



RESEARCH

Scion segmentation and clonal identity as primary determinants of graft success in *Theobroma cacao* L

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Abstract

Vegetative propagation through grafting remains central to cacao (*Theobroma cacao* L.) improvement, ensuring genetic fidelity, uniformity, and accelerated productivity. Yet, the determinants of graft success—particularly the optimal segmentation of budwood—remain poorly defined. This study evaluated the effects of scion partitioning (entire, tip, middle, basal) across six National Seed Industry Council (NSIC)-registered clones or cultivars (BR25, PBC123, UF18, K2, K9, K1) under nursery conditions using a 4 × 6 factorial RCBD. Results revealed that significant interaction between scion segment and clone was not detected for graft success, leaf development, or stem girth. The entire scions achieved the highest grafting success (88.88%), statistically comparable to tip segments (85.00%), while middle (80.00%) and basal (78.89%) segments performed less favorably. Foliar initiation at 28 days post-grafting (DPG) was most rapid in entire and tip scions, though by 90 DPG leaf counts did not vary across all segments. Clone type significantly impacted stem diameter. While ‘K2’ outperformed ‘K9’ and ‘K1’ in radial expansion, its growth was comparable to ‘UF18’, ‘BR25’, and ‘PBC123’. Collectively, these findings provide insight into graft union development and practical guidance for optimizing propagation protocols. By validating the compatibility of elite clones with ‘UF18’ rootstocks and demonstrating the viability of scion partitioning, this work strengthens nursery capacity to deliver high-quality planting materials essential for the sustainable expansion of cacao plantations.

Keywords Asexual propagation · Auxin/Cytokinin · Morpho-physiology · Orthotropic/Plagiotropic · Source-sink dynamics

1 Introduction

Theobroma cacao L., an evergreen perennial of the Malvaceae family (Bayer et al. 1999), represents one of the most economically and culturally significant tropical tree crops globally (Wickramasuriya and Dunwell 2018). As the primary raw material for the multi-billion-dollar chocolate and confectionery industry, cacao serves as a vital source of livelihood for millions of smallholder farmers (Osei-Gyabaah et al. 2023). In the Philippines, the cacao industry occupies a unique position characterized by increasing local demand and favorable soil and climatic conditions; however,

a continuing supply–demand deficit persists. With a total market requirement of 50,000 MT, the current production output of 10,000 MT highlights a critical reliance on external sources to bridge the 40,000 MT shortfall (Department of Agriculture - Bureau of Agricultural Research 2022). This productivity gap is primarily attributed to the prevalence of aging, low-yielding plantations managed by resource-limited farmers who often employ low-input extensification strategies rather than intensive, technology-driven management. A critical bottleneck in this value chain is the reliance on unselected, non-grafted planting materials of indeterminate genetic origin. Such trees exhibit extreme phenotypic heterogeneity, late bearing, and susceptibility to endemic pathogens like cacao pod borer (*Conopomorpha cramerella*) and black pod rot (*Phytophthora palmivora* Butler), ultimately compromising both bean yield and fermentation quality.

To revitalize the national cacao economy and enhance smallholder resilience, the establishment of new plantations utilizing early-bearing, high-yielding, and disease-tolerant varieties is imperative. While traditional seedling

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propagation is straightforward, it is inherently limited by the high degree of heterozygosity in cacao (N'Zi et al. 2017), leading to progeny that seldom mirror the superior traits of the parent tree. Furthermore, seedling-derived trees are characterized by an extended juvenile phase (Vidoy-Mercado et al. 2021) and inconsistent canopy architecture. Conversely, vegetative propagation—specifically grafting—offers transformative advantages: the maintenance of genetic fidelity, uniformity in tree architecture, earlier onset of flowering, and the strategic combination of desirable scion traits with robust rootstock characteristics (Habibi et al. 2022; Feng et al. 2024; Augstein and Melnyk 2025). Moreover, agronomic evaluation confirms that cacao grafting resulted in significant yield enhancement of approximately 47%; this precocity was observed in less than two years compared to non-grafted baseline trees (Ocampo-Ariza et al. 2025).

Grafting, an ancient horticultural technique (Nawaz et al. 2016; Wang et al. 2024), has become the cornerstone of modern arboriculture for the rapid dissemination of elite germplasm. Beyond simple physical contact, graft union ontogeny represents a sophisticated physiological coordination; it necessitates precise cambial alignment, the controlled development of a necrotic layer, and robust callus proliferation, culminating in the functional differentiation of a continuous vascular bridge (Jin et al. 2023). The efficiency of this process hinges on the graft union ontogeny, which is influenced by the physiological compatibility between the scion and the rootstock. Recent investigations into cacao genomics and physiology suggest that genetic relatedness and biochemical signaling between the two bionts are significant drivers of compatibility or rejection (DuVal et al. 2025).

Despite the high success rates of cacao grafting in controlled environments, a significant knowledge gap exists regarding the influence of scion provenance and partitioning on graft take and subsequent vigor. In commercial nursery operations, the availability of high-quality budwood from established scion groves or budwood gardens is frequently a limiting factor, particularly for newly released or locally adapted clones of the National Seed Industry Council (NSIC). When the demand for a specific variety exceeds the available scion supply, nursery operators are often forced to maximize the utility of every available orthotropic shoot. This necessitates the subdivision of long budsticks into distinct segments: the apical (tip), medial (middle), and proximal (basal) partitions.

From a physiological perspective, these partitions are not equivalent. A longitudinal gradient of phytohormones, particularly auxins and cytokinins, exists along the shoot axis (Liu et al. 2024), which dictates bud dormancy and cambial activity. The tip segment, containing the apical meristem, is a site of active cell division and high auxin synthesis (Vernoux et al. 2010), yet it often possesses less lignified

tissues that may be prone to desiccation. In contrast, the basal segment is more lignified and possesses higher starch reserves, yet it may exhibit reduced bud flush potential due to more profound dormancy or thicker bark that complicates cambial alignment. Furthermore, variations in bud density and the metabolic state of the vascular tissue across these segments likely influence the speed of callus bridge formation and the subsequent nutrient flux to the emerging scion (Jin et al. 2023). Understanding how these intrinsic factors interact within the Philippines context—where environmental stressors such as high humidity and fluctuating temperatures prevail—is essential for optimizing nursery protocols and ensuring the long-term productivity of the grafted tree.

In the Philippines, the mass production of NSIC-registered cacao clones is a regulated endeavor overseen by the Bureau of Plant Industry (BPI). However, current regulations primarily focus on the genetic identity of the scion, leaving a significant degree of ambiguity regarding rootstock selection and scion preparation techniques. Local nursery operators frequently prioritize vigor over specific compatibility, often selecting clones with large seeds, such as the 'UF 18' variety, as universal rootstocks to achieve faster girth increment. While 'UF 18' provides a robust base, its interaction with various scion partitions across different NSIC-registered clones remains under-researched. If specific scion partitions from certain clones exhibit superior graft success or more robust initial growth metrics (e.g., stem diameter, leaf area index, and biomass accumulation), this information could revolutionize nursery efficiency, allowing for the propagation of more trees from limited mother-plant material without sacrificing quality.

The lack of standardized data on scion partitioning and clonal interaction presents a barrier to the technical optimization of the Philippine cacao nursery sector. To address these challenges, this study provides a comprehensive evaluation of the morphological and phenological responses of cacao grafts to scion segmenting. By focusing on NSIC-registered varieties that are currently being promoted for national expansion, this research seeks to provide a data-driven framework for nursery management.

It is believed that the use of specific scion segments (entire, apical, middle, and basal) and the selection of NSIC-registered clones have a significant impact on grafting success and cacao seedling growth rate, where proper division of scions will increase the production of quality planting materials from limited maternal germplasm. Hence, this study aimed to (1) evaluate the impact of scion segments on the grafting success and early vegetative growth stages; (2) assess the graft affinity and phenotypic vigor of six recommended NSIC-registered clones using 'UF 18' as a standardized rootstock; and (3) determine the optimal scion partitioning strategy to maximize the output of elite planting materials from limited maternal germplasm.

2 Materials and methods

The study was conducted from November 2019 to February 2020 at the STCBF cacao nursery, Central Mindanao University (CMU), Musuan, Bukidnon, Philippines. The grafted cacao seedlings were established in a shade-controlled nursery utilizing bamboo infrastructure. To maintain optimal soil moisture levels and prevent moisture stress, a consistent manual irrigation regimen was implemented. All nursery operations strictly adhered to the protocols set by the Department of Agriculture's Administrative Order No. 01, Series of 2020 (chrome-extension://efaidnbmnnpacajpgclclefindmkaj/https://www.da.gov.ph/wp-content/uploads/2022/08/dc01_s2020.pdf).

2.1 Plant materials

Rootstocks were three-month-old seedlings of 'UF 18' cacao clone (Fig. 1), selected for uniform stem diameter (1–1.2 cm at grafting height). Scions were harvested from six NSIC-registered clones (BR25, PBC123,



Fig. 1 Three-month-old 'UF 18' cacao seedlings used as the rootstocks

Fig. 2 Field site view of the budwood garden where the scions of NSIC-registered cacao clones were collected



UF18, K2, K9, K1) at the cacao budwood garden (Fig. 2) between 6:00–8:00 a.m.

2.2 Experimental design

A factorial experiment (4×6) was arranged in Randomized Complete Block Design (RCBD) with three replications. Factor A consisted of four types of scion segments (entire, tip, middle, and basal), while Factor B consisted of six cacao clones (UF 18, PBC 123, BR 25, K9, K2, and K1). A total of 72 experimental units were examined, with each unit consisting of 10 sample seedlings.

2.3 Grafting procedure

Tools were sterilized with 20% sodium hypochlorite (NaClO) solution. Top cleft grafting technique was used. Rootstocks were prepared with a horizontal cut, retaining 3–5 leaves. Scions were wedge-cut and aligned with the rootstock cambium, secured with cellophane strips (Fig. 3). Post-grafting care included daily watering, weeding, and wrap removal at 21 days post-grafting (DPG).

2.4 Data collection

2.4.1 Evaluation of graft compatibility and success rate

The graft success rate was quantitatively assessed at 21 DPG, a duration sufficient for the establishment of vascular continuity between the bionts. To ensure an unobstructed evaluation of the graft union, the binding cellophane film was meticulously excised using a micro-surgical blade, preventing mechanical stress or displacement of the scion.

Graft survival was strictly defined by the presence of scion turgidity, lack of necrotic tissue at the interface, and the emergence of new foliar primordia, indicating functional xylem and phloem reconnection. Specimens exhibiting desiccation, chlorosis, or abscission of the scion were classified

Fig. 3 Graft union assembly of cacao seedlings secured with transparent plastic cellophane for structural integrity



as unsuccessful. The percentage of grafting success was calculated for each treatment block using the following standardized equation:

$$\text{Graft success (\%)} = \frac{\sum \text{successful grafts}}{\text{Number of seedlings grafted}} \times 100$$

2.4.2 Characterization of scion vegetative proliferation

The vegetative development of the scion was quantified through the longitudinal monitoring of leaf emergence and expansion. To ensure consistency in the developmental stage recorded, a "developed leaf" was strictly defined as a fully unfolded leaf possessing a visible petiole and a laminar angle of $\geq 45^\circ$ relative to the main scion axis.

Data collection was performed non-destructively at three critical phenological intervals: 28, 56, and 96 DPG. These intervals were selected to capture the initial transition from graft union healing to active scion growth, as well as the subsequent exponential expansion phase. The total leaf count per scion was manually recorded for all surviving individuals within each treatment block to assess the vigor and compatibility of the biont combination.

2.4.3 Assessment of scion radial expansion and growth kinetics

To quantify the secondary growth and radial expansion of the scion, stem diameter was monitored at two temporal checkpoints. The baseline scion diameter (D_0) was recorded immediately following the grafting procedure once the union was stabilized. Measurements were

standardized at a fixed vertical reference point 2.0 cm distal to the graft interface to mitigate the influence of localized callus proliferation on diameter readings.

Radial measurements were performed using a Carbon Fiber Composites Digital Caliper (Resolution: 0.01 mm/0.01; Accuracy ± 0.1 mm/0.01; Battery: SL44/LR44 1.5 V). To account for the inherent non-circularity of the stem, two orthogonal measurements (transverse and sagittal) were taken at the reference point, and the arithmetic mean was recorded for each individual plant. A final diameter measurement (D_{90}) was conducted at 90 DPG. The absolute scion diameter increment (ΔD) was calculated as a measure of radial growth vigor using the following expression: $\Delta D = D_{90} - D_0$; where ΔD = Absolute scion diameter increment (mm), D_{90} = Scion diameter at 90 days post-grafting (mm), and D_0 = Initial scion diameter at the time of grafting (mm).

2.5 Statistical analysis

Statistical analysis was conducted using the Statistical Analysis for Agricultural Research (STAR 2.0.1) software. Significant differences among treatment means were evaluated using Tukey's Honest Significant Difference (HSD) test at a 5% level of significance ($p \leq 0.05$).

3 Results

3.1 Efficiency of graft union formation and clonal compatibility

Statistical analysis revealed no significant interaction between scion segment and clone regarding cacao grafting success

($p > 0.9642$). However, the scion segment independently influenced success rates ($p > 0.0413$). Specifically, the use of the entire scion yielded the highest success rate at 88.88%, outperforming the middle and basal segments by approximately 10 percentage points. Lastly, the effect of clone on the grafting success of cacao was not significant (Table 1).

3.2 Dynamics of scion foliar proliferation and canopy ontogeny

The progression of leaf emergence served as a primary indicator of scion vigor and the successful restoration of functional xylem transport. Results showed no significant interaction between scion segment and clone on cacao foliar ontogeny at 28, 56, and 90 DPG (Table 2).

At the initial evaluation phase (28 DPG), entire scions exhibited the most rapid foliar initiation but was statistically comparable with tip partitions (Table 2). As development progressed to 56 DPG, entire scions (8.29 leaves) significantly outperformed basal segments (5.75 leaves), though they remained statistically similar to tip and middle partitions. At 90 DPG, scion segments had no significant influence on the number of leaves developed per grafted seedling.

At 28 DPG, 'UF 18', 'BR 25', and 'PBC 123' produced the most leaves, though their leaf number was statistically comparable to 'K9', 'K2', and 'K1'. By 56 DPG, 'UF 18' yielded

Table 2 Leaf number of grafted cacao seedlings as influenced by scion segment and clone

Factor	Days post-grafting (DPG)		
	28	56	90
Scion segment			
Entire	7.28 ± 0.36 ^a	8.29 ± 0.66 ^a	11.28 ± 0.58
Tip	6.53 ± 0.36 ^{ab}	7.48 ± 0.75 ^a	10.32 ± 0.61
Middle	4.88 ± 0.61 ^b	6.40 ± 0.62 ^a	9.94 ± 0.63
Base	5.15 ± 0.56 ^b	5.75 ± 0.53 ^b	9.38 ± 0.37
Clone			
BR 25	7.57 ± 0.45 ^a	6.60 ± 0.61 ^b	10.38 ± 0.52 ^{ab}
PBC 123	5.17 ± 0.65 ^a	7.28 ± 0.85 ^{ab}	10.37 ± 0.66 ^{ab}
UF 18	8.00 ± 0.43 ^a	9.62 ± 0.53 ^a	12.28 ± 0.54 ^a
K2	5.15 ± 0.61 ^{ab}	6.41 ± 0.78 ^b	9.99 ± 0.70 ^{ab}
K9	4.83 ± 0.64 ^{ab}	6.98 ± 1.11 ^{ab}	10.21 ± 0.79 ^{ab}
K1	5.03 ± 0.56 ^{ab}	5.00 ± 0.34 ^b	8.16 ± 0.49 ^b
P value			
Scion segment	0.0000	0.0132	0.0538
Clone	0.0000	0.0069	0.0012
Scion segment x Clone	0.0760	0.2391	0.4350
cv (%)	24.56	33.35	20.07

Means within column in each factor with the same letter(s) are not significantly different at 5% level of probability using Tukey's Honest Significant Difference (HSD) test

Table 1 Grafting success of cacao using different scion segments from six cacao clones

Factor	Grafted seedling survival (%)
Scion segment	
Entire	88.88 ± 2.78 ^a
Tip	85.00 ± 2.55 ^{ab}
Middle	80.00 ± 2.72 ^b
Basal	78.89 ± 1.11 ^b
Clone	
BR 25	85.84 ± 3.79
PBC 123	86.67 ± 2.84
UF 18	86.67 ± 2.56
K2	84.17 ± 3.98
K9	75.83 ± 2.88
K1	80.00 ± 2.46
P value	
Scion segment	0.0413
Clone	0.1436
Scion segment x Clone	0.9642
cv (%)	13.39

Means within column in each factor with the same letter(s) are not significantly different at 5% level of probability using Tukey's Honest Significant Difference (HSD) test

the highest leaf count, remaining statistically similar only to 'K9' and 'PBC 123'. By the recommended transplanting age (90 DPG), 'UF 18' maintained the greatest leaf production, significantly outperforming 'K1' while remaining comparable to all other clones.

3.3 Analysis of scion radial expansion and secondary growth dynamics

Analysis revealed no significant interaction between scion segment and clone regarding the mean diameter increment of grafted cacao seedlings. Similarly, scion segment did not significantly affect radial stem expansion ($p < 0.5113$; Fig. 4). In contrast, the clonal source had a significant effect on diameter increment ($p = 0.0085$; Fig. 5). At 90 DPG, 'K2' exhibited the greatest stem expansion, though it was comparable to 'BR 25', 'UF 18', and 'PBC 123'. Conversely, 'K9' and 'K1' showed the lowest increments.

4 Discussion

A critical bottleneck in the scalable establishment of cacao plantations remains the efficient production and delivery of high-quality, certified planting materials. In the Philippines,

Fig. 4 Radial scion expansion in cacao as influenced by scion segment. $p=0.5113$; $cv\ (\%)=20.52$. Means are not significantly different

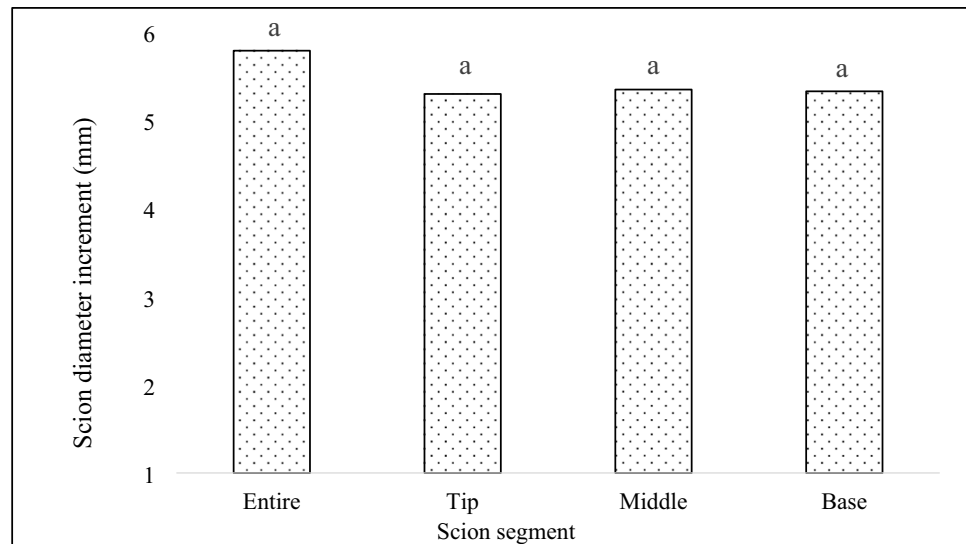
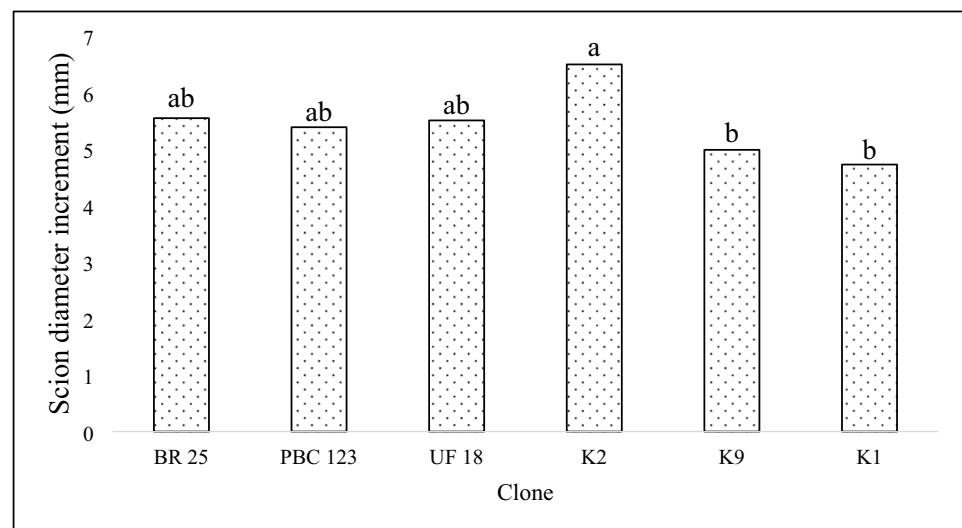


Fig. 5 Radial scion expansion in cacao as influenced by the different clones. $p=0.0085$; $cv\ (\%)=20.52$. Means with the same letter are not significantly different at 1% level of probability using Tukey's Honest Significant Difference (HSD) test



the production of these materials is strictly regulated by the Bureau of Plant Industry (BPI), which mandates the use of National Seed Industry Council (NSIC)-registered scions and rootstocks through accredited nurseries. Among available genotypes, 'UF 18' is a premier candidate for rootstock production due to its characteristically large seeds, which confer superior initial vigor and accelerated seedling development and better survival when grafted during the dry season (Fernandez 2022). However, despite these advantages, there is a distinct lack of empirical data regarding the graft compatibility between local elite clones and 'UF 18' rootstocks. Such intergenotypic compatibility is fundamental to optimizing graft union ontogeny (Wang et al. 2024; DuVal et al. 2025); without this information, nursery operators face unpredictable success rates, potentially compromising the output of field-ready, transplantable materials. Furthermore, the limited availability of certified budwood frequently

restricts the volume of planting materials. To mitigate this supply constraint, standard propagation protocols can be optimized by partitioning conventional ~27-cm scions (typically containing nine axillary buds) into discrete segments (tip, middle, and basal), each retaining at least three active axillary buds. This strategy aims to maximize the utilization of limited scion resources while maintaining the physiological integrity and developmental potential of the resulting grafts.

In the context of graft union ontogeny, the rootstock functions as the primary physiological conduit, supplying the scion with essential mineral nutrients, water, and phytohormones necessary for metabolic activation and subsequent growth. From a crop physiology perspective, the success of this asexual propagation technique is contingent upon the rapid restoration of vascular continuity—specifically the functional integration of the xylem and phloem—to facilitate the bidirectional translocation of assimilates and signaling

molecules between rootstocks and scions (Rasool et al. 2020; Razi et al. 2024; Wang et al. 2024). The high grafting success observed suggests a strong physiological affinity between the tested clones, indicating that the vascular connectivity required for scion survival was efficiently established. The significant influence of the scion segment further implies that the physical and physiological properties of the wood—rather than genetic differences—primarily drive grafting success. The entire scion achieved the highest success rate, likely due to greater carbohydrate reserves and more viable axillary buds compared to basal or middle segments. These reserves are essential for rapid callus formation and vascular re-establishment (Loescher et al. 1990). Similarly, the tip segment yielded comparable success, likely due to higher concentrations of growth-promoting hormones like auxins (Puig et al. 2012), which are crucial for stimulating cell division at the graft union.

After successful grafting, shoots will then emerge, followed by the development of leaves. Leaves constitute the primary photosynthetic apparatus (Mohr and Schopfer 1995), and their development is fundamental to the autotrophic transition of the newly grafted scion. In this study, the temporal progression of leaf emergence served as a critical physiological proxy for both scion vigor and the successful restoration of functional xylem hydraulic conductivity across the graft union (Rasool et al. 2020; Habibi et al. 2022; Wang et al. 2024). Initial assessments at 28 DPG revealed that entire scions and tip partitions exhibited the most rapid foliar initiation. This accelerated transition from post-grafting quiescence to active growth suggests that intact apical meristems, coupled with higher concentrations of endogenous auxin and cytokinin, facilitated early leaf development. Both hormones are critical for leaf growth (Hussain et al. 2021), with higher auxin levels typically concentrated in distal segments (Nanda and Melnyk 2018). By 56 DPG, leaf counts among the entire, tip, and middle segments reached statistical parity. This convergence indicates that while distal segments lead in early ontogeny, middle partitions possess sufficient carbohydrate reserves to support equivalent canopy establishment over time (Karabulut and Çelik 2022; Sallaku et al. 2022). By the transplantable age of 90 DPG, scion partitioning had no significant effect on leaf development; all segments (entire, tip, middle, and basal) produced at least nine leaves—the industry standard for transplantable cacao. These findings suggest that all four segment types are viable scion materials for the six clones tested ('BR 25', 'PBC 123', 'UF 18', 'K9', 'K2', and 'K1') when grafted onto 'UF 18' rootstocks.

Radial diameter increments served as a physiological proxy for the mechanical and vascular integration of the graft union (Lehnebach et al. 2018). Results indicated that all four scion segments across the six tested clones ('BR 25', 'PBC 123', 'UF 18', 'K9', 'K2', and 'K1') had comparable effects on stem girth.

This suggests that each segment provides sufficient initial vascular surface area and endogenous resources to facilitate robust secondary thickening and cambial ontogeny (Rasool et al. 2020). Furthermore, the specific clone significantly influenced radial expansion. In this study, 'K2' exhibited the greatest diameter increment, though it was statistically comparable to 'UF 18', 'BR 25', and 'PBC 123'. Because stem girth is an indicator of precocity in fruit trees (Owens 1995), using scions from these four clones on 'UF 18' rootstock likely supports the development of early-bearing cacao trees.

5 Conclusion and recommendation

The results of this study confirm that scion partitioning exerts a significant independent influence on cacao grafting success, with entire scions achieving the highest success rate, outperforming middle and basal segments. While clonal source did not significantly affect grafting success, the entire and tip scions demonstrated early foliar initiation, yet by 90 DPG all scion types converged to comparable leaf counts. Radial stem expansion was unaffected by scion segment but was significantly influenced by genotype, with 'K2' exhibiting the greatest diameter increment, comparable to 'UF 18', 'BR 25', and 'PBC 123'. These findings validate the broad compatibility of 'UF 18' rootstocks with diverse local clones, and provide practical guidance for optimizing propagation protocols to strengthen nursery capacity in delivering high-quality planting materials for sustainable plantation expansion.

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Author contribution The author designed and monitored the experiment, analyzed the data, interpreted the results, prepared the manuscript drafts, and approved the final version of the manuscript.

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Data availability Data are contained within the article.

Declarations

Competing interests The author has no relevant financial or non-financial interests to disclose.

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