpirational demands of the shoot (Wilson, 1988). High RDW is the single best predictor of field establishment success, as it enhances hydraulic conductivity and access to water post-transplant (Grossnickle, 2012).

Phytotoxicity thresholds and dose-response relationships

Unlike woody biochars, which are often carbon-rich but nutrient-poor, PMB provides significant amounts of P and K. These findings highlight the importance of dosage precision. The 5% dose successfully buffered the acidic substrate to pH 6.0, optimizing nutrient availability, as evidenced by the SPAD values. However, the decline in performance at 10% PMB serves as a critical warning for nursery managers. The drop in survival and root length at this dose correlates with elevated EC and pH, leading to osmotic stress. Furthermore, the significant rise in substrate pH at the 10% dosage likely induced micronutrient lock-up, particularly limiting the bioavailability of essential cations such as iron (Fe), manganese (Mn), and zinc (Zn). This alkalinity-induced nutrient deficiency, combined with osmotic stress, explains the phytotoxic symptoms observed at higher concentrations. This defines the narrow window between benefit and toxicity for nutrient-dense biochars.

Modulation of root architecture and rhizosphere synergy

The profound increase in total root number, surface area (RSA), and length (TRL) in T_2 (the 5% dosage) provides direct evidence of successful bio-acclimatization. Biochar's porous structure provides nucleation sites for microbial activity and physical channels for root initiation (Mafrica et al., 2025). By physically reducing substrate impedance and improving aeration, PMB essentially primed the Starmaya cuttings for self-sufficiency, resulting in a 92.1% survival rate. The successful acclimatization of Starmaya hybrids depends on the correlation between root dry weight (RDW) and phosphorus (P) uptake. Applying 5.0% poultry manure biochar (PMB) significantly increases RDW, expanding the surface area for intercepting immobile phosphorus ions. This morphological shift could be a direct response to high P availability in the PMB which could have improved the allocation of biomass and physiologically primed the coffee seedlings for growth. Following the dynamics described by Xu et al., (2026), the availability of macronutrients such as P facilitates development of photosynthetic efficiency, a synergy vital for drought tolerance. According to Pang et al., (2010), morphological variations in perennials respond directly to P supply. By maximizing RDW and chlorophyll content, seedlings maintain nutrient flow and energy production during the dry (Harmattan) season ensuring that the plantlets are morphologically primed for the volcanic soils of the Cameroon Highlands.

Economic viability and environmental sustainability of biochar application

For resource-limited nurseries, the dependency on mineral fertilizers can be a significant constraint (Dasgan et al., 2023; Côté and Khiari, 2026). Analogous to the significant income improvements observed in other sectors through the adoption of improved varieties, such as sweet corn (Priyadarshini and Nath, 2024), the finding that the 5% PMB treatment (T_2) sustained growth and survival compared to the fertilized treatment (T_4) for 24 weeks suggests the potential for PMB to replace or significantly delay the need for mineral fertilization in the early nursery stages. While a detailed cost-benefit analysis is required to quantify specific savings, the valorization of poultry waste (PMB application) into a growth substrate offers a promising strategy for improving resource efficiency. Environmentally, this approach contributes to a circular economy, mitigating the environmental burden of manure management (Bruun et al., 2011).

CONCLUSION

This study confirms that poultry manure biochar at 5% v/v (T_2) is a sustainable soil amendment that significantly improves cutting survival, root development, as well as the physiological health of mini-cuttings of Arabica coffee F1 hybrids during acclimatization. The high pH and cation exchange capacity (CEC) of PMB stabilized the substrate at an ideal pH of 6.0, contributing to a 35% increase in root dry weight and a balanced root-to-shoot ratio (0.6). Post-acclimatization over 24 weeks proved these benefits could be sustained, with T_2 maintaining a 90.5% survival rate compared to the unamended controls T_1 (65.1%). While the supplemental fertilization (T_4) maximized biomass, the PMB-only treatment (T_2) produced high-quality, field-ready plants, offering a cost-effective solution for resource-limited nurseries. Ultimately, valorizing poultry waste into biochar creates a circular-economy tool that optimizes the structural and nutritional stability of the rhizosphere thereby mitigating transplant shock, while accelerating the deployment of climate-resilient coffee clones as well as securing the long-term viability of the global coffee value chain.This study suggests the adoption of this specific PMB dose as a standard protocol for nurseries aiming to scale up the production of elite F1 coffee clones.

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