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Influence of Axillary Bud Types on the Branching Angle of New Shoots and the Growth Quality of Bud Sticks in Rubber Tree 'Reken 628'

Huizhen Yang [1, 2], Wenping Li [1, 2], Xianhong Chen[1 *], Jun Wang[1]

[1]Rubber Research Institute, Chinese Academy of Tropical Agricultural Sciences, Danzhou, Hainan, China
[2] College of Tropical Crops, Yunnan Agricultural University, Pu'er, Yunnan, China
*Corresponding author: chenxhongjane@163.com (X. Chen).

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Abstract—*To investigate how axillary bud type regulates shoot branching angle and bud stick quality in rubber trees, this study used 'Reken 628' budded seedlings (rootstock: GT1). Decapitation was performed during the top leaf whorl sprouting stage at two positions: between the second and top whorls, and 1 cm below the lowest leaf of the second whorl, creating petiole bud and scale bud treatments. Phenological development and morphological indices—plant height, stem diameter, branching angle, leaf dimensions, N content, and surface temperature—were measured through three leaf whorl stages. At the first whorl, scale buds produced significantly wider leaves at the small bronze and color-changing stages, with longer phenological duration, while petiole buds had larger branching angles. By the second whorl, scale bud shoots showed superior plant height, stem diameter, leaf size, and surface temperature, but lower leaf N and larger branching angles. At the third whorl, scale bud branching angle was 88.44% higher than petiole buds, and leaf surface temperature was 1.02% higher. Correlation analysis indicated stronger growth synergy in scale buds, while petiole buds showed tighter links between branching angle and leaf traits. In conclusion, axillary bud type influences branching angle and bud stick quality by modulating growth traits and their correlations, offering a theoretical basis for optimizing rubber tree seedling cultivation and plant architecture.*

Keywords—Hevea brasiliensis; axillary bud type; branching angle; new shoot growth; morphological indices

I. INTRODUCTION

As a globally important tropical cash crop, *Hevea brasiliensis* produces natural rubber, a vital industrial raw material and strategic resource. In recent years, the persistent slump in natural rubber prices and the decline in economic benefits have weakened the willingness of rubber cultivation entities to expand production. Nevertheless, the natural rubber industry is a pillar agricultural industry in tropical regions of China [1]. The Central Government Document No.1 in 2025 clearly stated the need to promote the stable production and quality improvement of natural rubber, and the document in 2026 further required advancing the steady development of the industry. Rubber tree seedlings are a key factor restricting the production capacity of natural rubber [2]. Intercropping in rubber plantations is an effective approach to address the persistent low rubber prices and the prevalent long-term losses in rubber cultivation. In the cultivation and management of rubber trees, the plant architecture of budded seedlings exerts a decisive influence on the field ventilation and light transmission efficiency, nutrient transport and yield of intercropped crops in rubber plantations. Among them, the branching angle, as a core index for regulating rubber tree plant architecture, is closely related to crown structure and light energy utilization efficiency, and has a profound impact on the growth and development of intercropped crops in rubber plantations. *Hevea brasiliensis* 'Reken 628' features a tall tree body, high branching position, small crown ratio, a more compact and sparse crown structure, a small number of primary branches with narrow branching angles and a high crown roundness, accompanied by an obvious natural self-pruning phenomenon from bottom to top. These characteristics result in a low canopy density of its plantations, making it more suitable for the growth of intercropped crops [3]. A comprehensive evaluation system for the growth quality of its bud sticks is of great guiding significance for the high-quality and efficient cultivation of this cultivar.

At present, the natural rubber industry is faced with numerous challenges in the standardized cultivation of high-quality seedlings and the precise regulation technology of plant architecture, such as low seedling raising efficiency, insufficient seedling uniformity and unsatisfactory branching angles [4-5], which directly affect the production efficiency and management costs of rubber plantations. Mini-seedling budding technology has become the core method for factory seedling raising due to its remarkable advantages [6-7]. By utilizing seed nutrients for early budding when the cotyledons of mini-seedlings are unexpanded, this technology shortens the growth period of rootstocks, realizes the miniaturization of seedlings and shortens the seedling raising cycle. It boasts high seedling raising efficiency, low cost and easy transportation, and the resulting seedlings have a well-developed root system, strong stress resistance and an early tapping age [8-11]. It has been widely applied in rubber cultivation areas of Yunnan and Guangdong Provinces [8-15]. However, its promotion is hindered in producing areas such as Hainan due to the low rubber prices and labor shortage, with the core problems being the low survival rate of budding affected by rootstock seeds, bud stick quality and climate conditions, which leads to seedling waste, increased subsequent tending and management costs, and inconsistent quality of outplanted seedlings. Previous studies have mostly focused on the effects of rootstock seed types(4), survival rate of mini-seedling budding [10,16], sprouting dynamics [17-21], the position of bud pieces on the leaf whorls of bud sticks [22], bud piece types [23]and bud piece sources [24-26] on the post-budding effects. Yet, the intrinsic mechanism by which axillary bud types (scale buds and petiole buds), the core organs for shoot sprouting of budded seedlings, regulate the sprouting rhythm and growth vigor of bud sticks, and thereby affect the formation of branching angles and the growth quality of bud sticks, has not been systematically elucidated. Clarifying the correlations between different axillary bud types and branching angles as well as bud stick growth indices can provide a new theoretical basis and practical approach for the precise bud selection and plant architecture optimization of rubber tree budded seedlings. Existing studies have confirmed that the branching characteristics of plants have a genetic basis, and there are obvious genetic variation characteristics in branching angles among different cultivars [3], which lays a foundation for the research on regulating branching angles through axillary bud types. In addition, the formation of plant branching is a complex biological process, precisely regulated by multiple factors such as genetic factors, hormones, metabolic pathways and environmental conditions [26-36], and exerts a significant impact on plant growth, development and yield [37]. These findings provide a multi-dimensional analytical perspective for this study, and an in-depth understanding of these regulatory mechanisms is crucial for the precise improvement of rubber tree plant architecture.

In view of this, this study innovatively focuses on the differences in axillary bud types of *Hevea brasiliensis* 'Reken 628', constructs two treatments of petiole buds and scale buds through differential topping methods, systematically observes the growth phenological process of the first leaf whorl after topping, and determines the stem and leaf morphological indices of newly sprouted shoots at the stable stages of the first to third leaf whorls (including mother stem, plant height, stem diameter, branching angle, leaf length, leaf width, leaf N content, leaf SPAD value, leaf surface humidity and leaf surface temperature of newly sprouted shoots). The aim is to deeply explore the regulatory effects and potential mechanisms of different axillary bud types on the branching angle of newly sprouted shoots and the growth quality of bud sticks. The results of this study will fill the research gap in this field, provide a new theoretical basis and practical guidance for the precise bud selection and plant architecture optimization of rubber tree budded seedlings, and thus promote the high-quality and efficient development of the natural rubber industry.

II. MATERIAL AND METHODS

Experimental site The experiment was conducted at the Rubber Tree Mini-seedling Budding Demonstration Base of Rubber Research Institute, Chinese Academy of Tropical Agricultural Sciences, Danzhou City, Hainan Province (109°29′E, 19°30′N, with an altitude of 116.9 m). The base has a tropical monsoon climate. During the experiment, the annual average temperature was 21 ~ 30°C, the annual average precipitation was 1652.3 mm, and the annual average sunshine duration was 1734 h, which is suitable for the growth of rubber trees.

Experimental Materials GT1 seeds were sown in sand beds in October 2021, and GT1 seedlings were obtained in November. In December, the GT1 seedlings were transplanted into single-hole inverted conical seedling raising tubes for further cultivation until the root system grew to the bottom holes of the tubes. In May 2022, 135 rootstock tube seedlings with consistent growth were selected and planted in the base, with a plant spacing of 40 cm and a row spacing of 60 cm. Budding was performed on GT1 seedling rootstocks in the middle and late October 2022. The bud sticks were collected from the Improved Rubber Tree Seedling Breeding Base of Rubber Research Institute, Chinese Academy of Tropical Agricultural Sciences, with the cultivar of 'Reken 628'. The bud sticks had 5 leaf whorls when collected, and plump axillary buds between the 3rd and 4th leaf whorls from the top were selected for budding.

The binding was removed in December 2022, and rootstock sawing was conducted in March 2023 to cultivate one-year-old single-stem bud sticks. In September 2023, the bud sticks were sawn for the second time at 15 cm above the budding interface, and only one robust bud stick was retained on each rootstock of each treatment after sawing. In September 2024, the bud sticks were sawn for the third time at 30 cm above the budding interface, and three-year-old single-stem bud sticks of *Hevea brasiliensis* 'Reken 628'-GT1 seedling rootstocks with consistent growth and four-leaf whorls were cultivated. When the top leaf whorl was in the stage of sprouting and elongation with unexpanded leaflets, topping was carried out at the junction of the second leaf whorl from the top and the top leaf whorl, and 1 cm below the first petiolate leaf from the bottom of the second leaf whorl from the top, respectively, to form two treatments of petiole buds and scale buds. Each treatment had 3 replicates with 10 plants per replicate. Unified water and fertilizer management and pest and disease control were adopted during the experiment to ensure consistent environmental conditions.

Experimental Methods In the late July 2025, phenological observations (from axillary bud sprouting after topping to the senescence stage) were carried out on 30 tagged plants with consistent growth in the two experimental treatments. The time nodes of each key phenological stage were recorded, and the phenological duration of one leaf whorl was counted. Plant height, leaf length, leaf width and branching angle (the included angle between newly sprouted shoots and the mother stem, measured at 4 cm above the junction of newly sprouted shoots and the mother stem) were measured at the stages of fully expanded small bronze leaflets, large bronze stage, color-changing stage, light green stage, stable stage and senescence stage, respectively.

From September to December 2025, the morphological indices of the mother stem (mother stem diameter) and newly sprouted shoots, including branching angle, plant height (from the dense node bud of each leaf whorl to the stem apex of the corresponding leaf whorl), stem diameter (measured at the dense node bud of each leaf whorl), leaf length (from the junction of petiole and leaf blade to the leaf tip), leaf width (the widest part in the middle of the leaf blade), leaf SPAD value, leaf N content, leaf surface temperature and leaf relative humidity, were measured from bottom to top at the 1st, 2nd and 3rd leaf whorl positions of the tagged plants in the two experimental treatments, respectively.

The mother stem diameter and the stem diameter of newly sprouted shoots were measured with a vernier caliper with an accuracy of 0.01 mm. The branching angle was determined by measuring the distance of the included angle between newly sprouted shoots and the mother stem with a vernier caliper (0.01 mm accuracy) to analyze the differences in the included angle between newly sprouted shoots from different bud sources and the mother stem. Plant height was measured with a tape measure with an accuracy of 1 mm to compare the plant height differences of shoots sprouted from scale buds and petiole buds. Leaf length and leaf width were measured with a transparent straight ruler (1 mm accuracy); leaf SPAD value, leaf N content, leaf surface temperature and leaf relative humidity was determined with a chlorophyll meter (TYS-N, Beijing Zhongke Weier Technology Development Co., Ltd.).

Data processing and analysis Excel 2021 was used for data collation, data processing system statistical software package (DPS) 20.05 for significance test of differences (Student's t-test), GraphPad Prism 8.3 for mapping, and Origin 2024 for Spearman correlation analysis and corresponding mapping.

III. RESULT AND ANALYSIS

Comparison of the Growth Process of the First Leaf Whorl

After topping (Fig. 1a, 1b), axillary buds sprouted (Fig. 1c, 1d). During the leaf phenological development, at the S4 stage (small bronze stage, Fig. 1e), the leaf width of shoots sprouted from scale buds (mean: 2.1 cm) was significantly 15.81% wider than that from petiole buds (mean: 1.813 cm), with a difference of 0.2867 cm (Fig. 2c). At the S6 stage (color-changing stage, Fig. 1f), the leaf width of shoots from scale buds (mean: 6.521 cm, Fig. 2d) was significantly 11.47% wider than that from petiole buds (mean: 5.85 cm), with a difference of 0.6708 cm.

Fig.1 Comparison of stem and leaf morphology during the phenological growth of bud sticks from two axillary bud types

Note: Fig. 1a represents petiole buds after topping; Fig. 1b represents scale buds after topping; Fig. 1c represents axillary bud sprouting of petiole buds; Fig. 1d represents axillary bud sprouting of scale buds; Fig. 1e represents the small bronze stage; Fig. 1f represents the color-changing stage; Fig. 1g represents the stable stage; Fig. 1h represents the included angle (branching angle) between newly sprouted shoots and the mother stem.

When the top leaf whorl (the 1st leaf whorl) reached the stable stage (Fig. 1g), the included angle (branching angle) between newly sprouted shoots from petiole buds and the mother stem (mean: 3.467 cm, Fig. 1h) was significantly 15.86% larger than that from scale buds (mean: 2.917 cm), with a difference of 0.55 cm (Fig. 2b). Additionally, the phenological duration required for the leaves of newly sprouted shoots from scale buds to develop into a complete leaf whorl (mean: 45 days) was significantly 23.29% longer than that from petiole buds (mean: 36.5 days), with a difference of 8.5 days (Fig. 2a).

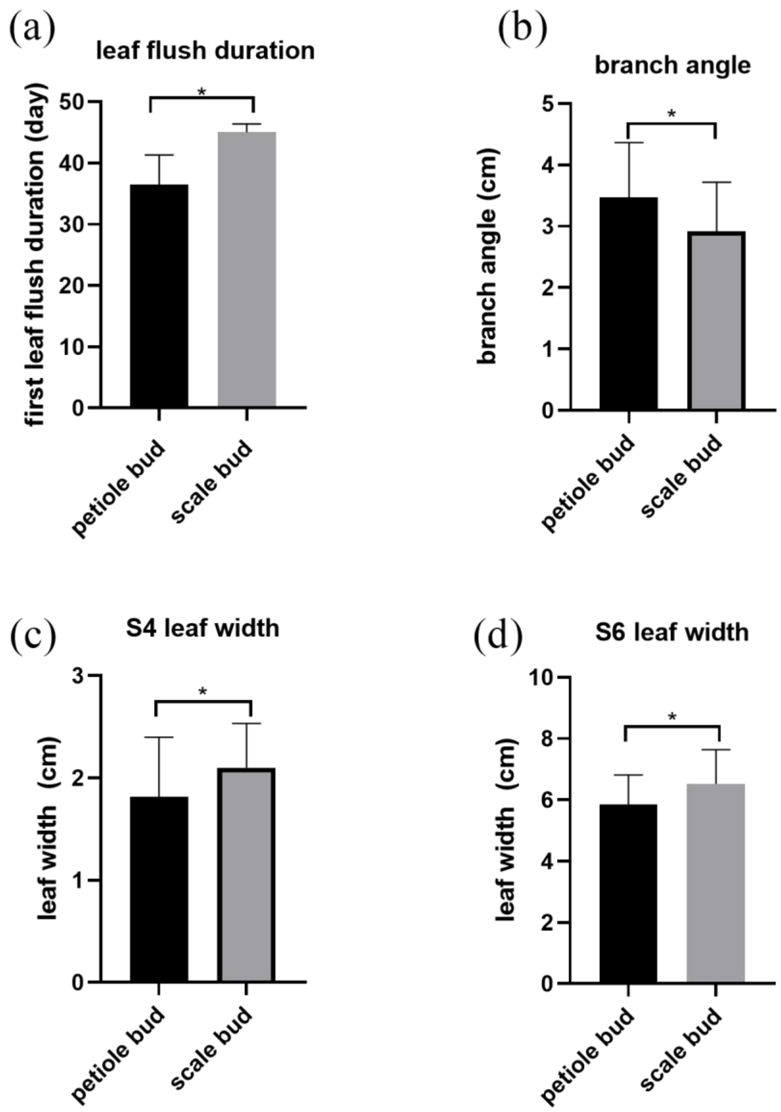

Fig.2 Comparison of stem and leaf morphology during the growth of the first leaf whorl of bud sticks from two axillary bud types

Note: * in the figure indicates a significant difference between treatments at the $p < 0.05$ level, and error bars represent the standard deviation. S4, small bronze stage. S6, color-changing stage.

Comparison of Stem and Leaf Morphology at the Stable Stage of the First Leaf Whorl

When the bud sticks grew to the stable stage of the first leaf whorl, the plant height of newly sprouted shoots from petiole buds (Fig. 3a, mean: 39.08 cm) was significantly lower by approximately 25.69% than that from scale buds (mean: 49.13 cm), with a difference of 10.04 cm. The stem diameter of shoots from scale buds (Fig. 3b, mean: 8.737 mm) was significantly 17.79% thicker than that from petiole buds (mean: 7.418 mm), with a difference of 1.32 mm. The leaf length of shoots from scale buds (Fig. 3c, mean: 16.64 cm) was significantly 17.52% longer than that from petiole buds (mean: 14.16 cm), with a difference of 2.481 cm. The leaf width of shoots from scale buds (Fig. 3d, mean: 6.939 cm) was significantly 20.47% wider than that from petiole buds (mean: 5.76 cm), with a difference of 1.179 cm.

In contrast, the leaf N content of shoots from scale buds (Fig. 3e, mean: 16.76 mg/g) was significantly 4.86% lower than that from petiole buds (mean: 17.61 mg/g), with a difference of 0.8556 mg/g. The leaf surface temperature of shoots from scale buds (Fig. 3f, mean: 31.02 ℃) was significantly 3.66% higher than that from petiole buds (mean: 29.92 ℃), with a difference of 1.096℃.

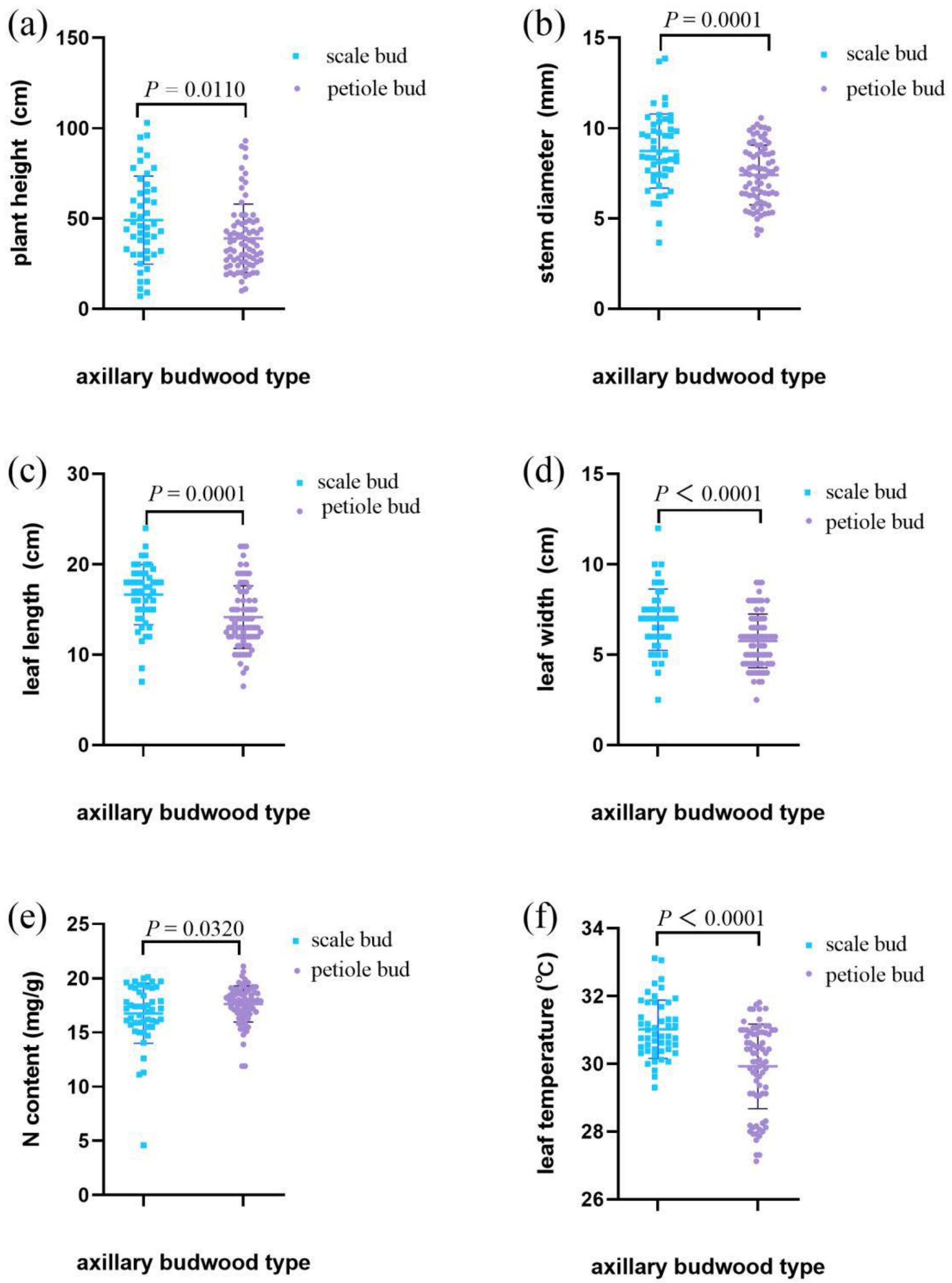

Fig.3 Comparison of stem and leaf morphological traits of bud sticks at the first leaf whorl stage between two axillary bud types

Note: *p*-values in the figure indicate significant differences between treatments at the 0.05 level ($p < 0.05$) and highly significant differences at the 0.01 level ($p < 0.01$). Error bars represent the standard deviation.

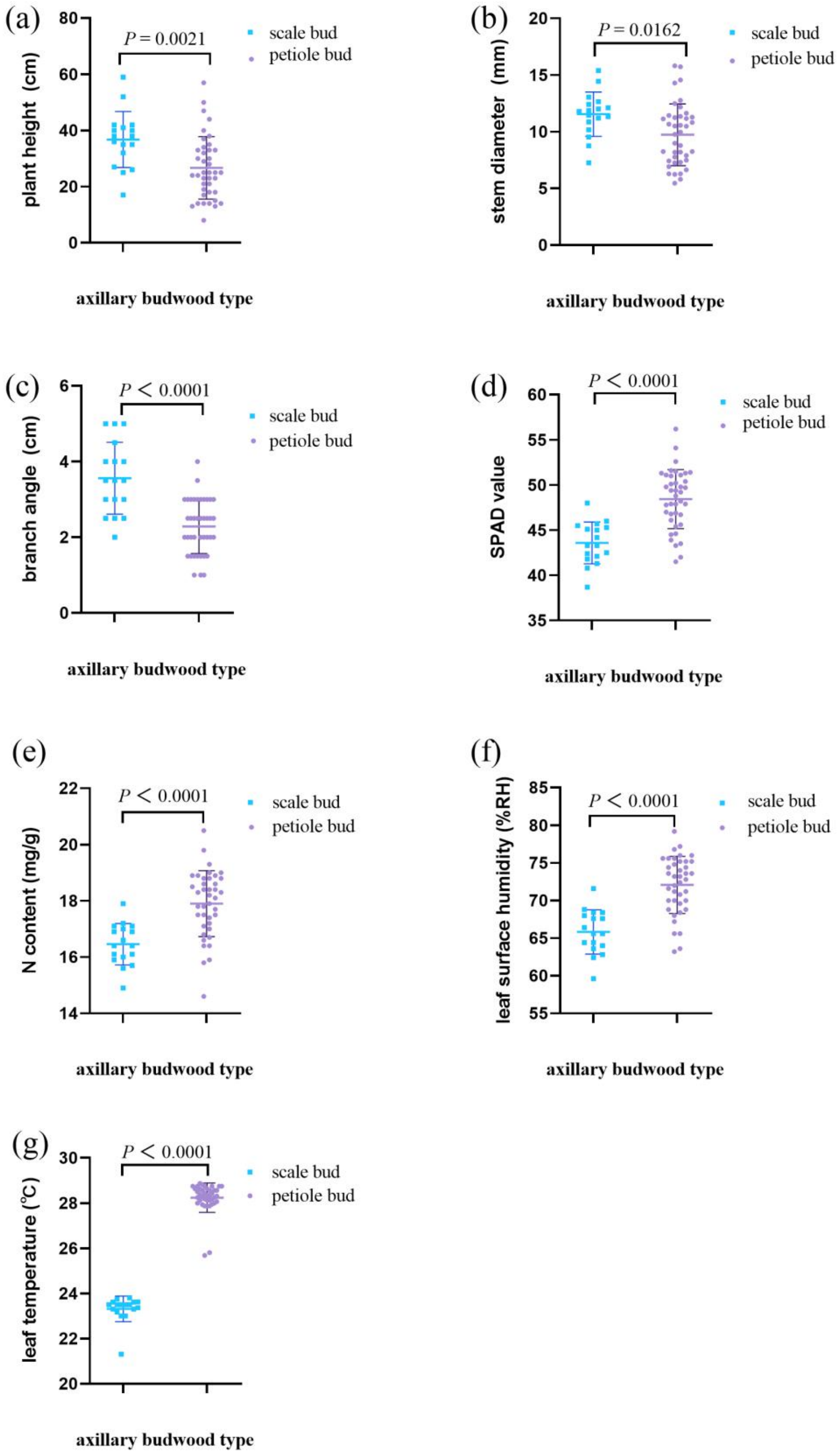

Fig.4 Comparison of stem and leaf morphological traits of bud sticks at the second leaf whorl stage between two axillary bud types

Note: p-values in the figure indicate significant differences ($p < 0.05$) and highly significant differences ($p < 0.01$) between treatments. Error bars represent the standard deviation.

Comparison of Stem and Leaf Morphology at the Stable Stage of the Second Leaf Whorl

When the bud sticks developed to the stable stage of the second leaf whorl, the plant height of newly sprouted shoots from petiole buds (Fig. 4a, mean: 26.65 cm) was extremely significantly lower by approximately 27.50% than that from scale buds (mean: 36.76 cm), with a difference of 10.11 cm. The stem diameter of shoots from scale buds (Fig. 4b, mean: 11.54 mm) was significantly 18.60% thicker than that from petiole buds (mean: 9.732 mm), with a difference of 1.811 mm. The branching angle of shoots from scale buds (Fig. 4c, mean: 3.559 cm) was extremely significantly 55.55% larger than that from petiole buds (mean: 2.288 cm), with a difference of 1.271 cm. The chlorophyll SPAD value of shoots from scale buds (Fig. 4d, mean: 43.59) was extremely significantly lower by approximately 9.99% than that from petiole buds (mean: 48.44), with a difference of 4.849. The leaf N content of shoots from scale buds (Fig. 4e, mean: 16.46 mg/g) was extremely significantly lower by approximately 8.04% than that from petiole buds (mean: 17.90 mg/g), with a difference of 1.444 mg/g. The leaf surface humidity of shoots from scale buds (Fig. 4f, mean: 65.84%) was extremely significantly lower by approximately 8.67% than that from petiole buds (mean: 72.08%), with a difference of 6.245 percentage points. The leaf surface temperature of shoots from scale buds (Fig. 4g, mean: 23.32 ℃) was extremely significantly lower by approximately 17.42% than that from petiole buds (mean: 28.24℃), with a difference of 4.922℃.

Comparison of Stem and Leaf Morphology at the Stable Stage of the Third Leaf Whorl

When the bud sticks grew to the stable stage of the third leaf whorl, the branching angle of newly sprouted shoots from scale buds (Fig. 5a, mean: 3.455 cm) was extremely significantly 88.49% larger than that from petiole buds (mean: 1.833 cm), with a difference of 1.621 cm. The leaf surface temperature of shoots from scale buds (Fig. 5b, mean: 21.99 ℃) was extremely significantly 1.02% higher than that from petiole buds (mean: 21.77 ℃), with a difference of 0.2227 ℃. No significant differences were observed in the indices of mother stem, plant height, stem diameter, leaf length, leaf width, SPAD value, leaf N content and leaf surface humidity between the two treatments.

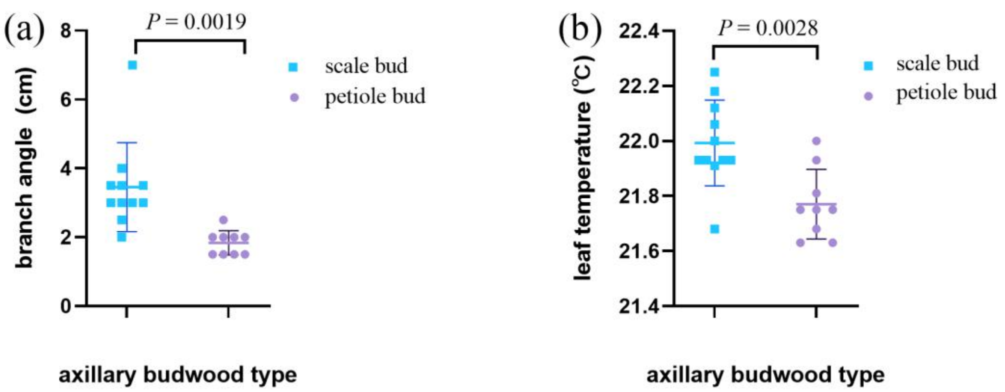

Fig.5 Comparison of stem and leaf morphological traits of bud sticks at the third leaf whorl stage between two axillary bud types

Note: *p*-values in the figure indicate significant differences ($p < 0.05$) and highly significant differences ($p < 0.01$) between treatments. Error bars represent the standard deviation.

Correlation analysis

Figure 6 presents the correlations among various stem and leaf morphological indices of newly sprouted shoots from the two axillary bud types (scale buds and petiole buds) of *Hevea brasiliensis* 'Reken 628' at the first, second and third leaf whorl stages.

At the stable stage of the first leaf whorl for shoots from scale buds (Fig. 6A), the mother stem was extremely significantly positively correlated with the plant height and stem diameter of the newly sprouted shoots, and significantly positively correlated with the leaf width, SPAD value and leaf surface temperature of the shoots; the plant height of the shoots was extremely significantly positively correlated with their stem diameter and leaf width, very significantly positively correlated with their leaf length and leaf surface temperature, and significantly positively correlated with their SPAD value and leaf N content; the stem diameter of the shoots was extremely significantly positively correlated with their leaf length and leaf width, and significantly positively correlated with their leaf N content; the branching angle of the shoots was very significantly positively correlated with leaf surface temperature; the leaf length of the shoots was extremely significantly positively correlated with their leaf width, very significantly positively correlated with their leaf N content, and significantly positively correlated with their SPAD value and leaf surface humidity, respectively; the leaf width of the shoots was extremely significantly positively correlated with their SPAD value, leaf N content and leaf surface humidity, respectively; the SPAD value of the shoots was extremely significantly positively correlated with their leaf N content and leaf surface humidity; the leaf N content of the shoots was extremely significantly positively correlated with their leaf surface humidity.

At the stable stage of the second leaf whorl for shoots from scale buds (Fig. 6B), the plant height of the newly sprouted shoots was significantly positively correlated with their SPAD value, leaf N content and leaf surface humidity, respectively; the stem diameter of the shoots was significantly positively correlated with their leaf width; the branching angle of the shoots was very significantly negatively correlated with their leaf length, significantly negatively correlated with their leaf width, and significantly positively correlated with leaf surface temperature; the leaf length of the shoots was extremely significantly positively correlated with their leaf width; the SPAD value of the shoots was extremely significantly positively correlated with their leaf N content and leaf surface humidity, respectively; the leaf N content of the shoots was extremely significantly positively correlated with their leaf surface humidity.

At the stable stage of the third leaf whorl for shoots from scale buds (Fig. 6C), the mother stem was very significantly positively correlated with the plant height of the newly sprouted shoots; the plant height of the shoots was very significantly positively correlated with their stem diameter and significantly positively correlated with their leaf width; the stem diameter of the shoots was significantly positively correlated with their leaf length and very significantly positively correlated with their leaf width; the leaf length of the shoots was extremely significantly positively correlated with their leaf width; the SPAD value of the shoots was extremely significantly positively correlated with their leaf N content and leaf surface humidity; the leaf N content of the shoots was extremely significantly positively correlated with their leaf surface humidity.

At the stable stage of the first leaf whorl for shoots from petiole buds (Fig. 6D), the mother stem was extremely significantly positively correlated with the plant height and stem diameter of the newly sprouted shoots, and significantly positively correlated with the branching angle of the shoots; the plant height of the shoots was extremely significantly positively correlated with their stem diameter, leaf length and leaf width, and significantly positively correlated with their branching angle, SPAD value, leaf N content, leaf surface humidity and leaf surface temperature; the stem diameter of the shoots was extremely significantly positively correlated with their leaf length and leaf width, and significantly positively correlated with their SPAD value, leaf N content and leaf surface humidity, respectively; the branching angle of the shoots was significantly positively correlated with their leaf width; the leaf length of the shoots was extremely significantly positively correlated with their leaf width and SPAD value, very significantly positively correlated with their leaf N content and leaf surface humidity, and significantly positively correlated with their leaf surface temperature; the leaf width of the shoots was very significantly positively correlated with their SPAD value, leaf N content and leaf surface humidity; the SPAD value of the shoots was extremely significantly positively correlated with their leaf N content, leaf surface humidity and leaf surface temperature; the leaf N content of the shoots was extremely significantly positively correlated with their leaf surface humidity and leaf surface temperature; the leaf surface humidity of the shoots was extremely significantly positively correlated with their leaf surface temperature.

At the stable stage of the second leaf whorl for shoots from petiole buds (Fig. 6E), the mother stem was significantly positively correlated with the stem diameter and branching angle of the newly sprouted shoots, and significantly negatively correlated with the SPAD value and leaf N content of the shoots; the plant height of the shoots was extremely significantly positively correlated with their stem diameter and leaf length, and very significantly positively correlated with their leaf width; the stem diameter of the shoots was extremely significantly positively correlated with their leaf length and leaf width; the leaf length of the shoots was extremely significantly positively correlated with their leaf width; the SPAD value of the shoots was extremely significantly positively correlated with their leaf N content and leaf surface humidity; the leaf N content of the shoots was extremely significantly positively correlated with their leaf surface humidity.

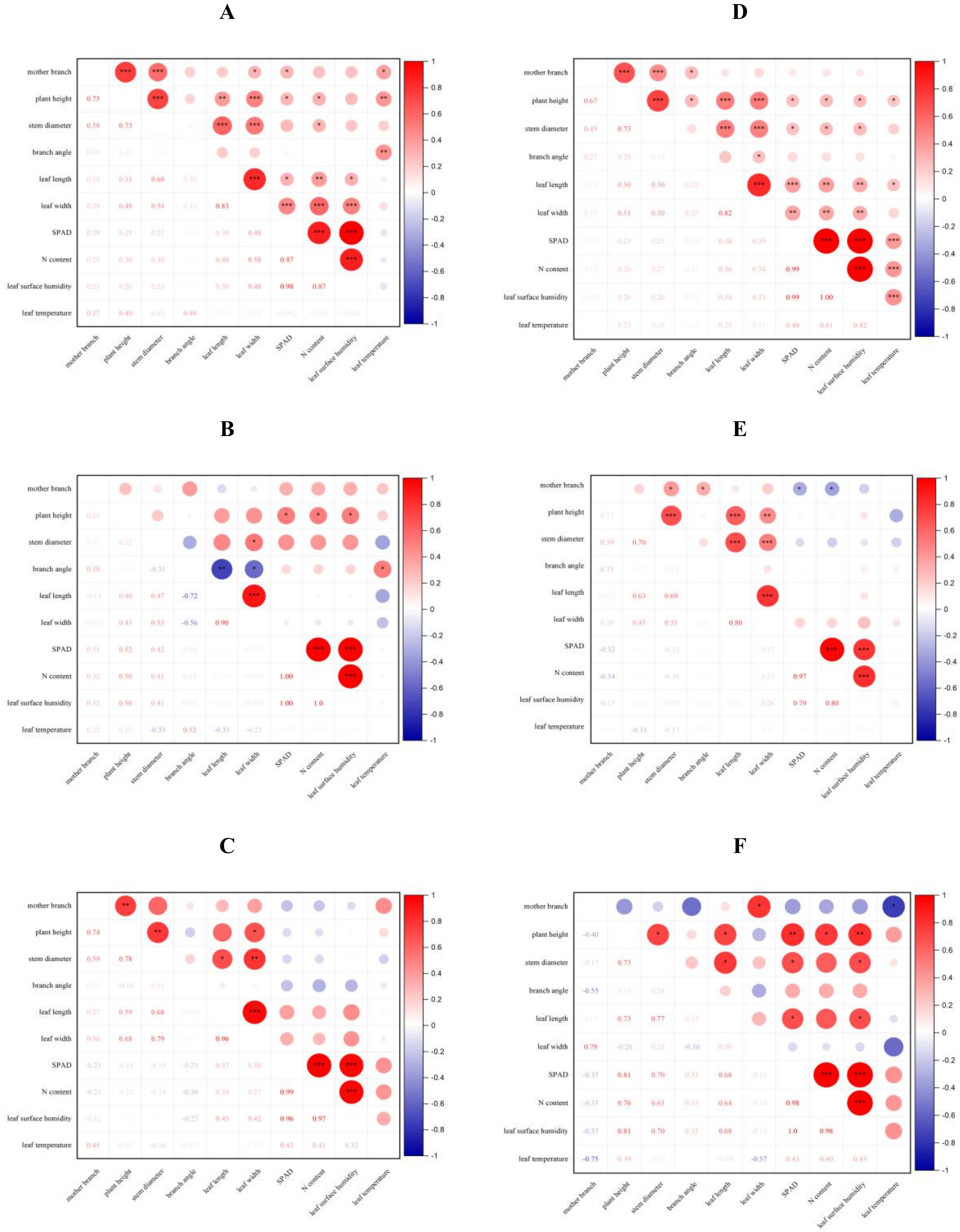

Fig.6 Correlation analysis of stem and leaf morphological indices of newly sprouted shoots from two axillary bud types

Note: Panels A–C represent the correlation analysis of stem and leaf morphological indices of newly sprouted shoots from scale buds at the first, second and third leaf whorl stages, respectively; Panels D–F represent the correlation analysis of stem and leaf morphological indices of newly sprouted shoots from petiole buds at the first, second and third leaf whorl stages, respectively. The size of the circles and the depth of the color represent the magnitude of correlation coefficients and the level of significance, with blue indicating negative correlation and red indicating positive correlation. The upper triangle shows the significance markers of correlations, where *, ** and *** indicate statistically significant ($p<0.05$), very significant ($p<0.01$) and extremely significant ($p<0.001$) correlation coefficients, respectively. The lower triangle shows the values of correlation coefficients, where $|r|\geq0.7$ indicates a strong correlation, $0.3\leq|r|<0.7$ indicates a moderate correlation, and $|r|<0.3$ indicates a weak correlation.

At the stable stage of the third leaf whorl for shoots from petiole buds (Fig. 6F), the mother stem was significantly positively correlated with the leaf width of the newly sprouted shoots and significantly negatively correlated with their leaf surface temperature; the plant height of the shoots was significantly positively correlated with their stem diameter, leaf length and leaf N content, respectively, and very significantly positively correlated with their SPAD value and leaf surface humidity; the stem diameter of the shoots was significantly positively correlated with their leaf length, SPAD value and leaf surface humidity, respectively; the leaf length of the shoots was significantly positively correlated with their SPAD value and leaf surface humidity; the SPAD value of the shoots was extremely significantly positively correlated with their leaf N content and leaf surface humidity; the leaf N content of the shoots was extremely significantly positively correlated with their leaf surface humidity.

Comprehensive analysis

Using branching angle as a lower-is-better indicator, combined with mother stem, plant height, stem diameter, leaf length, leaf width, SPAD value, leaf N content, leaf surface humidity and leaf surface temperature of newly sprouted shoots, the TOPSIS method was used to conduct a multi-index comprehensive evaluation on the overall performance of newly sprouted shoots from two axillary bud types at different leaf whorl stages. The results are shown in Table 1. According to the comprehensive index and ranking, newly sprouted shoots from petiole buds at the third leaf whorl had the highest comprehensive index (0.5176), ranking first; followed by shoots from petiole buds at the first leaf whorl (0.5068), ranking second. Shoots from scale buds at the third leaf whorl (0.4793) and at the first leaf whorl (0.4661) ranked third and fourth, respectively. Both types of newly sprouted shoots showed relatively poor comprehensive performance at the second leaf whorl stage: shoots from petiole buds at the second leaf whorl had a comprehensive index of 0.4091, ranking fifth, and shoots from scale buds at the second leaf whorl had the lowest comprehensive index (0.4047), ranking sixth. Overall, the comprehensive performance of newly sprouted shoots from petiole buds showed a gradually increasing trend with growth process, while shoots from scale buds showed a growth trough at the second leaf whorl stage, with relatively unstable comprehensive performance.

Table 1 Comprehensive Evaluation of Newly Sprouted Shoots Using the TOPSIS Method Based on Stem and Leaf Morphological Indices

Leaf whorl - bud type	Statistic CI	Rank
3rd-leaf whorl (petiole buds)	0.5176	1
1st-leaf whorl (petiole buds)	0.5068	2
3rd-leaf whorl (scale buds)	0.4793	3
1st-leaf whorl (scale buds)	0.4661	4
2nd-leaf whorl (petiole buds)	0.4091	5
2nd-leaf whorl (scale buds)	0.4047	6

Note: CI, approximation to the Optimal Vectors.

IV. DISCUSSION AND CONCLUSION

DISCUSSION

In this study, two axillary bud types of *Hevea brasiliensis* 'Reken 628', namely petiole buds and scale buds, were successfully induced by differentiated decapitation treatments, and their regulatory effects on the branching angle and growth quality of newly sprouted shoots were systematically investigated. The results clearly demonstrated significant differences in phenological progression, morphological and physiological indices, and correlation patterns between the two axillary bud types. The fundamental reason for these differences lies in the inherent distinctions in the occurrence position and developmental basis of axillary buds. Scale buds developed more sufficiently and accumulated more abundant nutrients, whereas petiole buds germinated faster but had a relatively weak growth foundation. This study is the first to systematically compare the effects of these two axillary bud types on shoot growth, branching angle and phenological progression in rubber trees, filling the research gap in this field.

The present study found that axillary bud type significantly shaped the growth pattern of rubber tree shoots. Shoots derived from scale buds exhibited a robust growth strategy. In terms of phenological progression, scale buds had a longer leaf whorl development cycle, which provided sufficient time for full leaf expansion and establishment of photosynthetic capacity. At the first leaf whorl stage, scale buds showed significantly greater leaf width than petiole buds, indicating an advantage in early photosynthetic potential. During the stable periods of the first and second leaf whorls, scale buds consistently exhibited significant advantages in key vegetative growth indices such as plant height, stem diameter, leaf length and leaf width. This was attributed to their sufficient nutrient reserves and more efficient nitrogen utilization, allowing nutrients to be more effectively converted into biomass accumulation. Such a stable growth pattern enabled scale-bud shoots to form thicker stems and larger leaf areas, laying a solid foundation for subsequent growth.

In contrast, shoots from petiole buds displayed a fast-germinating growth pattern. They had a relatively shorter leaf whorl phenological period, indicating faster germination and growth. At the first leaf whorl stage, the branching angle of petiole-bud shoots was significantly larger than that of scale-bud shoots, which might be related to their insertion position and germination direction, leading to an outward growth tendency in the early stage. Although petiole buds were slightly inferior to scale buds in vegetative growth indices at the initial stage, their fast-germinating characteristic allowed them to quickly occupy space, which could be advantageous under certain cultivation objectives.

As a core index regulating rubber tree plant architecture [3, 39–40], branching angle was dynamically regulated by axillary bud type, and such regulation showed obvious stage-specific characteristics. At the first leaf whorl stage, petiole-bud shoots had a significantly larger branching angle than scale-bud shoots, reflecting their early outward growth tendency. However, with further shoot development, at the second and third leaf whorl stages, the branching angle of scale-bud shoots became significantly larger instead. This shift revealed that rubber tree plant architecture is not static but possesses dynamic regulatory ability. The rapid germination of petiole buds might lead to a larger branching angle in the early stage, while the vegetative growth advantage of scale buds may enable them to form a larger branching angle in the later stage to adapt to their stronger growth vigor and leaf expansion. Such stage-specific differences suggest that flexible regulation strategies should be adopted in cultivation management according to different growth stages and target plant architectures.

Correlation analysis further revealed differences in the coordination of growth indices between the two axillary bud types. Shoots from scale buds showed stronger synergy among growth indices, with closer coordinated growth relationships among various vegetative organs, which complemented their "robust" growth pattern. In contrast, the branching angle of shoots from petiole buds was more closely correlated with leaf indices, which may reflect a specific balancing mechanism between branching angle formation and leaf development during rapid germination [38].

The TOPSIS comprehensive evaluation results provided a more comprehensive perspective. Petiole bud shoots at the third leaf whorl stage showed the best overall performance, confirming their characteristic of "fast germination followed by steady growth". Although not dominant in the early stage, their comprehensive performance continuously improved with growth. In contrast, scale bud shoots at the second leaf whorl stage showed the poorest overall performance, which may be related to the critical period of nutrient distribution at this stage, during which a large amount of nutrients was preferentially allocated to leaf and stem construction, leading to a temporary decline in some comprehensive evaluation indices. Such stage-specific differences in overall performance provide an important basis for formulating refined cultivation and management measures.

The results of this study provide a theoretical basis and practical guidance for precise bud selection and plant architecture optimization of rubber tree budded seedlings. With their "robust" growth pattern, scale bud shoots exhibited excellent vegetative growth indices and stronger index coordination at all leaf whorl stages, making them suitable for cultivating high-quality, robust and uniform budded seedlings. In contrast, petiole bud shoots, with their "fast-germinating" growth pattern, had a larger branching angle in the early stage and a prominent correlation between branching angle and leaf or stem indices, making them more suitable for optimizing rubber tree plant architecture to improve field ventilation and light transmission efficiency.

Therefore, in production practice, axillary bud types should be selectively chosen according to specific cultivation objectives. Scale buds are preferred for overall robustness and uniformity of seedlings, while petiole buds can be considered if the focus is on optimizing plant architecture by adjusting branching angle. Meanwhile, combined with the growth characteristics of different axillary bud types, implementing differentiated cultivation and management measures — such as strengthening nutrient management during the growth trough of scale buds, or regulating the branching angle of petiole buds via pruning and branch pulling — will significantly improve the breeding efficiency and seedling quality of rubber tree budded seedlings, thereby providing strong technical support for quality improvement and efficiency enhancement of the natural rubber industry.

CONCLUSION

Through an in-depth investigation of axillary bud types (scale buds and petiole buds) in *Hevea brasiliensis* 'Reken 628', this study systematically clarified their key roles in regulating the branching angle and growth quality of newly sprouted shoots, and revealed significant differences in phenological progression, morphological and physiological indices, and overall performance between the two bud types. These findings not only fill the research gap in this field but also provide a solid theoretical basis for high-quality breeding and plant architecture optimization of rubber tree budded seedlings.

Specifically, scale buds exhibited a robust growth pattern, characterized by a longer leaf whorl phenological period. At multiple growth stages, their vegetative growth indices including plant height, stem diameter, leaf length, and leaf width were significantly superior to those of petiole-bud shoots, and their growth indices showed stronger synergy. Scale buds had higher nitrogen use efficiency and more effective biomass accumulation, making them an ideal choice for cultivating robust and uniform high-quality seedlings.

In contrast, petiole buds displayed a fast-germinating growth pattern, with a relatively shorter phenological period, rapid early germination, and a significantly larger branching angle at the first leaf whorl stage. Although slightly inferior in early vegetative growth, the TOPSIS comprehensive evaluation showed that the overall performance of petiole-bud shoots gradually optimized with growth, especially reaching the optimum at the third leaf whorl stage. This indicated their late steady growth characteristic, endowing them with unique potential in optimizing plant architecture and improving field ventilation and light transmission efficiency.

The results of this study have important practical guiding significance for the natural rubber industry. In production, a precise bud selection strategy can be implemented according to specific seedling breeding objectives: scale buds should be prioritized for cultivating robust and uniform high-quality seedlings, while petiole buds are preferred for optimizing plant architecture and effectively regulating branching angle to improve field ventilation and light transmission. Meanwhile, combined with the growth characteristics of different axillary bud types, formulating and implementing differentiated cultivation management measures — such as strengthening nutrient management during the growth trough of scale buds, or regulating the branching angle of petiole buds via pruning and branch pulling — can significantly improve the breeding efficiency and seedling quality of rubber tree budded seedlings, thus strongly promoting the quality improvement, efficiency enhancement, and sustainable development of the natural rubber industry.

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