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Exploring the Relationship Between Growth Strain and Growth Traits in *Eucalyptus cloeziana* at Different Age Stages

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Abstract: The harvesting period is determined by forest maturity. However, there are few studies on the continuity of assessing cultivation duration based on both growth and wood quality, especially for *Eucalyptus* plantations. This study measures growth traits, such as the diameter at breast height (DBH), oblateness, and other characteristics, as well as wood properties like density and crystallinity, and axial surface growth strain levels at four age stages (6, 10, 22, and 34 years) of *Eucalyptus cloeziana (E. cloeziana)*. By analyzing these factors, particularly the changes in growth strain throughout the tree's development, the study aims to determine the optimal cultivation period for using *E. cloeziana* as solid wood. The survey revealed a two-stage pattern in the annual change rate of DBH, tree height, and oblateness: a decrease from 6 to 22 years followed by an increase from 22 to 34 years. In *E. cloeziana*, heartwood percentage and density rapidly declined during the first 6–10 years, then stabilized between 10 and 34 years. This suggested differential rates of growth and maturation. By analyzing the growth strain, it was observed that the growth strain of *E. cloeziana* exhibited an initial increase followed by a subsequent decrease with age. It reached its peak at 22 years and then gradually declined. Remarkably, at 34 years, the growth strain was even lower than that of 10-year-old *E. cloeziana*, measuring only 2148 $\mu\varepsilon$. This reduction in growth strain is advantageous for minimizing defects such as brittle core formation, cracking, and warping during harvesting. In practical cultivation aimed at solid wood utilization, harvesting can be conducted between 22 and 34 years based on management strategies to reduce operating costs. However, with close-to-nature management practices and sufficient financial resources, extending the cultivation period to 34 years or beyond may result in superior wood quality. We aim to achieve the sustainable utilization of resources, foster the long-term development of the wood processing and solid wood utilization industries, and guide the entire sector towards the goal of sustainable development.

Keywords: cracking; solid wood; utilization; wood properties; crystallinity; FTIR; sustainable use

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1. Introduction

As global demand for wood grows alongside the need for sustainable development, the pursuit of high-quality wood resources has become a key focus in the modern timber industry. China is the world's largest consumer of timber [1], and the significance of

Eucalyptus spp. as a crucial fast-growing tree species in southern China can not be overstated in terms of timber internal demand. Among them, *Eucalyptus cloeziana* (*E. cloeziana*) exhibits a clear-cut texture and delicate texture, resembling redwood in appearance, thus earning the moniker "Australian delbergia odorifera" [2]. Due to its solid wood composition, uniform structure, stable and corrosion-resistant ecological characteristics, and wide distribution range, it has emerged as a significant candidate species for sustainable timber utilization. As a result, it not only helps replenish natural forests but also plays a key role in advancing the construction of ecological civilization. Simultaneously, it addresses the supply–demand imbalance in the timber market. Since 1972, *E. cloeziana* has been introduced to China and significant exploratory efforts have been undertaken in Guangxi province to conduct provenance tests for this species, as well as studies on its wood properties and processing characteristics [3]. Guidan [4] conducted a comparative analysis of fiber characteristics among six *Eucalyptus* species, including *Eucalyptus grandis* (*E. grandis*) and *Eucalyptus urophylla* (*E. urophylla*). Their findings revealed that *E. cloeziana* exhibited significantly greater fiber length, width, and double wall thickness compared to the other five species. Furthermore, extensive scholarly research has been conducted on the wood properties, mechanical processing attributes, and drying characteristics of *E. cloeziana*. The findings revealed that the average heartwood proportion of 17-year-old *E. cloeziana* was determined to be 37.42%, with an average raw wood density measuring at 1.11 g/cm^3 [5]. Moreover, it was observed that *E. cloeziana* demonstrated exceptional performance in sand cutting and milling processes at ages of 17, 29, and 35 years [5,6]. In promoting the utilization of *E. cloeziana* solid wood, investigations into its physical and mechanical properties show that it has a high comprehensive mechanical strength, indicating its potential for use in furniture manufacturing, building materials, and other fields [7,8]. The quality of wood used for solid wood processing tends to improve with longer growth periods, owing to the enhanced perfection of the fiber structure, the increased wood density, and the reduced water content over extended durations. Consequently, these factors contribute to the heightened hardness and stability of the wood, making it more suitable for solid wood processing and utilization. The optimal age stage for solid wood utilization in *E. cloeziana* currently lacks sufficient research. The presence of defects, such as a brittle core and cracking, which are attributed to growth stress, significantly hinders both the quality and yield of the wood.

During the growth process of trees, the interaction force between cells occurring within the cambium during cell differentiation and maturation is commonly referred to as growth stress [9]. Growth stress is the result of the normal development of wood tissue cells. Under the accumulation of intercellular forces year by year, the stress shows a holistic distribution in trees, but it has different rules due to differences in tree species, tree age, trunk parts, and growth status [10]. The formation mechanism of growth stress is primarily elucidated by three hypotheses: the "Lignin swelling hypothesis", the "Cellulose tension hypothesis", and the "Unified hypothesis" [11–13]. These hypotheses investigate growth stress formation from distinct perspectives and have been progressively refined through ongoing experimental verification and theoretical research. When wood is cut, processed, and dried from tree species with higher growth stress, it disrupts the internal stress balance of the wood, leading to a redistribution of residual stress that can result in issues such as brittleness, cracking, bending, and other related problems [14]. Consequently, this can lead to significant losses in both wood processing and utilization [15]. Therefore, numerous scholars both domestically and internationally have conducted extensive research on the influencing factors, formation mechanisms, and regulatory approaches pertaining to growth stress [16]. Among them, *Eucalyptus* is renowned for its elevated growth stress level, and substantial variations in growth stress exist among different *Eucalyptus* species [17]. For instance, Malan [18] investigated the correlation between the growth rate and crown width of

E. grandis and its associated growth stress, concluding that these factors accounted for only a minor portion of the variation in growth stress. Trugilho [19] observed a linear increase in axial growth stress with age by measuring the growth stress of *Eucalyptus dunnii* (*E. dunnii*) at 8, 13, 15, and 19 years old. Biechele [20] reported a significant increase in growth stress from ages 3 to 10 years followed by a decrease from ages 10 to 14 years. Furthermore, they noted that different growth parameters influenced the development stage–dependent variations in growth stress. Since growth strain results from the deformation caused by growth stress, the average growth strain can be used to compare and assess the growth stress of standing trees and logs [21]. However, a limited amount of research has been conducted on the growth strain variation in the growth process of *E. cloeziana*.

As operating costs rise, the development of the solid wood industry is increasingly constrained, particularly for wood species with long cultivation periods. Current research on *E. cloeziana* predominantly focuses on a single age stage, with a notable absence of systematic and continuous studies on its growth and timber properties. Consequently, existing studies offer limited guidance for the effective forest management and timber utilization of *E. cloeziana.* To address this research gap, this study proposes investigating the growth and wood properties of *E. cloeziana* at different ages using a space-for-time approach. Growth traits (diameter at breast height (DBH), tree height, and oblateness) and wood properties (density, heartwood percentage, fiber morphology, crystallinity, and lignin content) were analyzed for four representative age stages (6, 10, 22, and 34 years) in a seedling trial plantation at Dongmen Forestry Farm in Guangxi. Furthermore, the relationship between these traits and axial surface growth strain was examined. The goal is to elucidate the growth patterns of *E. cloeziana* and their implications for solid wood utilization. This will provide theoretical support for its efficient cultivation and wood processing, while also contributing to the sustainable development of the solid wood processing industry.

2. Materials and Methods

The experimental site is situated within the state-owned Dongmen Forest Farm in the Guangxi Zhuang Autonomous Region, which falls within the subtropical humid monsoon climate zone. The average annual temperature ranges from 18 °C to 22 °C, with an average annual rainfall of 1200 mm. The site is situated at an elevation of 100–130 m, with the predominant soil type being red soil and a pH ranging from 4.5 to 5.6. No noticeable diseases or pest infestations have been observed on the *Eucalyptus* leaves within the forest stand. Three 20 × 20 m quadrats were established in a large-flower *Eucalyptus* forest stand at four different age stages (6, 10, 22, and 34 years). Within each quadrat, the longest and shortest diameters at breast height were measured, and the oblateness was subsequently calculated. Growth traits, including DBH, tree height, slenderness and oblateness, were recorded and analyzed for each quadrat. The basic information of the quadrats is shown in Table 1. Three average trees were selected from each quadrat, with a total of nine trees per age stage, making thirty-six trees in total. Growth strain was assessed using the strain gauge method [22]. Additionally, wood cores were extracted from the 36 trees that had growth strain measurements; three cores were taken from each tree. These wood samples were used to determine heartwood percentage, density, fiber morphology, crystallinity, and lignin content. The reagents used in this study were ethanol (analytically pure AR, Chengdu Kelon Chemical Co., Ltd. Chengdu, China), potassium bromide (spectrally pure SP, Shanghai Guoyao Reagent Group, Shanghai, China), hydrogen peroxide (analytically pure AR, Shanghai Titan Technology Co., Ltd. Shanghai, China), and glacial acetic acid (analytically pure AR, Tianjin Komio Chemical Reagent Co., Ltd. Tianjin, China). The instruments used in the experiment are listed in Table 2.

Table 1. Basic information for quadrats.

Age, y	DBH, cm	Tree Height, m	Oblateness	Slenderness
6	18.89 ± 2.38	18.23 ± 0.88	0.03 ± 0.01	0.98 ± 0.13
10	28.83 ± 0.76	23.26 ± 1.64	0.03 ± 0.01	0.78 ± 0.05
22	29.39 ± 2.88	25.50 ± 2.46	0.02 ± 0.01	0.81 ± 0.03
34	40.19 ± 1.57	36.54 ± 2.57	0.02 ± 0.00	0.89 ± 0.05

Table 2. Instruments and equipment.

Device	Model	Manufacturers	Country
Strain meter	YJW-8	Beijing Tairui Venus Instrument Co., Ltd.	Beijing, China
Strain gage	BE120-10AA-P150	AVIC Electric Measuring Instrument Co., Ltd. manufactured	Shanxi, China
Brulai altimeter	DGQ-1	Harbin Optical Instrument Co., Ltd.	Harbin, China
Electronic balance	YH-A3003	Yingheng Electric Co., Ltd.	Ruian, China
Vernier caliper	SF2000	Guilin Guanglu Digital Measurement and Control Co., Ltd.	Guilin, China
Oven	ED260	Binder GmbH	Tutlingen, Germany
X-ray diffractometer	A24A10	BRUKER AXS GMBH	Karlsruhe, Germany
Fourier transform infrared spectrometer	IRTracer-100	Shimadzu Corporation	Shima, Japan

The calculation formula for the trunk oblateness is as follows:

$$\text{Oblateness} = (D_{max} - D_{min})/D_{max} \tag{1}$$

D_{max} is the maximum diameter of the trunk at breast height in the horizontal cross-section.

D_{min} is the minimum diameter of the trunk at breast height in the horizontal cross-section.

The calculation formula for the slenderness is as follows:

$$\text{Slenderness} = \text{Tree Height}/\text{DBH} \tag{2}$$

2.1. Growth Strain Measurement

At a distance of 1.3 m above the ground surface on the selected average wood trunk, the four cardinal directions (east, south, west, north) were determined using a compass (Figure 1a). Using a knife, the bark, phloem, and cambium from each of these directions were removed, exposing the fresh and smooth xylem, approximately 5 cm × 5 cm in size (Figure 1b). First, wood debris was sanded away from the surface using sandpaper, and impurities were wiped off with a tissue dampened in alcohol. Once the surface of the wood was dry, the strain gauges were affixed with attached wires onto the surface of the wood to be tested using quick-drying adhesive. The strain gauges were gently pressed along the axial direction with the thumb for approximately 30 s until they were firmly attached and did not slide off (Figure 1c). Then, the wires of the strain gauges were connected to the strain gauge meter and zeroed. Next, a saw blade was used to create a 5 mm × 5 mm groove 5 mm deep at a distance of 5 mm above and below the strain gauge (Figure 1d). The change in strain on the strain gauge meter was recorded until the recorded strain value stabilized. The stable strain value recorded at this point was the axial growth strain value on the surface of the wood at that location. Growth strain is the deformation caused by the effect of growth stress. In general, the strength of wood growth stress is calculated using the mathematical formula GL ≈ -EL·εL, where EL represents the axial elastic modulus of the wood, εL is the axial growth stress, and GL is the axial growth stress. This formula indicates a linear relationship between strain and stress. Instead of exploring the axial elastic modulus of the wood in detail, this study directly utilizes the growth stress values to compare the strength of the growth stress. Specifically, growth stress in the samples is measured using strain gauges, with the strain quantified in microstrains (με) [23].

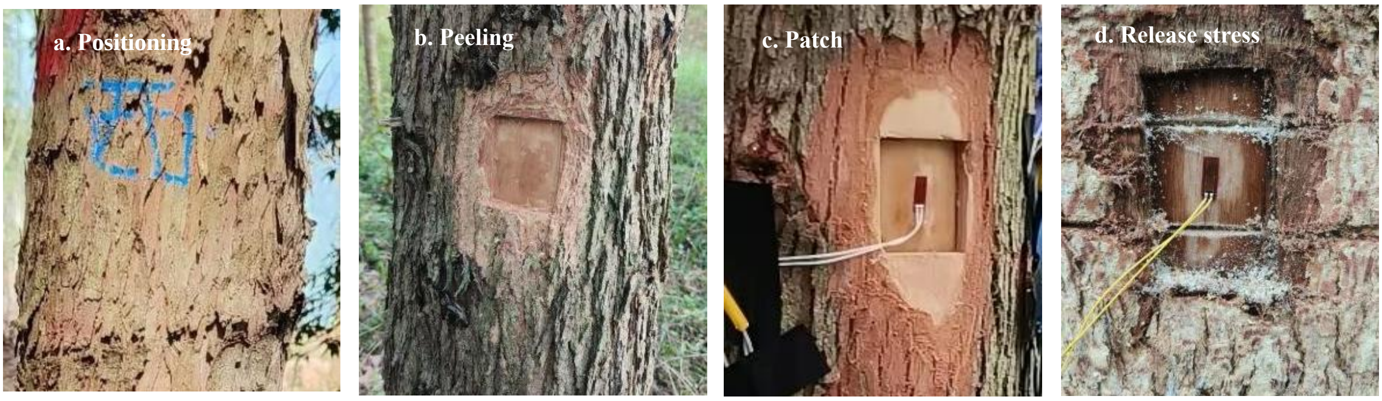

Figure 1. Growth strain measurement of *Eucalyptus cloeziana* (*E. cloeziana*).

2.2. Measurement of Density and Heartwood Percentage

Wood cores were drilled from the trees in order to measure the growth strain. Three cores were drilled from each tree, and the raw wood mass was obtained by weighing immediately. For trees that had their growth strain measured, wood cores were extracted (9 trees per stand age), with 3 cores taken from each tree, and the average value was calculated after measurement. The extracted wood cores were soaked in water until fully submerged to ensure saturation, then their volume was measured using the displacement method. Subsequently, they were placed in an oven at 103 °C for 6–8 h to dry. During the drying process, 3–4 samples were weighed every two hours, and the drying was considered complete when the mass of the last two weightings did not exceed 0.5% of the mass of the wood core, indicating the attainment of a bone-dry condition. At that time, the wood core was weighed to obtain the absolute dry mass. Each sample was measured 5 times.

$$\text{Green density} = \text{raw wood mass}/\text{green volume} \tag{3}$$

$$\text{Basic density} = \text{absolute dry mass}/\text{impregnation volume} \tag{4}$$

$$\text{heartwood percentage} = \text{heartwood length}/\text{total wood core length} \tag{5}$$

2.3. Determination of Fiber Cell Morphology

The outermost xylem at both ends of the wood core was sampled; one portion was utilized for fiber morphology analysis, while the other was employed to evaluate crystallinity and lignin content. The wood core was immersed in a 1:1 mixture of hydrogen peroxide and glacial acetic acid, followed by heating in a water bath at 96 °C for 5 h to facilitate separation. After film preparation, fiber cell morphology was observed using an optical microscope equipped with a 10 × 4 objective lens, and fiber length was measured. Subsequently, fiber width and cavity diameter were measured using a 10 × 40 objective lens. Three standard trees were selected from each age group, and three wood cores were extracted from each tree. Subsequently, 50 fiber cells were measured per sample with a precision of 0.01 μm after thorough mixing.

2.4. Determination of Crystallinity

The test materials were measured according to the standard [24]. The outermost xylem of the wood core, corresponding to the measured growth strain, was extracted. After drying, the material was ground into a fine powder. For the wide-angle X-ray diffraction analysis, 60 mesh powder samples were used. A small amount of the wood powder was placed in the sample holder, compacted, and then loaded into the instrument for measurement. The parameters were set as a scanning speed of 6°/min and a scanning range of 5° to 55°. The crystallinity of the surface xylem of *E. cloeziana* at four age stages was determined using the Segal empirical method [25]. The calculation formula is as follows:

$$C_r = \frac{I_u - I_a}{I_u} \times 100\% \tag{6}$$

Among them were the maximum integral strength at $I_u - 2\theta = 22°$ and the minimum integral strength at $I_a - 2\theta = 18°$.

2.5. Determination of Relative Content of Lignin by Fourier Transform Infrared Spectroscopy

The outermost xylem of the wood core was dried and ground through a 60-mesh sieve. A small quantity of the powdered *Eucalyptus* was then mixed with potassium bromide in a 1:100 ratio and dried. The test sample was prepared using the potassium bromide pellet method, and the spectrum was collected using a Fourier transform infrared spectrometer. The scan parameters were as follows: 64 scans, a resolution of 4 cm^{-1}, and a scanning range of 4000 to 400 cm^{-1} [26].

2.6. Data Processing

Excel 2016 was used to calculate the measurement data and make tables. Drawing was conducted with origin 2021. Correlation analysis (Pearson) and one-way analysis of variance (ANOVA) were performed on the data using SPSS 26.0. Prior to ANOVA, the normality and homogeneity of variance tests were conducted. If significant differences were found in the ANOVA, post hoc comparisons were performed to identify group differences. Otherwise, nonparametric tests (Kruskal–Wallis) were used, followed by pairwise post hoc comparisons for significant differences. X-ray diffraction patterns were treated with MDI Jade9.

3. Results

3.1. Analysis of Growth Traits of E. cloeziana in Four Age Groups

The growth characteristics of wood play a pivotal role in assessing wood quality and performance, serving as a fundamental basis for the rational utilization of wood [22,27]. Therefore, this study aims to investigate the growth traits of *E. cloeziana* at four distinct developmental stages in order to obtain a comprehensive understanding of its growth patterns. This study examined the trends of tree height, DBH, and oblateness across four age stages (6a, 10a, 22a, 34a), conducting variance analysis accordingly. The findings were illustrated in Figure 2a–c. The DBH and tree height of 34-year-old *E. cloeziana* notably surpassed those of the 6a, 10a, and 22a specimens, reaching an extremely significant level ($p < 0.01$), while exhibiting a low degree of dispersion. Measurements were taken of the long and short radii of the tree, and the trunk's oblateness was calculated. A smaller oblateness indicated a more cylindrical trunk shape, resulting in higher lumber yield. Observing the change in oblateness with forest age (Figure 2c), it was apparent that the trunk's oblateness decreases as the tree ages. The oblateness of 34-year-old *E. cloeziana* remained consistently low, significantly lower than that of the 10-year-old specimens ($p < 0.05$). This suggests that *E. cloeziana* promoted trunk rounding during the cultivation of large-diameter timber, resulting in higher yields for 34-year-old *E. cloeziana*.

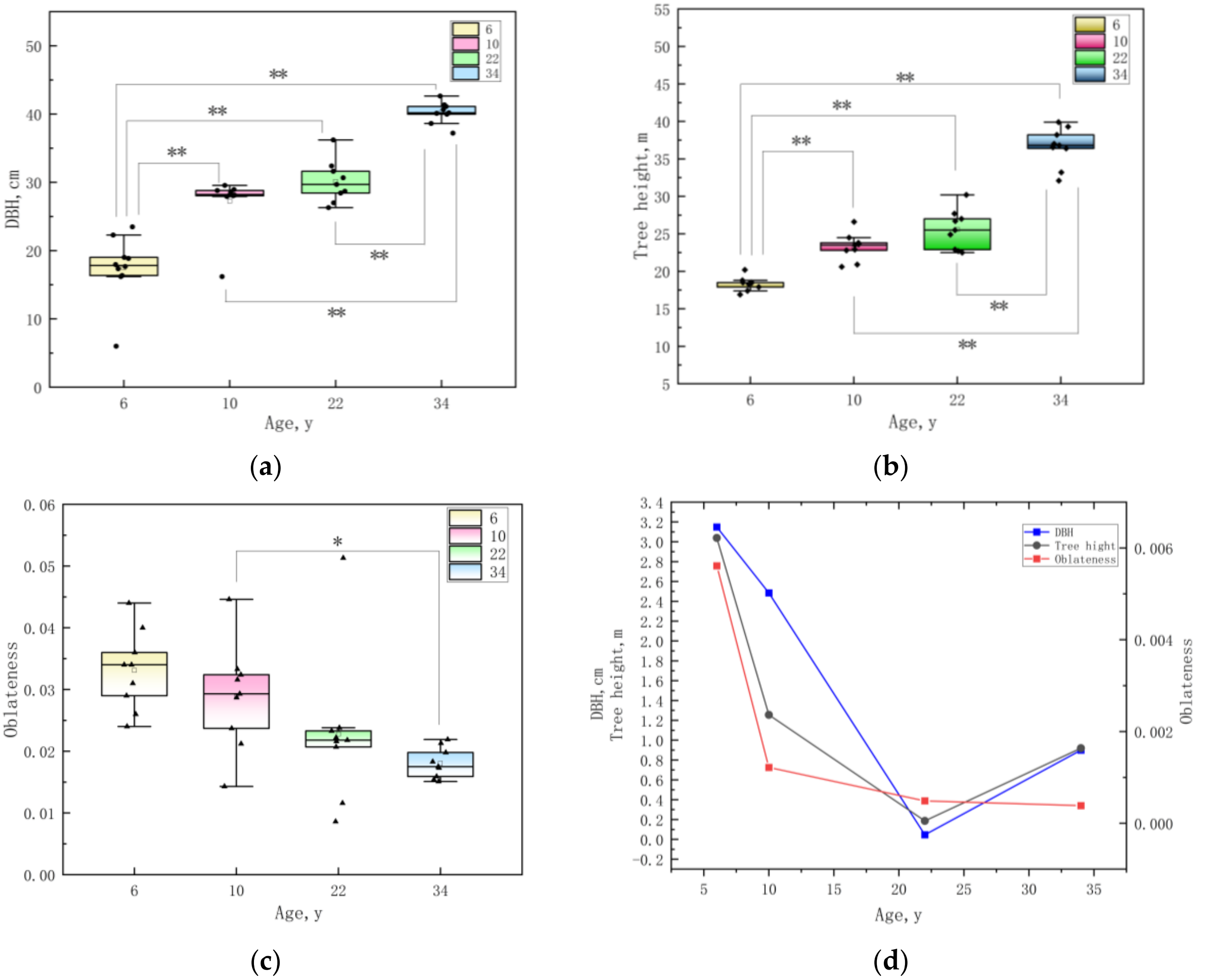

Figure 2. (**a**–**c**) show the changes in diameter at breast height (DBH, tree height, and oblateness at different age stages. (**d**) is the annual rate of change in DBH, tree height, and oblateness in four ages; '*' indicates that DBH, tree height, and oblateness were significantly different at different age stages ($p < 0.05$); '**' indicates that DBH, tree height, and oblateness showed extremely significant differences at different ages ($p < 0.01$).

The annual rates of change in DBH, tree height, and oblateness were analyzed (Figure 2d). It was observed that the changes in growth traits could be divided into two stages. During the first stage, spanning from 6 to 22 years, there was a downward trend in the annual rates of change. Notably, the slope between 6 and 10 years exhibited the steepest decline, indicating a rapid decrease in growth rate during this period which rendered it unsuitable for harvesting. The second stage spans from 22 to 34 years, during which the annual rate of change in both DBH and tree height exhibited a rebound, indicating that *E. cloeziana* maintained significant physiological activity even at 34 years. In terms of solid wood utilization objectives, logging after 22 years can yield a substantial output considering operational costs.

3.2. The Changes In Density and Heartwood Percentage of E. cloeziana at Four Age Stages

As a species highly valued for its application in solid wood, the wood density of *E. cloeziana* plays a crucial role in assessing both the quality of the wood and its suitability for processing. Furthermore, an increased heartwood percentage corresponds to greater value. Throughout the tree's growth, there exists a close relationship between growth strain and wood density, as well as heartwood percentage, influencing one another. Therefore, this study aimed to investigate the variations in wood properties of *E. cloeziana* by green density, basic density, and heartwood percentage across four different growth stages. This comprehensive analysis proved instrumental in elucidating the growth patterns associated with growth strain. The results of the determination were presented in Figure 3a–c. Regarding the variation in heartwood rate with forest age (Figure 3a), a consistent annual increase in heartwood rate was observed, and at 34 years, *E. cloeziana* exhibited an average heartwood rate of approximately 87%. In the analysis of wood density and basic density across different age stages (Figure 3b,c), there is an upward trend in density with increasing forest age. Specifically, the basic density of 34-year-old *E. cloeziana* is notably higher than that of 6-year-old ones, while the density variations between adjacent age stages did not reach significant levels.

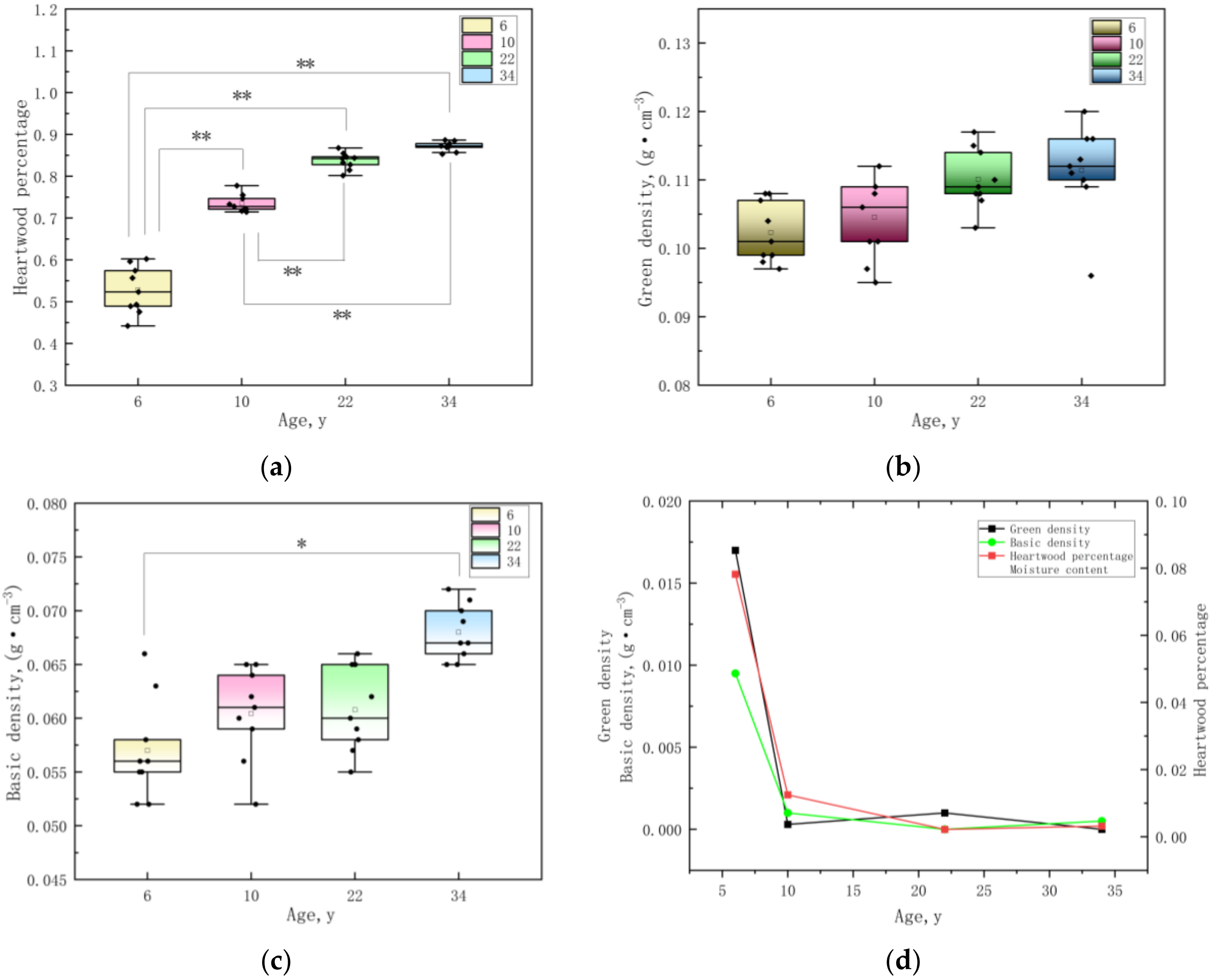

Figure 3. (**a**–**c**) show the changes in heartwood percentage, greenwood density, and basic density of *E. cloeziana* at different ages. (**d**) is the annual rate of change in heartwood percentage and density in four age stages; '*' indicated that DBH, tree height, and oblateness were significantly different at different age stages ($p < 0.05$); '**' indicated that DBH, tree height, and oblateness showed extremely significant differences at different ages ($p < 0.01$).

By analyzing the annual rate of heartwood rate and density (Figure 3d), it was observed that their changes can be primarily divided into two stages. The initial stage encompassed a rapid decline in heartwood rate and density from 6 to 10 years, indicating a slower growth state after 6 years. This age range also corresponded to the principal harvesting period for *Eucalyptus* as a timber forest. In the second stage, from 10 to 34 years, the annual change rate remained relatively stable, suggesting an almost equal annual rate for both heartwood and density during this period. These findings slightly differ from those observed in growth traits (Figure 2d). While the annual change rate of heartwood rate and density remained nearly constant at 10–22 years, the annual rates of change in DBH and tree height continued to decline. During the 22–34 year period, there was an increase in the annual rate of change in DBH and tree height, while the heartwood rate and density exhibited stable variations. These findings suggested that the growth of heartwood and density was not synchronized with the growth of DBH and tree height.

3.3. Growth Strain Analysis of E. cloeziana in Four Age Stages

Due to the growth strain generated during secondary growth in trees, the accumulated growth strain varies across different age stages of the species. Therefore, measuring and analyzing the growth strain at different age stages allows for judging the potential occurrence of cracking and a brittle core during the harvesting of *E. cloeziana* based on the magnitude of growth strain, ultimately leading to increased yield. The data presented in Figure 4a demonstrated a distinct pattern of increasing and then decreasing total growth strain across the four age stages measured. Notably, the maximum growth strain was observed at 22 years old, reaching 3400 με. Notably, the maximum growth strain value of 3400 με was observed at 22 years, followed by a subsequent decline. At 34 years, the growth strain was lower than that of 10-year-old *E. cloeziana*, which was 2148 με. At this time, the defects caused by harvesting were relatively small. In the four directions of the measurement, except for the 6-year-old *E. cloeziana*, the growth strain of the other ages was the largest in the north, which may be related to the slope direction of the stand. When the tree bends to the sun, the back curved surface forms a tension wood to increase its growth strain. Nonparametric tests were conducted on the growth strain of trees at four different ages (Table 3). The results revealed significant differences in the changes in the west, north, and total growth strains across ages ($p < 0.05$). A further comparison of total growth strain (Table 4) showed significant differences between the 22-year-old *E. cloeziana* and those at 6 and 34 years of age ($p < 0.05$). Therefore, it is recommended to avoid harvesting trees at 22 years of age to minimize defects such as cracking and warping.

Table 3. Nonparametric test of growth strain of *E. cloeziana*.

Sample Group	Sample Size	Test Method	Test Statistic	*p*
East	36	Kruskal–Wallis	3.487	0.322
South	36	Kruskal–Wallis	5.460	0.141
West	36	Kruskal–Wallis	10.370	0.016
North	36	Kruskal–Wallis	11.587	0.009
Total	36	Kruskal–Wallis	16.913	0.001

$p < 0.05$ indicates statistical significance.

In order to further investigate the distribution of growth strain across four age stages, we conducted a frequency analysis on the total growth strain (Figure 4b). The total growth strain values were categorized into four gradients, revealing that strains at 6 and 34 years predominantly fell within the first gradient. However, the 22-year-old *E. cloeziana* accounted for 50% in the third and fourth gradients, respectively, and the overall size was large. In practical cultivation and production, it was advisable to refrain from utilizing solid wood during the period of peak growth strain in *E. cloeziana* at 22 years. Following the actual management plan, a cutting strategy between 22 and 34 years can be chosen to achieve a higher yield of superior quality timber while appropriately reducing operational costs.

Table 4. Post hoc comparison of growth strain nonparametric tests.

Sample Group	Multiple Comparisons, Age	Test Statistic	Standard Error	Standard Test Statistic	Significance	Adjusted Significance
Total	6–34	−3.500	4.082	−0.857	0.391	1.000
	6–10	−10.660	4.082	−2.613	0.009	0.054
	6–22	−15.160	4.082	−3.715	0.000	0.001
	34–10	7.167	4.082	1.755	0.079	0.475
	34–22	11.667	4.082	2.858	0.004	0.026
	10–22	−4.500	4.082	−1.102	0.270	1.000

$p < 0.05$ indicates statistical significance.

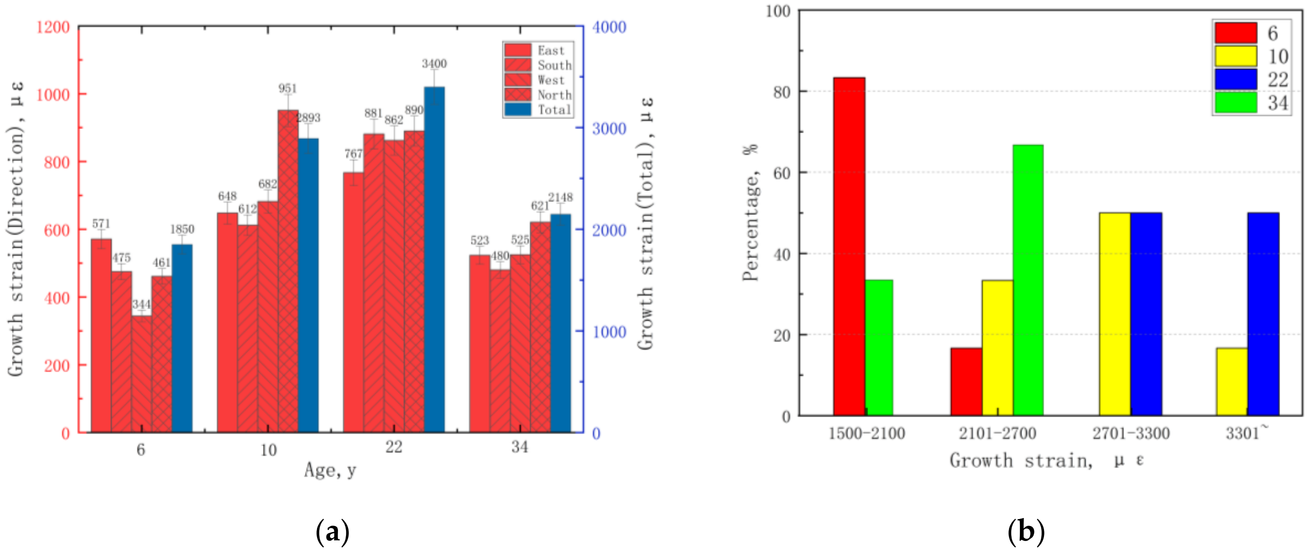

Figure 4. (**a**) Growth strain analysis of *E. cloeziana* at different ages. (**b**) Distribution frequency diagram of total growth strain.

Effects of Growth Traits and Physical Properties on Growth Strain

Through the examination of the relationship between growth characteristics, physical properties, and growth strain, the determinants of growth strain were identified. The results presented in Figure 5 demonstrate an extremely significant positive correlation (sig. < 0.01) between heartwood percentage and growth strain, indicating that an increase in heartwood percentage was associated with greater growth strain. This could be attributed to the accumulation of wood and the expansion of cells as the heartwood rate of *E. cloeziana* increased, leading to an elevation in growth strain levels [28,29]. Consequently, the heartwood ratio can serve as a valuable reference index for predicting and regulating axial surface growth strain. The height–diameter ratio exhibited a significant negative correlation with growth strain and heartwood rate, while the heartwood rate showed a significant positive correlation with DBH and growth strain. This phenomenon may be attributed to the uneven growth rates of heartwood, DBH, and tree height, highlighting the pivotal role played by heartwood size in determining growth strain.

In the relationships between other factors, there was an extremely significant correlation ($p < 0.01$) observed between DBH, tree height, basic density, wood density, and heartwood rate. Furthermore, tree height exhibited an extremely significant negative correlation with oblateness and partial crown ($p < 0.01$), indicating that taller trees tend to have more uniform trunk and crown adjustments.

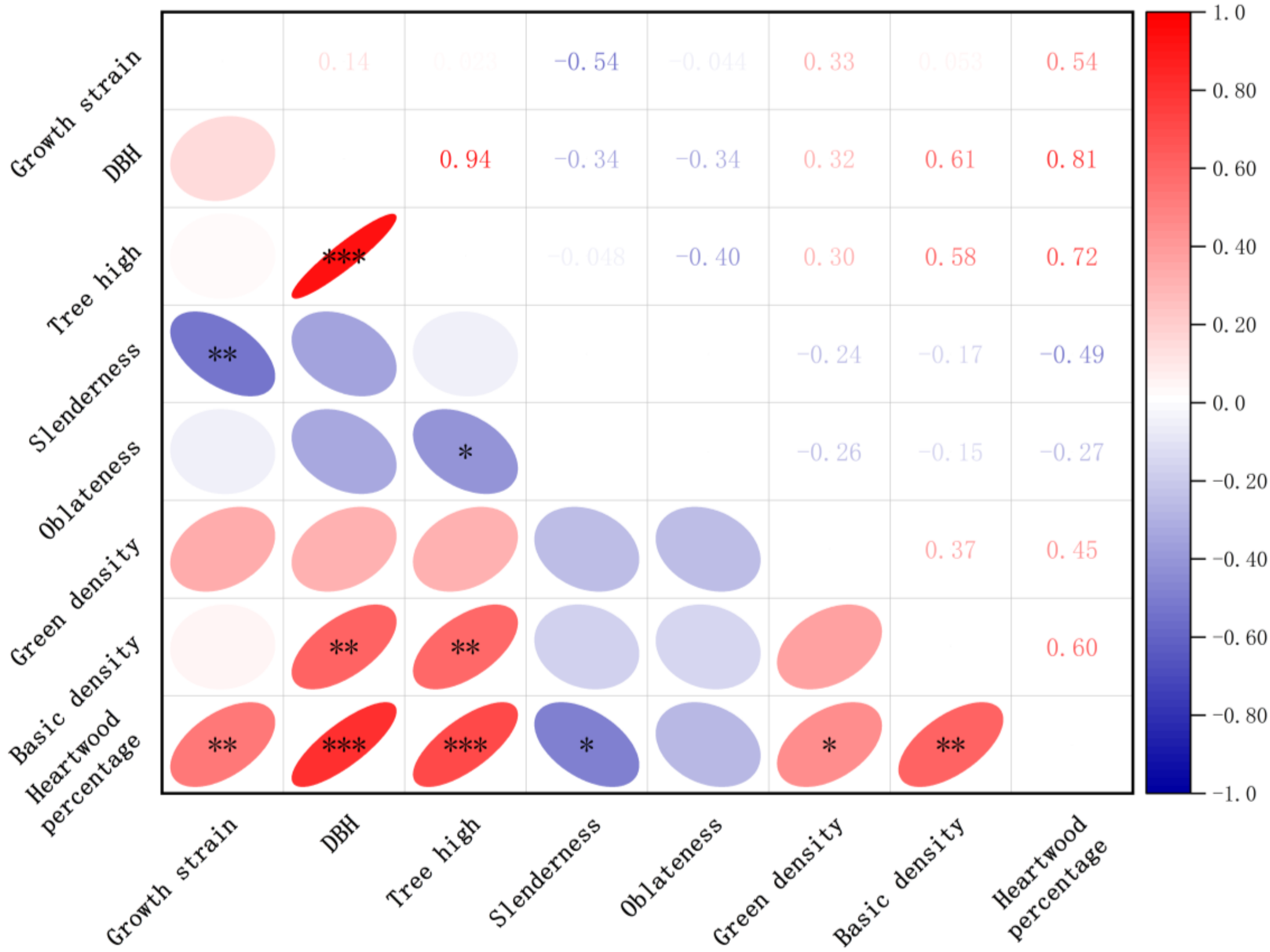

Figure 5. Correlation between growth traits, physical properties, and growth strain of *E. cloeziana*; '*' indicates that there is a significant correlation between different indicators and growth strain ($p < 0.05$); '**' indicates that there was an extremely significant correlation between difference indexes and growth strain ($p < 0.01$). '***' indicates that there was an extremely significant correlation between difference indexes and growth strain ($p < 0.001$).

3.4. Correlation Analysis of Fiber Morphology and Growth Strain

The measurements of fiber length, lumen diameter, double wall thickness, and the wall–cavity ratio of surface wood fiber cells at the DBH of *E. cloeziana* across four age stages were presented in Table 5. The findings suggested that fiber length, double wall thickness, and the wall–cavity ratio exhibit an increasing trend with age. Significant differences in fiber length were observed between the ages of 6 and 10 years, 22 and 34 years, as well as 10 and 34 years. Furthermore, there were significant disparities in double wall thickness and the wall–cavity ratio between the ages of 6 and 22 years, 6 and 34 years, along with 22 and 34 years. The correlation between the anatomical structure of fiber cells, age, and growth strain was analyzed, and the results were presented in Table 6. Fiber length, cavity diameter, double wall thickness, and wall–cavity ratio exhibited extremely significant correlations with age ($p < 0.01$). However, no significant correlation was observed with growth strain, suggesting that there was no direct association between wood fiber characteristics and surface axial growth strain measurements. Furthermore, variations in circumferential directions of growth strain did not directly impact wood fiber morphology.

Table 5. Anatomical structure parameters of wood fiber cells of *E. cloeziana*.

Age, y	Fiber Length, μm	Cavity Diameter Value, μm	Double Wall Thickness, μm	Wall and Cavity Ratio, %
6	1172.883 ± 94.085 a (0.080)	9.506 ± 1.360 a (0.143)	12.193 ± 0.489 a (0.040)	1.693 ± 0.250 a (0.147)
10	1235.567 ± 21.488 b (0.017)	8.985 ± 1.324 ab (0.147)	14.433 ± 0.718 ab (0.050)	1.886 ± 0.415 ab (0.220)
22	1343.782 ± 63.516 bc (0.047)	6.418 ± 0.712 b (0.111)	15.467 ± 0.670 b (0.043)	2.785 ± 0.376 b (0.135)
34	1517.681 ± 55.495 c (0.037)	6.478 ± 0.932 b (0.144)	16.967 ± 0.586 c (0.035)	2.937 ± 0.437 c (0.149)

Based on the ANOVA analysis, the letters a, b, and c indicated significant differences between different age groups ($p < 0.05$). The coefficient of variation is in parentheses.

Table 6. Correlation analysis of anatomical structure of wood fiber cells in *E. cloeziana*.

Age, y	Growth Strain, με	Fiber Length Correlation Coefficient		Cavity Diameter Value Correlation Coefficient		Double Wall Thickness Correlation Coefficient		Correlation Coefficient of Wall–Cavity Ratio	
		Age	Growth Strain	Age	Growth strain	Age	Growth Strain	Age	Growth Strain
6 10 22 34	1850.17 2574.17 3080.50 2148.17	0.893 **	0.121	−0.719 **	−0.402	0.885 **	0.374	0.785 **	0.352

'**' indicated that there was an extremely significant correlation between different indexes and growth strain ($p < 0.01$).

3.5. Correlation Analysis Between Crystallinity and Growth Strain

The surface xylem samples were analyzed to quantify the cellulose crystallinity in relation to the axial growth strain of the surface. Figure 6 illustrated the X-ray diffraction patterns of *E. cloeziana* at four distinct developmental stages. The observed trends in the overall pattern remained consistent across all ages, exhibiting prominent diffraction peaks corresponding to the (101) crystal plane at 2θ = 16°, the (002) crystal plane at 22°, and a near-35° peak for the (040) crystal plane. The peak intensity and half-height of *E. cloeziana* exhibited slight variations across the four age stages. Variance and correlation analyses were conducted on crystallinity and growth strain, as presented in Table 7. Both crystallinity and growth strain demonstrated a similar pattern: they initially increased, reaching their maximum crystallinity of 39.42% at 22 years, followed by a subsequent decrease. The surface xylem's crystallinity reached its lowest point at 34 years, measuring 34.85%. The crystallinity at 22 and 6 years exhibited significant differences ($p < 0.05$), while the crystallinity at 34 years showed a highly significant difference ($p < 0.01$). Correlation analysis revealed a positive association between growth strain and cellulose crystallinity, with the correlation being statistically significant (sig. < 0.05). These findings suggest that an increase in cellulose crystallinity is linked to elevated growth strain.

3.6. Lignin Content and Correlation Analysis with Growth Strain

The Fourier infrared spectra of *E. cloeziana* at four age stages were presented in Figure 7, following smoothing and baseline correction. The overall spectral pattern remained consistent across the different age stages, exhibiting similar absorption peak positions and shapes. The infrared characteristic peaks of *E. cloeziana* wood's chemical composition primarily occur within the range of 1800–800 cm^{-1}. Specifically, the peak at approximately 1745 cm^{-1} corresponds to the non-conjugated carbonyl C=O stretching vibration, while the peak around 1510 cm^{-1} is attributed to the stretching vibration of the benzene ring skeleton. The intensity of these peaks can serve as an indicator for lignin content. Additionally, the CH_2 shear and bending vibration peaks are observed at approximately 1425 cm^{-1}, and the C-H bond stretching peak in the CH_3 side chain appears at 1377 cm^{-1}. The influence of variations in wood flour content and operational errors on the experimental results was mitigated using the characteristic peak ratio method. The ratios of I_{1510}/I_{1377}, I_{1510}/I_{1745}, and I_{1510}/I_{1425} were calculated to analyze the relative lignin content in *E. cloeziana* at four different age stages [30]. The results were presented in Table 8. It could be observed that all three characteristic peak height ratios ranged between 0.971 and 1.011, with the ratios of I_{1510}/I_{1377} and I_{1510}/I_{1425} exhibiting an initial increase followed by a decrease with age progression. While both ratios peaked at 22 years, there was no significant difference in the characteristic peak height ratio among the four age groups. The relationship between the characteristic peak of lignin and growth strain was analyzed, revealing a significant positive correlation between the relative lignin content and growth strain. This finding suggests that the enhanced deposition of lignin may contribute to elevated growth strain levels.

Table 7. Variance analysis of crystallinity and correlation analysis with growth strain of *E. cloeziana*.

Age (I)	Growth Strain, με	Crystallinity, %	Age (J)	Average Difference in Crystallinity (I–J)	Significance	Correlation Between Crystallinity and Growth Strain	
						sig. (Double Tail)	Pearson Correlation
6	1850.17	36.37	10	−1.29000	0.331	0.014	0.683 *
			22	−3.05000 *	0.040		
			34	1.52000	0.257		
10	2574.17	37.66	6	1.29000	0.331		
			22	−1.76000	0.195		
			34	2.81000	0.054		
22	3080.50	39.42	6	3.05000 *	0.040		
			10	1.76000	0.195		
			34	4.57000 **	0.006		
34	2148.17	34.85	6	−1.52000	0.257		
			10	−2.81000	0.054		
			22	−4.57000 **	0.006		

'*' indicated that there was a significant difference between the crystallinity and growth strain of different tree ages ($p < 0.05$); '**' indicated that the difference between crystallinity and growth strain of different tree ages was extremely significant ($p < 0.01$).

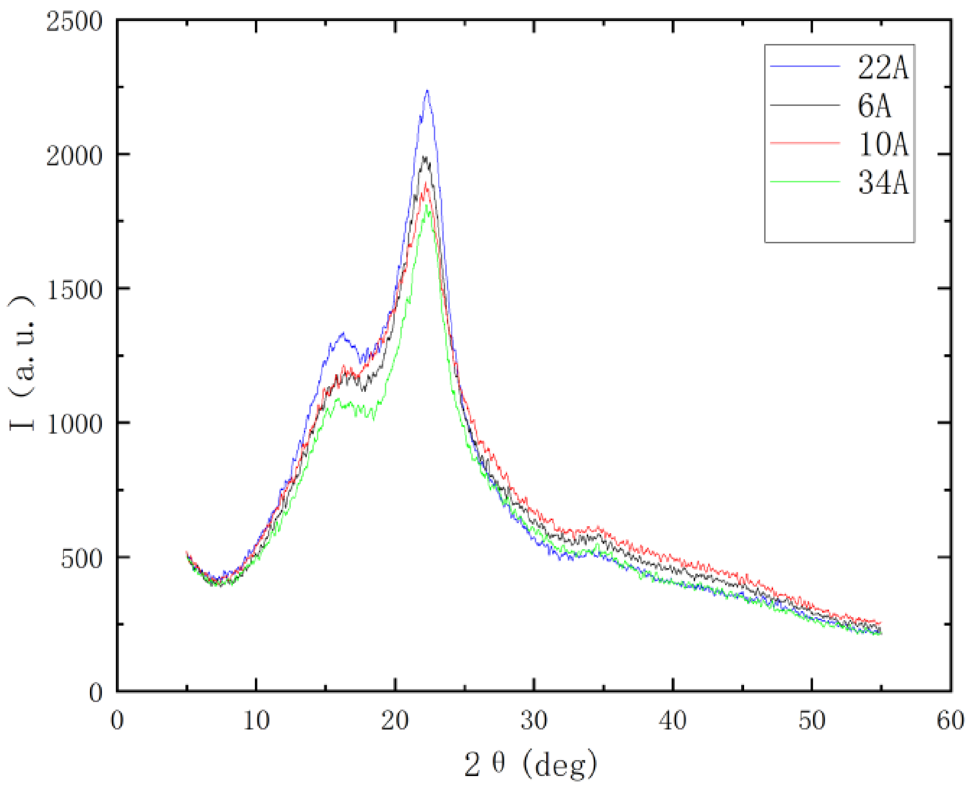

Figure 6. X-ray diffraction pattern of *E. cloeziana*.

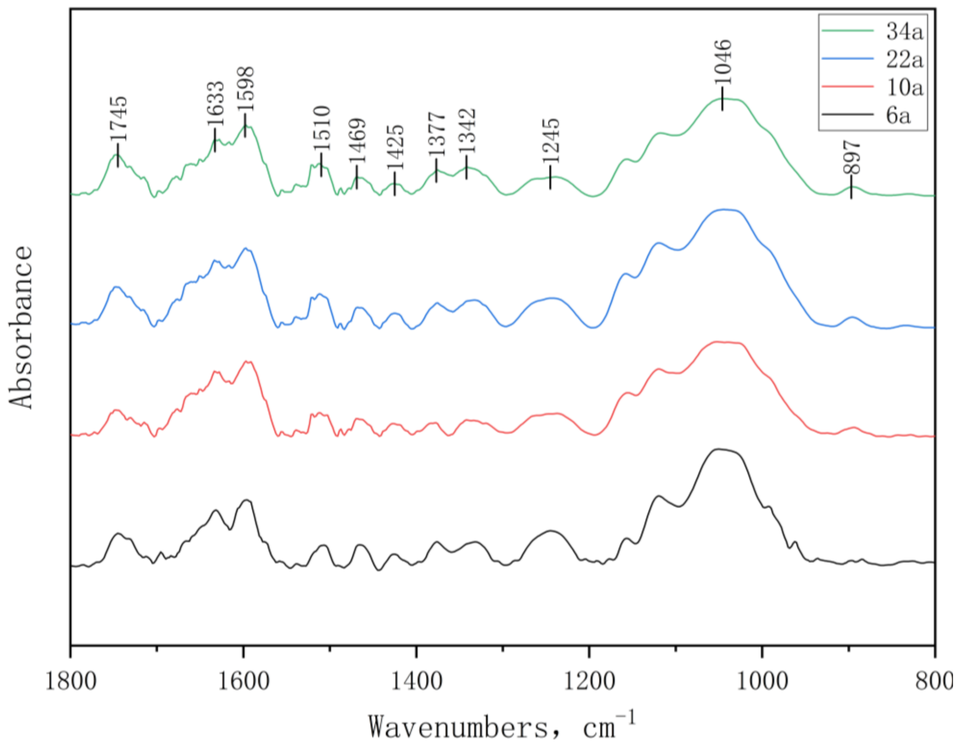

Figure 7. Fourier transform infrared spectroscopy of wood cell wall of *E. cloeziana*.

Table 8. Analysis of lignin characteristic peak height ratio in infrared spectrum of *E. cloeziana*.

Age, y	Growth Strain, με	Characteristic Peak Height Ratio			The Relative Content of Lignin and Growth Strain Correlation	
		I_{1510}/I_{1377}	I_{1510}/I_{1745}	I_{1510}/I_{1425}	sig. (Double Tail)	Pearson Correlation
4	1850.17	0.971 ± 0.066 a (0.068)	0.984 ± 0.040 a (0.041)	0.981 ± 0.043 a (0.043)	0.044	0.588 *
10	2574.17	0.985 ± 0.028 a (0.028)	0.979 ± 0.022 a (0.022)	0.996 ± 0.041 a (0.041)		
22	3080.50	0.987 ± 0.015 a (0.015)	1.011 ± 0.025 a (0.026)	0.986 ± 0.013 a (0.013)		
34	2148.17	0.981 ± 0.015 a (0.015)	0.981 ± 0.026 a (0.026)	0.991 ± 0.025 a (0.025)		

'*' indicated that there was a significant difference between the relative content of lignin and the growth strain at different tree ages ($p < 0.05$); Based on the ANOVA analysis, the letters a, there are no significant differences between different ages, all of which are marked with the letter 'a'. ($p > 0.05$). The coefficient of variation is in parentheses.

4. Discussion

In order to investigate the growth patterns of *E. cloeziana* and its potential as a material for solid wood processing and utilization, four distinct growth stages (6 years, 10 years, 22 years, and 34 years) were established to represent young forests, middle-aged forests, near-mature forests, and mature forests, respectively. The changes in DBH, tree height, density, and heartwood percentage of *E. cloeziana* were analyzed across different age stages to infer the physiological activity of the species and to measure its axial surface growth strain. By conducting an analysis on the growth strain levels across various age groups, we were able to assess the potential occurrence of trunk cracking during the harvesting process of *E. cloeziana*. Selecting the age with smaller growth strain for solid wood processing can improve the quality and yield of wood. The study reveals a strong correlation between growth strain and the morphological characteristics as well as the growth rate of trees, with this relationship being influenced by the age of the trees.

The results indicated a growth strain trend in *E. cloeziana* across the four age stages, characterized by an initial increase followed by a subsequent decrease. The maximum growth strain level was observed at 22 years of age, followed by a subsequent decline. At the age of 34, the growth strain even exhibited a lower level compared to that observed in *E. cloeziana* at 10 years old. This trend may be closely associated with changes in the growth stages and physiological characteristics of the trees. During the juvenile and early mature stages, the development of the woody structure and cell walls is not fully completed, leading to higher growth strain. However, as the trees progress into the mature stage, the woody structure strengthens, enhancing the trees' resistance to stress, and consequently, growth strain begins to decrease. Furthermore, a comparison with the findings of other researchers reveals notable variations in the growth strain of *Eucalyptus* across different growth stages and environmental conditions. According to Fournier [31], the growth strain represents the mature strain generated in the cambium, and this mature strain can be considered as a form of growth strain. Therefore, it is expected that the growth strain would accompany tree development. From early stages to maturity, the growth strain should gradually diminish until reaching a state of relative constancy in mature wood. By conducting growth strain measurements on *E. dunnii* Maiden at ages 8, 13, 15, and 19 years, Pádua [32] observed a linear increase in axial growth strain with age. Jiqing [33] discovered that the growth strain of *Eucalyptus citriodora (E. citriodora)* initially decreased and then increased across three different age classes. These findings differ from those of the present study. However, Biechele [20] demonstrated a significant increase in growth strain with ages between 3 and 10 years, followed by a decrease in growth strain between 10 and 14 years. Furthermore, the growth parameters influencing the growth strain varied according to developmental stage. Jiqing [33] conducted an analysis on the growth strain of Leizhou No.1 *Eucalyptus* and observed a pattern where the growth strain initially increased, followed by a subsequent decrease with increasing tree age, reaching its peak at 17 years old. These findings were consistent with those of the present study. In the determination of lignin and cellulose crystallinity, the observed age-related changes align consistently with the growth strain trend. Okuyama [34] postulates that growth strain arises from a combination of tensile stress on cellulose microfibers and compressive stress induced by matrix material deposition (such as lignin) (the "unified hypothesis"), further corroborating the observed growth stress pattern in this study. During the process of forest growth, there is a concurrent deposition of lignin at each stage. However, as *E. cloeziana* ages beyond 22 years, there was a decrease in the relative content of lignin, resulting in reduced growth strain. The investigation of whether the degradation of lignin contributes to a reduction in growth strain or the accumulation of chemical substances influenced by other biological activities necessitates further exploration. Additionally, we observed that environmental factors, such as climate conditions and soil types, may influence tree growth strain. Specifically, factors like temperature, precipitation, soil fertility, and moisture content can all impact the growth process of *E. cloeziana* [35]. Generally, under more favorable growing conditions, trees exhibit faster growth rates and lower growth strain; conversely, in regions with less optimal conditions, tree growth slows, and growth strain may increase. This phenomenon underscores the critical role of climate and soil factors in tree growth strain, suggesting that these environmental variables should be considered in forest management and tree cultivation practices. Given the intensification of climate change, future research should focus on the effects of different climate zones and soil types on tree growth strain. Furthermore, this research could explore how forest management can be adapted to environmental changes to foster healthy forest development and the sustainable utilization of timber resources.

The results are presented in Figure 2 indicate significant differences in the DBH and tree height of *E. cloeziana* at 34 years old compared to the other three age groups. Furthermore, the correlation analysis between DBH, tree height, and growth strain (Figure 5) reveals a positive correlation between DBH and growth strain, while a minimal correlation is observed between tree height and growth strain. The findings of Jiqing [33] revealed a significant correlation between growth strain and DBH in Leizhou No.1 *Eucalyptus* and *E. citriodora.* A positive correlation was observed for the former species, while a negative correlation was found for the latter species. However, no significant association between DBH and growth strain was observed in *E. urophylla*. Yamamoto [36] observed a significant positive linear correlation between growth strain and DBH in 4-year-old *E. urophylla*, while no significant correlation was found between tree height and DBH. Jullien [37] conducted a comprehensive study involving over 400 beech plants across five European countries, suggesting that a higher height–diameter ratio corresponds to greater growth strain. The findings of this study were in line with the observed outcomes. Jianxiong [38], in his research on *E. urophylla* × *E. grandis*, *E. urophylla*, *E. cloeziana*, and *E. pellita* in southern China, noted the highest level of growth strain in *E. urophylla*, possibly attributed to its rapid DBH growth. These findings exhibit both similarities and contrasting conclusions within this study. The intricate relationship between DBH, tree height, and growth strain may be attributed to variations in species origins and tree ages. Growth strain is an inherent mechanism in trees that enables them to withstand external forces during the growth process, facilitating their adaptation through self-support and adjustment. The relationship between tree morphology and growth strain remains uncertain as to whether the dwarfing of trees, the rounding of trunks, and the uniform growth of crowns gradually diminishes the role of growth strain in maintaining stability or if it is the alteration of growth strain that adjusts tree morphology.

This study provides new theoretical insights into the growth strain characteristics of *E. cloeziana*, contributing to a deeper understanding of its growth mechanisms and strain variation patterns, while also offering scientific references for forest management and the timber industry. By analyzing the growth strain characteristics of trees, forest managers can implement informed logging and cultivation strategies based on strain patterns and tree growth stages. Specifically, in timber production, prioritizing trees with a lower growth strain can enhance processing efficiency and stability, reduce cracks and deformations, and ultimately increase the market value of the timber. However, due to the limited sample size and the insufficient consideration of the interaction between phenotypic traits and environmental factors, future research should focus on expanding the sample size and incorporating a broader range of environmental variables. This would further enhance the reliability of the findings and provide crucial insights for future forest management practices and timber processing strategies.

5. Conclusions

The trees at four different age stages exhibit two distinct phases of variation in growth characteristics and wood properties, providing valuable guidance for forest management. For short-term management, harvesting is recommended at 6 years, as the trees display excellent growth traits with minimal growth strain. For long-term management, harvesting between 22 and 34 years is ideal, as wood density and heartwood percentage increase, and growth strain is lower, which helps to reduce wood defects and management costs. If cost is not a concern, harvesting at 34 years or longer is advised to achieve high yield and superior quality, in alignment with the near-natural forest management philosophy. Future research should further explore the impact of environmental factors, nutrients, and silvicultural practices on growth strain, in order to optimize the solid wood utilization strategy for Eucalyptus grandis and foster the efficient development of the solid wood industry.

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Abbreviations

The following abbreviations are used in this manuscript:

DBH	Diameter at breast height

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