

Field Growth Performances of Different *Eucalyptus pellita* Genotypes

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Eucalyptus is a key species in global tropical hardwood industries and has gained importance in Malaysia since the establishment of *Eucalyptus pellita* plantations in 2008. Its versatile, durable wood supports various sectors, such as furniture, construction, and pulp production. High-quality wood enhances product longevity, reduces processing costs, and increases plantation value. To improve productivity and wood quality, selecting superior planting materials through genotype screening is vital. This study evaluated the growth performance of eight *E. pellita* genotypes as part of a breeding program for industrial applications. A progeny trial was conducted at Agricultural Park UPM, Puchong, Selangor, with field measurements including tree height, diameter at breast height (DBH), root collar diameter, volume, crown health, multiple leaders, and leaf browning recorded over a year after 31 months of planting. Genotype EP03 achieved the greatest height (17.7 to 18.0 m), while EP03 and EP11 had the largest DBH (14.1 to 14.0 cm). U × G recorded the highest volume (0.17 m³), followed by EP03 (0.15 m³) and EP11 (0.14 m³). EP03 and EP11 also exhibited superior crown health and lower leaf disease severity. Strong correlations were observed between DBH and both height and volume. Overall, EP03 and EP11 showed consistently superior growth and qualitative traits, making them promising candidates for forestry applications.

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INTRODUCTION

According to the Food and Agriculture Organization of the United Nations, forests encompass 4.06 billion hectares (ha), representing 31% of the land area globally in 2022. In addition, the demand for primary processed wood products is predicted to rise by 37% by 2050 (FAO, 2022). The demand for wood products continues to increase, making higher productivity essential. At the same time, forest plantations offer an important alternative to natural forests, providing timber without excessive loss of biodiversity while also supporting livelihoods and infrastructure development (Latif *et al.* 2018; Sacco *et al.* 2021; Yasin *et al.* 2024).

In addition to economic benefits, forest plantations offer numerous advantages to the environment. The advantages of forest plantation include reducing pressure on natural

forests, restoration of degraded land, increasing soil nutrients, preventing soil erosion, and mitigating climate change *via* carbon sequestration (Smith *et al.* 2019). Forest plantations are sustainable and ecologically suitable options for addressing the increasing demand for timber products. Forest plantations have arisen as a feasible alternative to fulfil the demand for timber while maintaining biodiversity and ecological equilibrium (Chen *et al.* 2024). The woods that are harvested from the specific cultivated area can protect the natural forests from deforestation. This facilitates effective management strategies, such as replanting, thinning and harvesting, to reduce environmental effects while increasing productivity (Latif *et al.* 2018).

Forest plantations are frequently subjected to intense management and face negative perceptions, sometimes encroaching on adjacent land and leading to disputes with local populations. They may also deteriorate soil health, degrade indigenous grasslands, cause loss of essential habitats, and increase vulnerability to pests and diseases (Huang *et al.* 2011; Koons 2022; Getnet *et al.* 2024).

Forest plantations, often utilizing fast-growing woody species such as *Eucalyptus* are an initiative for promoting sustainability (McEwan *et al.* 2019). Globally, *Eucalyptus* is the most planted hardwood tree, with its plantation area exceeding 22.57 million hectares across 95 countries (Hua *et al.* 2022). Specifically, in Indonesia, *Eucalyptus pellita* has been rapidly adopted as a replacement for *Acacia mangium* plantations, with an estimated 465,000 hectares in Sumatra and 225,500 hectares in Kalimantan converted to *E. pellita* by 2021 (Hardiyanto *et al.* 2022; Zuhaidi *et al.* 2020). This expansion is driven by *E. pellita*'s higher disease resistance, which is a key factor given the severe impact of diseases on other species (Setyaji *et al.* 2016).

Foresters can improve plantation productivity and sustainability by selecting superior clones, which maximizes timber yield and reduces the need for chemical treatments by choosing pest-resistant types (Setyaji *et al.* 2016). Currently, *Eucalyptus pellita* is a key species in the hardwood industry, and its mechanical properties make it highly valuable for solid wood and veneer applications including furniture and flooring (Hii *et al.* 2017). A study by Japarudin *et al.* (2021) found that *E. pellita* has adequate mechanical properties, with an average density of 658 kgm⁻³, a bending modulus of elasticity (MOE) of 11.7 to 15.5 GPa, and a compression strength parallel to the grain of 52.3 to 67.8 MPa. When compared to other commercial eucalyptus species, *E. pellita* demonstrates competitive properties. For instance, its density is similar to that of *E. globulus* (around 680 kgm⁻³) and *E. grandis* (around 600 kgm⁻³). Similarly, its MOE values are comparable to or even exceed those of *E. grandis* (10 to 12 GPa) and *E. urophylla* (12 to 14 GPa), making it a suitable and often superior alternative for a wide range of applications.

Despite its importance, relatively few studies have examined the genetic and propagation variation within *E. pellita*. In contrast to the extensive work on species such as *E. globulus* and *E. camaldulensis*, knowledge of *E. pellita* genotypes remains limited. This study addresses this gap by evaluating the growth performance of multiple *E. pellita* genotypes and comparing propagation techniques (seed vs. *in vitro*).

Another notable research gap related to *E. pellita* cultivation is lack of study on comparison between seed propagation and tissue culture techniques. Vegetative propagation is frequently used in forestry, yet it poses issues, such as genetic heterogeneity, which resulted in producing non uniform growth performance (Wu 2018). In contrast, plant tissue culture technique could be introduced as an alternative propagation technique due to the capability of this technique to produce a disease-free and genetically stable plant.

Hence, the growth performance is more stable (Negi *et al.* 2024). However, literature related to the long-term growth performance between *E. pellita* propagated through seed and tissue culture techniques is limited.

Hence, the finding from this study will aid the research gap by providing extensive data on the growth performance of different genotypes of *E. pellita* and providing a comparative analysis of seed and tissue culture propagation techniques. This study will enhance an understanding relative to diversity of genetic and phenotypic of *E. pellita* and suitable superior genotypes for plantation. Moreover, it facilitates the establishment of robust and efficient *E. pellita* plantations, in accordance with overarching objectives of sustainable forest conservation and management. Therefore, the objective of this study was to evaluate the growth performance of different genotypes of *E. pellita*. Hence, this study sought answers for two specific research questions, as follows:

1. Does different *E. pellita* genotypes exhibit different growth parameters based on quantitative and qualitative traits?
2. What is the different in term of growth performance between *E. pellita* cultivated from seed and plant tissue culture technique?

Results of this study will offer critical insights into the significance of tree selection and screening for *E. pellita* in determining the high-yielding genotypes. Furthermore, this will provide the knowledge on propagation technique (*i.e.*, seed vs tissue culture) for high production of *E. pellita*, resulting in cost-effective and sustainable and resilient forest planation techniques.

EXPERIMENTAL

Site Characteristics

In 2019, a Genetic Gain Plot trial was set up at Puchong, Selangor's UPM University Agricultural Park, located at 2°59'13.18"N latitude and 101°39'9.18"E longitude. The location is at a slightly sloping elevation of 24.7 m above sea level. The soil type, known as the Bungor Series, is composed of reddish-yellow, fine-grained, kaolinitic, isohyperthermic Tipik Lutualemkuts formed over a mixture of sedimentary rocks (Department of Agriculture Malaysia 2024). These soils are distinguished by deep B horizons with colours ranging from brownish yellow to yellowish brown with fine sandy clay textures and dark greyish brown A horizons with fine sandy loam textures. In addition, soils of the Bungor Series are described as deep, well-drained, and having good permeability (Department of Agriculture Malaysia 2024).

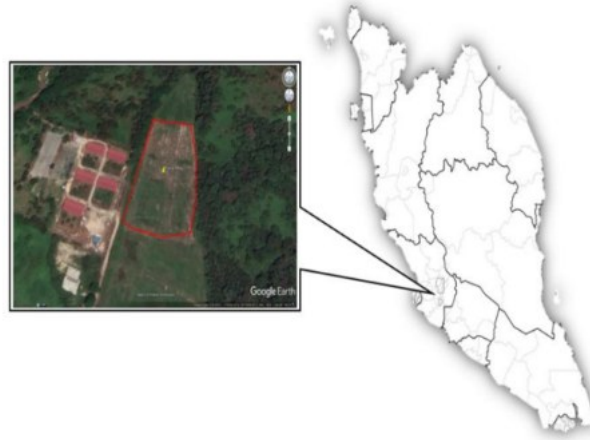


Fig. 1. Location of the *E. pellita* trial plot. (Source: Thibom 2019)

The average rainfall recorded at the site is approximately 3200 mm per year in the neighbouring town of Puchong, with about 120 mm in the driest month. The mean daily temperature is 29 °C, with minimum and maximum averages of 25 °C and 33 °C, respectively (MetMalaysia 2024).

Seed Source and Origin

The genotypes used in this study were carefully selected to represent different propagation methods and genetic backgrounds, which is a critical factor for evaluating their performance. The three genotypes, EP03, EP01, and EP11 originate from *in vitro* tissue cultures, chosen for their superior growth traits, wood quality, and pest resistance. These clones were previously identified through extensive genetic screening programs to be high-performing. In contrast, the other four genotypes, SSB17038, SSB17040, 12041, and SSB18001 were sourced as seedlings from a mother plant. This selection strategy allows for a direct comparison of the growth, yield, and mechanical properties between vegetatively propagated clones and sexually reproduced seedlings, providing valuable insights into the efficiency of different breeding strategies. The specific origins and characteristics of these genotypes are detailed in Table 1.

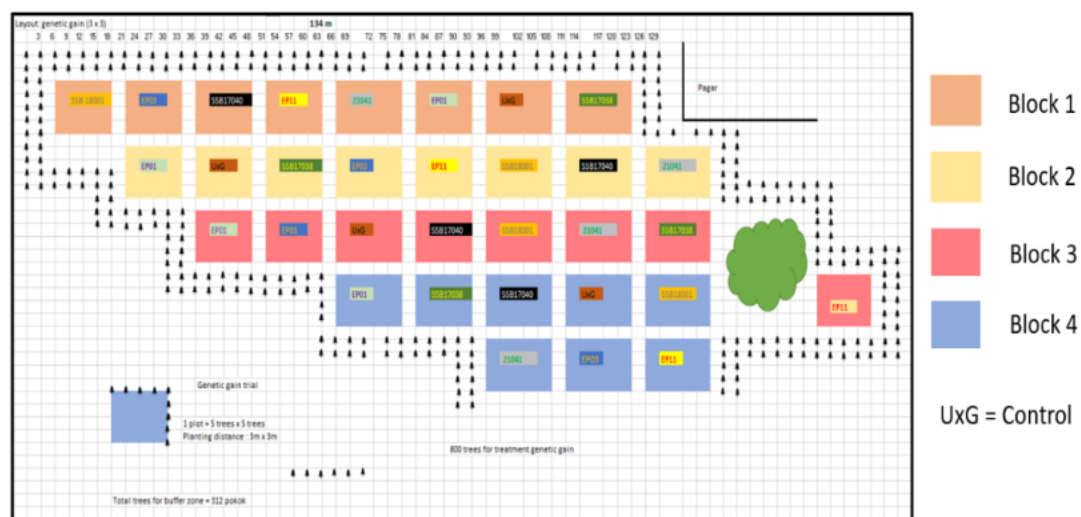


Fig. 2. Experimental design of *E. pellita* trial plot at Agricultural Park UPM

Table 1. *E. pellita* Genotypes Used in this Study and their Sources

Species	Material Type	ID
<i>E. pellita</i>	Seed	21041
<i>E. pellita</i>	Seed	SSB17038
<i>E. pellita</i>	Seed	SSB17040
<i>E. pellita</i>	Seed	SSB18001
<i>E. pellita</i>	Clone	EP01
<i>E. pellita</i>	Clone	EP03
<i>E. pellita</i>	Clone	EP11
<i>Eucalyptus urophylla</i> x <i>grandis</i> hybrid	Clone	UxG

Based on Fig. 2, it was decided to adopt the experimental design of randomized complete block design (RCBD) and the planting arrangement was made for each genotype by placing five trees vertically and horizontally with a displacement of 3 m × 3 m. A total of 25 plants of each *E. pellita* genotype were planted for each subplot. A total of three replicate subplots were planted for each genotype.

Experimental Design

The measurements were initiated in October 2021, 31 months after planting, and continued for 12 months until October 2022. The growth measurements were recorded every third week of each month. The measured growth traits were quantitative of tree height, diameter breast height (DBH), root collar diameter (RCD), volume and qualitative parameters of crown health (CH), multiple leaders (ML), and leaf disease (LD).

The height was measured precisely using a clinometer, and the DBH and the RCD were calculated using metal metric diameter tape at 1.3 m above ground level. The root collar diameter was measured 10 cm from the ground to the nearest millimetre. After obtaining DBH and H, timber volume (VOL) was calculated with Eq. 1,

$$VOL = \pi \times (DBH/2)^2 \times H \times FF \quad (1)$$

where the form factor (FF = 0.5) presented by Oliveira *et al.* (2018). The data were analysed for 12 months (From October 2021 to October 2022) after 31 months of planting. The periodic annual diameter increment (PAId) and periodic annual height increment (PAIh), introduced by Zuhaidi *et al.* (2020), were calculated as follows,

$$PAId = [(d_{t+k} - dt) / k] * t \quad (2)$$

$$PAIh = [(h_{t+k} - ht) / k] * t \quad (3)$$

where *PAId* is the observed periodic annual diameter increment (cm/year), *PAIh* is the observed periodic annual height increment (m/year), *dt+k* is the diameter at the end of the growth period (cm), *ht+k* is the total height at the end of the growth period (m), *dt* is the diameter at the beginning of the growth period (cm), *ht* is the total height at the beginning of the growth period (m), *k* is the length of growth period (days), and *t* is the 365 days.



Fig. 3. Comparison of crown health, leaf disease and multiple leaders of *E. pellita*

A subjective score was used to measure the qualitative traits of crown health (CH), multiple leaders (ML), and leaf disease (LD). For each subplot, all trees were visually assessed, and scores were assigned following established forestry scoring methods adapted from Shen *et al.* (2023).

Data Analysis

The Statistical Package for the Social Sciences (SPSS) was used for the data analysis. Quantitative traits were analysed using a one-way ANOVA at $p \leq 0.05$, followed by Duncan's Multiple Range Test. For ordinal categorical data (crown health, multiple leaders, leaf disease), ANOVA was applied with caution following previous forestry studies (Hakkem, 2019; Thibom 2019) and acknowledge that non-parametric tests such as Kruskal–Wallis may also be suitable.

RESULTS AND DISCUSSION

Mean Comparison of Growth Traits Between Different *E. pellita* Genotypes

From Table 2, the ANOVA analysis showed significant differences between the groups for all tree growth traits of height, DBH, RCD, Volume, CH, LD, and ML ($p = 0.000$). Analysis of the health-related traits (crown health, leaf disease, and multiple leaders) revealed significant differences among the genotypes.

Table 2. ANOVA Analysis Between Quantitative and Qualitative Traits

Growth Variables	Sum of Squares	df	Mean Square	F	Sig.
Height	10199.278	7	1457.040	115.326	.000
Diameter Breast Height	6074.907	7	867.844	73.014	.000
Root Collar Diameter	8533.326	7	1219.047	53.917	.000
Volume	5701.460	7	814.494	128.590	.000
Crown Health	187.907	7	26.844	28.844	.000
Leaf Disease	19.897	7	2.842	22.574	.000
Multiple Leader	27.513	7	3.930	8.496	.000

The analysis of tree growth traits revealed significant differences among all genotypes for mean height, diameter at breast height (DBH), root collar diameter (RCD), and volume ($p=0.000$). The results, as detailed in Fig. 4 and Table 2, show a clear hierarchy of growth performance. U $\times$ G and EP03 consistently demonstrated the most vigorous growth. These genotypes had the greatest mean height and volume, significantly outperforming all other genotypes. Specifically, U $\times$ G had the largest DBH (14.51 cm) and volume (0.17 m³), while EP03 was notably tall (17.7 m).

Following the top performers, EP11 and EP01 showed intermediate growth. EP11 was consistently among the top three for all growth traits, while EP01 was slightly less vigorous. Their DBH and RCD values were comparable to or slightly lower than the leading genotypes, but their mean height and volume were significantly greater than the lowest-performing groups. In contrast, SSB17038 and SSB18001 consistently exhibited the slowest growth across all measured traits. These genotypes had the smallest mean height, DBH, RCD, and volume, with no significant difference between their performance. This suggests these genotypes are not as well-suited for high-yield timber production under the conditions.

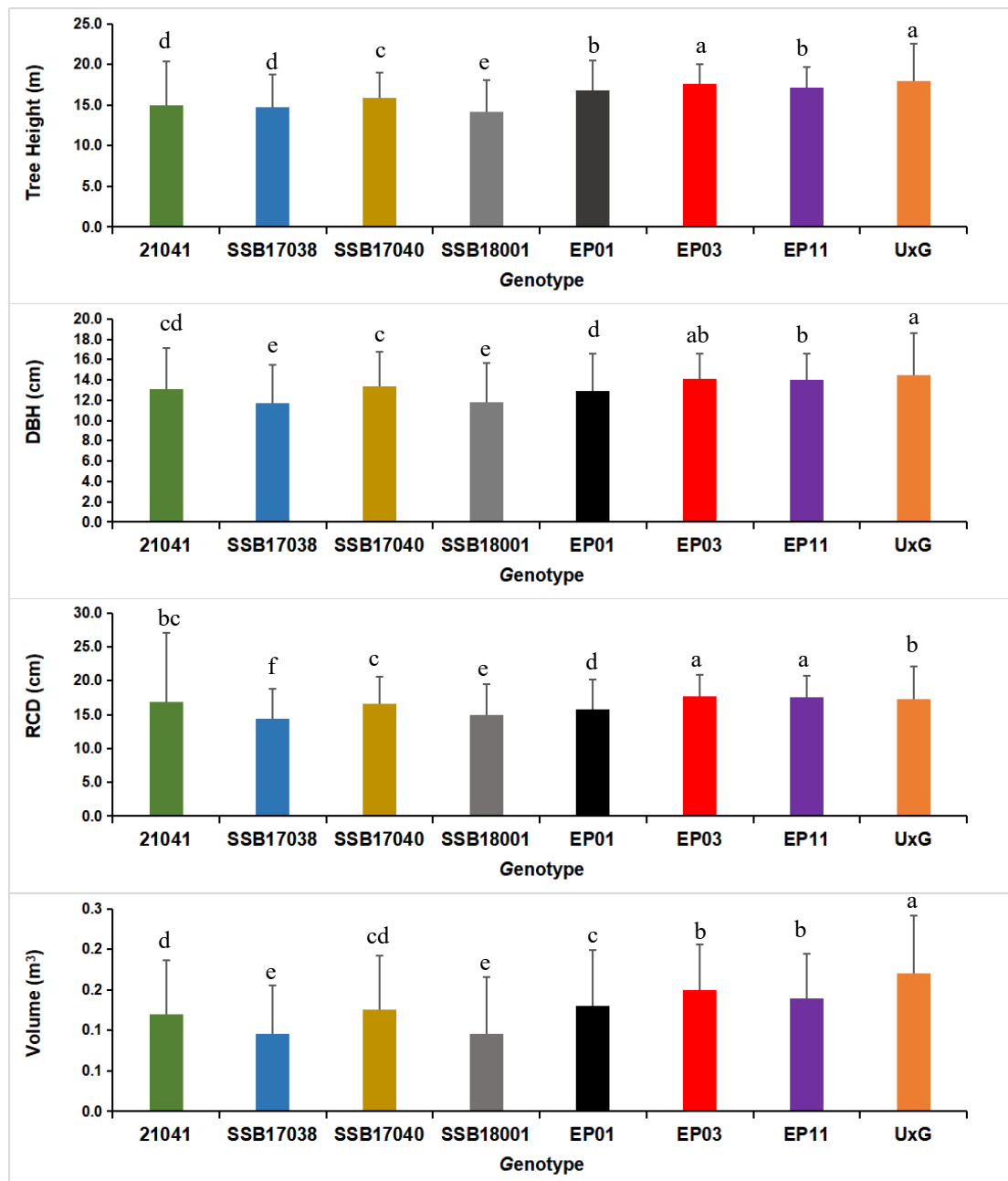


Fig. 4. Mean comparison between genotypes from the quantitative traits of height, DBH, RCD and volume of *E. pellita* trees; different letters denote significant differences between genotypes. The error bars show the standard deviation (SD) for each traits.

The superior performance of genotypes U × G and EP03 in terms of mean height, DBH, and volume can be attributed to their specific genetic traits. Both genotypes are clones selected for their high vigor and growth rates, a result of targeted breeding programs aimed at maximizing yield. The consistent outperformance of these clones, particularly compared to the seedling-sourced genotypes (SSB series), highlights the effectiveness of clonal forestry in capturing and reproducing desirable traits. Clones, unlike seedlings, are genetically identical replicates of a high-performing mother tree, which guarantees consistent and superior growth (Tewari and Pande 2020). This genetic uniformity

minimizes variability and ensures that the positive traits, such as rapid growth and efficient nutrient uptake, are expressed across the entire plantation. In contrast, seedlings are the product of sexual reproduction, leading to greater genetic diversity and a wider range of growth performance. Therefore, the consistent and high-level performance of $U \times G$ and EP03 demonstrates the successful application of clonal selection to meet productivity goals.

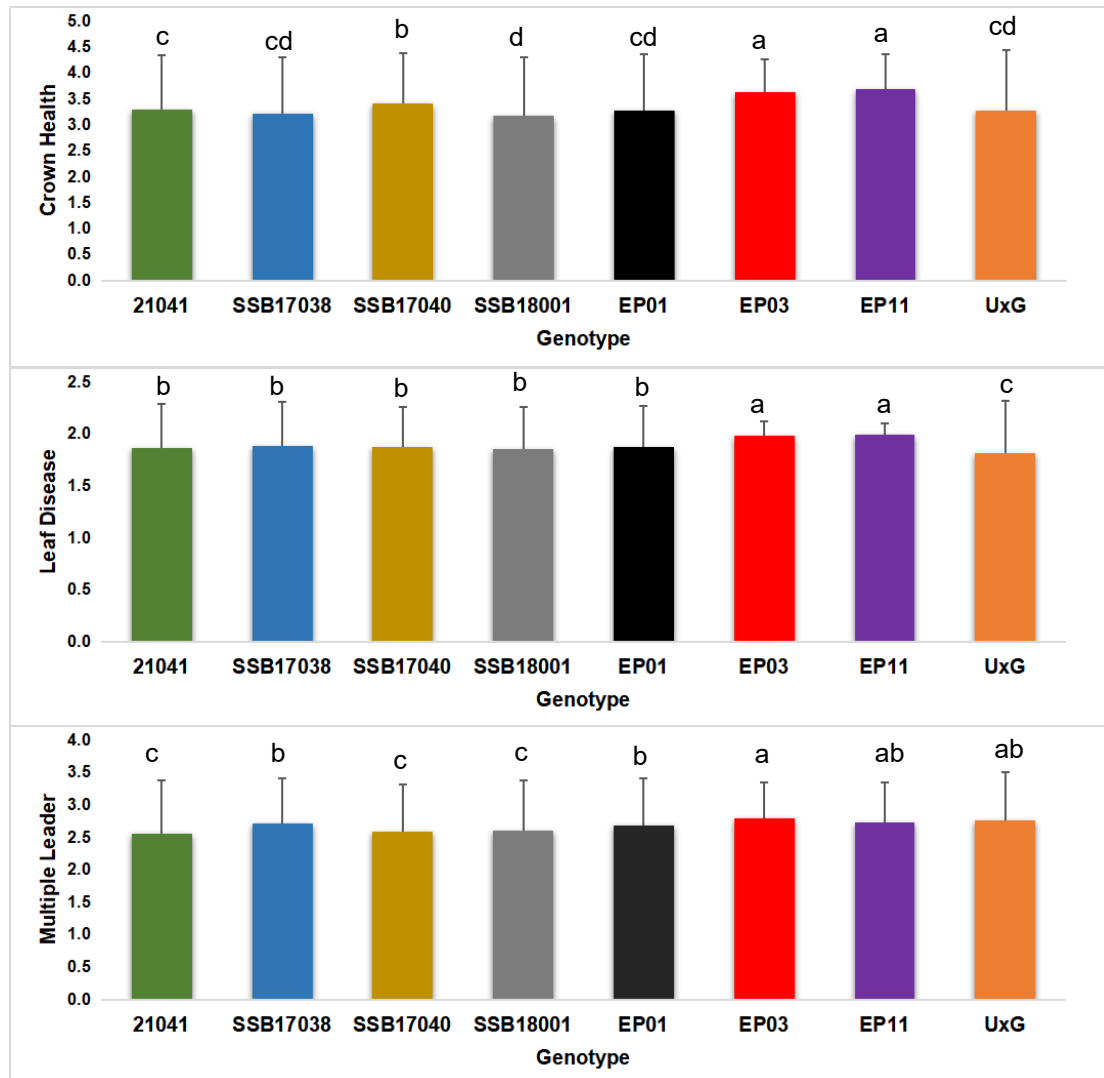


Fig. 5. Mean comparison between genotypes for the qualitative traits of crown health, leaf disease, and multiple leaders for *Eucalyptus* trees; different letters denote significant differences between genotypes. The error bars shows the standard deviation (SD) for each traits.

This study identified significant variations in growth performance among different *E. pellita* genotypes, with EP03 and EP11 consistently demonstrating superior results. The findings suggest that these clones have greater growth potential than those examined in much of the earlier research, as evidenced by their mean annual height (17.66 m and 17.2 m, respectively), DBH (14.14 cm and 14.01 cm), and volume (0.15 m³ and 0.14 m³). While some studies report similar or greater heights for older trees (Ramadan *et al.* 2018), the performance of our genotypes in a relatively shorter timeframe highlights their inherent

vigor and suitability for high-yield plantations. The notable outperformance of EP03 and EP11 over other clones and seedling genotypes underscores the critical role of clonal selection in maximizing productivity, which is consistent with the findings of other studies that have identified superior growth in specific eucalyptus clones (Behera *et al.* 2016; Nirsatmanto *et al.* 2022).

This superior performance is likely due to the genetic factors of these specific genotypes. The fact that both EP03 and EP11 were regenerated *in vitro* suggests that tissue culture methods successfully capture and propagate elite genetic traits. This shared origin, in contrast to the sexually reproduced seedlings, explains their similar growth potential and consistently high performance across all measured traits. This finding strongly supports the use of advanced clonal propagation techniques in breeding programs. By selecting and crossing these elite genotypes, breeders can develop new varieties that are not only high-yielding but also possess desirable traits such as adaptability and disease resistance, enhancing the survival and productivity of plantations in challenging environments (Butler *et al.* 2017; Shen *et al.* 2023).

Based on qualitative analysis in Fig. 5, genotypes EP03 and EP11 exhibited significantly better crown health and lower leaf disease scores compared to all other genotypes. This indicates that these two genotypes possess superior resistance or resilience to health stressors. The remaining genotypes (21041, SSB17038, SSB17040, SSB18001, EP01, and U × G) showed statistically similar but poorer scores for both traits. In terms of multiple leaders, genotype EP03 displayed a significantly higher incidence of this trait. While EP11, SSB17038, and EP01 had lower occurrences than EP03, they were still statistically distinct from other genotypes, suggesting a tendency for these clones to develop multiple stems. Genotypes 21041 and SSB1801 fell into a moderate category with a statistically significant difference with scores of 2.46 and 2.53, respectively, from both the higher groups (EP03, EP11, SSB17038, and EP01) and the lower group of SSB17040 and U × G. Specifically genotypes SSB17040 and U × G had a relatively lower number of multiple leaders than most other genotypes with scores of 2.32 and 2.34, respectively.

However, the observation that EP03 had the highest incidence of multiple leaders presents a potential trade-off. While this genotype excelled in growth, a high number of multiple leaders can negatively affect timber quality and the final product's value. A tree with a single, straight trunk is often more valuable for sawn timber and veneer production. Therefore, future breeding programs must balance high growth rates with desirable crown architecture and stem form. This requires a holistic approach to genotype selection that considers not just productivity, but also the long-term economic viability and end-use of the timber. Research into the specific genetic factors influencing crown architecture, as well as the effects of light interception and competition on trees with multiple leaders, will be essential for optimizing plantation management and maximizing profitability (Qian *et al.* 2022).

Research has shown that certain *Eucalyptus* genotypes exhibit superior growth rates and wood properties, making them ideal samples for commercial cultivation (Arunkumar and Chauhan 2020). Notably, EP03 and EP11 demonstrated statistically similar growth rates, suggesting potential shared genetic factors, as both were *in vitro* regenerated, which may contribute to their high growth potential. Handayani *et al.* (2020) noted that improved *E. pellita* seeds from two seed orchards outperformed controls, further emphasising the significance of genetic factors in growth performance.

Mean comparison of annual increment based on quantitative traits between different E. pellita genotypes

Table 3 displays the Duncan results showing that Genotype SSB17040, with an annual height increment (PAI_h) of 3.02 m/year, exhibited the highest growth and significantly differed from most other genotypes. EP03, with a height increment of 2.60 m/year, and EP11, at 2.32 m/year, also showed high growth increments but were not significantly different from SSB17040. Genotype 21041, with PAI_h of 1.71 m/year, showed moderate growth, significantly different from SSB17040 and $U \times G$ but not from EP03 and EP11. SSB17038, with a PAI_h of 1.63 m/year. This was similar to 21041 but exhibited slightly lower growth. SSB18001, at 0.82 m/year, demonstrates lower growth and significantly differs from most of the other genotypes. EP01, with a height increment of -0.05 m per year, showed almost no growth, while $U \times G$ had the lowest value at -2.30 m/year, significantly different from all other genotypes.

Then, regarding annual DBH increment (PAI_d), EP11 exhibited the highest growth rate at 2.32 cm/year, closely followed by EP03 at 2.21 cm/year, with no significant difference between the two. SSB17040, with a PAI_d of 2.04 cm/year, and SSB18001, at 1.91 cm/year, also showed high growth rates, although these were significantly smaller than those of EP11 and EP03. Genotypes 21041 (1.50 cm/year), SSB17038 (1.22 cm/year), and EP01 (1.15 cm/year) exhibited significantly lower PAI_d compared to other genotypes. $U \times G$, with a PAI_d of -0.41 cm/year, showed a significantly lower growth value than all other genotypes.

Next, regarding annual RCD increment (PAI_r), EP03 demonstrated the highest rate at 2.89 cm/year, significantly greater than all other genotypes. EP11 followed closely with a PAI_r of 2.73 cm/year, slightly lower but not significantly different from EP03. SSB17040, at 2.17 cm/year, and SSB18001, at 2.03 cm/year, exhibited moderate increments, significantly lower than those of EP03 and EP11 but higher than most other genotypes. Genotype 21041 had a PAI_r of 1.79 cm/year, showing a moderate increase, although significantly lower than the other performers. SSB17038, with a PAI_r of 0.71 cm/year, and EP01, at 1.02 cm/year, exhibited the lowest growth rates, while $U \times G$, with a PAI_r of -0.12 cm/year, showed decreasing growth, which was significantly lower than all other genotypes.

Finally, regarding annual volume increment (PAI_v), SSB17040 recorded the highest at 0.072 m³/year, which was significantly different from most other genotypes. Then, it was followed by EP03, with a PAI_v of 0.069 m³/year, and EP11, at 0.065 m³/year, followed closely, showing high increments that were not significantly different from SSB17040. Genotype 21041 had a PAI_v of 0.058 m³/year, similar to that of EP11 but lower than the increments of SSB17040 and EP03. SSB17038, with a PAI_v of 0.048 m³/year, and SSB18001, at 0.047 m³/year, showed significantly lower increments than other genotypes. EP01, with the lowest positive value of 0.043 m³/year, also demonstrated a lower growth rate. $U \times G$, with a PAI_v of 0.02 m³/year, had the lowest growth, significantly different from all other genotypes. Overall, genotypes EP03 and EP11 consistently performed well across all traits, showing significantly higher annual tree height, DBH, RCD, and volume increments, while $U \times G$ consistently exhibited poor performance with negative or significantly lower values across all traits. Other genotypes, such as EP01 and SSB18001, showed moderate to low annual increments, with EP01 being among the lowest in multiple characteristics.

Table 3. Mean Comparison Between Genotypes and Periodic Annual Increment Based on Quantitative Traits

Growth Parameter	Genotype							
	21041	SSB 17038	SSB 17040	SSB 18001	EP01	EP03	EP11	UxG
Tree height increment (m/year)	1.71 ab	1.63 abc	3.02 a	0.82 bc	-0.05 c	2.60 ab	2.32 ab	-2.30 d
DBH increment (cm/year)	1.50 a	1.22 a	2.04 a	1.91 a	1.15 a	2.21 a	2.32 a	-0.41 b
RCD increment (cm/year)	1.79 ab	0.71 bc	2.17 ab	2.03 ab	1.02 bc	2.89 a	2.73 a	-0.12 c
Volume increment (m ³ /year)	0.058 abc	0.048 bc	0.072 a	0.047 bc	0.043 c	0.069 a	0.065 ab	0.02 d

The *in vitro* cultivation of *E. pellita* clones, particularly EP11 and EP03, demonstrated the potential of tissue culture as an effective propagation method for *Eucalyptus* species. This technique offers significant advantages over traditional methods, ensuring the rapid multiplication of genetically identical plants and guaranteeing uniformity across large-scale plantations. This uniformity is crucial for maintaining desirable traits such as high productivity and enhanced disease resistance (Rajasekharan and Sahijram 2015).

The superior performance of the clones EP03 and EP11, which were regenerated *in vitro*, has direct and tangible benefits for plantation establishment and management. By using tissue culture, foresters can produce a high volume of elite plant material that consistently expresses superior growth rates and pest resistance. This genetic uniformity leads to more predictable yields, a major advantage for commercial forestry. Clonal plantations, established from *in vitro*-propagated material, exhibit uniform growth and development, leading to synchronized harvesting schedules and simplified management. This reduces operational costs and enhances overall efficiency. The ability to select and propagate clones with proven resistance to diseases such as the lower leaf disease scores seen in EP03 and EP11 is a powerful tool for safeguarding plantations. This reduces reliance on chemical treatments, making cultivation more sustainable and environmentally friendly. With less variability in growth and form, plantations can produce a more consistent and higher-quality timber product, which increases its market value. Tissue culture allows for the rapid deployment of clones that are well-adapted to specific environmental conditions, enabling the establishment of productive plantations in diverse and challenging landscapes. Additionally, it allows precise control over environmental factors such as temperature, light, and humidity which can be optimised to enhance plant development (Abiri *et al.* 2020). Studies have demonstrated that culture media and growth regulators significantly improve the *in vitro* multiplication of *Eucalyptus* species, facilitating high-quality plantation establishment (Setyaji *et al.* 2016). Through propagating clones with superior traits, forestry practices can be optimised to ensure sustainable management and increased productivity, contributing to afforestation and environmental sustainability (Setyaji *et al.* 2016).

Insights gained from these studies can inform sustainable forest management practices and guide policymakers. Understanding the growth characteristics and environmental adaptability of different *E. pellita* genotypes allows for informed decisions about species best suited to specific regions and market demands. For example, prioritising

genotypes resistant to pests or diseases can enhance the sustainability and profitability of *Eucalyptus* plantations, especially in areas with such threats (Li *et al.* 2015). These findings also contribute to developing sustainable forest management plans that minimise negative environmental impacts while promoting long-term productivity (Pozo and Säumel 2018). Through strategically selecting genotypes suited to environmental conditions, such as soil type, climate, and moisture availability, forest managers can reduce plantation failure risks and maximise growth potential (Rawal *et al.* 2013; Wang *et al.* 2019). For example, drought stress can severely limit tree transpiration and growth, leading to a slow-fast-slow growth pattern in *Eucalyptus* trees. Conversely, adequate fertilisation, particularly with phosphorus, has been shown to alleviate drought effects and improve growth rates by enhancing root development and water use efficiency (Tariq *et al.* 2019). This highlights the importance of tailored management practices considering the specific nutrient requirements and environmental tolerances of selected *Eucalyptus* genotypes. Moreover, the knowledge of genotype-specific responses to environmental stressors can guide site preparation and management strategies. As such, tree responses to soil fertility and water availability can be used to know the suitable actions to be taken for management practices, such as irrigation, in addition to properly selecting tree genotypes. This additional information can potentially be useful to improve the efficiency of future *Eucalyptus* plantation management.

To place these findings into practice, policymakers and forest managers should focus on integrating genetic selection into forest management strategies. Based on the present work, it is recommend to prioritize the use of elite clones, such as the *in vitro*-propagated EP03 and EP11, to establish new plantations. This approach ensures consistent growth, high yields, and greater resilience to pests and diseases, which in turn reduces the need for costly chemical interventions. Furthermore, policies should be developed to encourage investment in advanced breeding programs and tissue culture facilities to continuously produce and deploy superior, climate-resilient genotypes. Ultimately, the strategic selection of genetically superior clones is a critical step toward achieving sustainable, profitable, and environmentally responsible forestry.

Pearson's correlation analysis

Based on Table 4, the Pearson correlation analysis revealed significant relationships between several growth and qualitative traits in *E. pellita*. Tree height showed a strong positive correlation with DBH, RCD, and volume, with correlation coefficients of 0.784, 0.666, and 0.764, respectively. This indicates that taller trees tended to have larger diameters and greater volumes. Additionally, tree height was moderately correlated with crown health (0.499) and leaf disease (0.485), suggesting that taller trees are associated with healthier crowns and less leaf disease. The correlation with multiple leaders was weaker but still significant at 0.340.

The DBH also exhibited strong positive correlations with RCD (0.844) and volume (0.921), indicating that trees with larger diameters at breast height tend to have larger root collars and volumes. Moreover, DBH was moderately correlated with crown health (0.522) and leaf disease (0.456), meaning that healthier crowns and less leaf disease are typically associated with greater DBH. A weak but significant correlation was found between DBH and multiple leaders (0.208). Additionally, RCD strongly correlated with volume (0.760), indicating that trees with larger root collars tended to have more volume. It also showed moderate correlations with crown health (0.465) and leaf disease (0.412), suggesting that healthier trees with less leaf disease tended to have larger root collars. A weak but

significant correlation (0.186) between RCD and multiple leaders was also observed. In contrast, volume strongly correlated with tree height, DBH, and RCD, confirming the relationship between overall tree size and volume. Volume also showed moderate correlations with crown health (0.419) and leaf disease (0.288), suggesting that larger trees tend to have healthier crowns and less disease. The correlation between volume and multiple leaders was weak (0.099), indicating a minimal relationship.

The Pearson correlation analysis revealed significant relationships among the growth and qualitative traits of *E. pellita*, with key findings holding important implications for forest management. Strong positive correlations were found among tree height, DBH, RCD, and volume, confirming that these variables are excellent indicators of tree performance and productivity. Specifically, the strong correlations between tree height and volume (0.764), and DBH and volume (0.921), underscore the established role of height and diameter measurements as crucial metrics for estimating wood volume and biomass accumulation (Nunes *et al.* 2017; Sumida *et al.* 2013). This means that foresters can accurately predict a plantation's yield by simply measuring these easily obtainable traits.

Table 4. Correlations Between Each Quantitative Parameter with the Genotypes

Correlations								
		Tree Height	DBH	RCD	Volume	CH	LD	ML
Pearsons Correlation	Tree Height	1.000						
	DBH	0.784**	1.000					
	RCD	0.666**	0.844**	1.000				
	Volume	0.764**	0.921**	0.760**	1.000			
	CH	0.499**	0.522**	0.465**	0.419**	1.000		
	LD	0.485**	0.456**	0.412**	0.288**	0.596**	1.000	
	ML	0.340**	0.208**	0.186**	0.099**	0.287**	0.400**	1.000
Note: ** Correlation is significant at the 0.05 level (2-tailed)								

Qualitative traits also exhibited meaningful correlations with growth. Crown health showed a moderate positive correlation with tree height (0.499), DBH (0.522), and volume (0.419), indicating that healthier crowns were directly associated with more vigorous growth. This suggests that maintaining crown health, perhaps through appropriate spacing or nutrient management, is a viable strategy for enhancing overall plantation productivity. Similarly, leaf disease was moderately correlated with crown health (0.596) and growth traits like height (0.485) and DBH (0.456), demonstrating that plantations with less disease tend to be healthier and more productive. This finding reinforces the importance of selecting disease-resistant clones, which can reduce the need for chemical treatments and promote sustainable forestry.

Lastly, multiple leaders had a moderate correlation with leaf disease (0.400) and a weaker correlation with most growth traits. This suggests that trees with poor stem form may be more susceptible to disease, but that this trait was not a strong predictor of growth performance in this study. From a management perspective, this finding emphasizes that while selecting for good tree form is important for timber quality, it may not be the primary driver of overall volume (Sumida *et al.* 2013). The RCD also correlates positively with volume (0.760) and moderately with crown health (0.465) and leaf disease (0.412), highlighting the significance of root systems in tree health (Pankau 2021). These findings emphasise the interconnectedness of growth traits and their implications for tree management and productivity.

Looking at its weakest growth performance, the hybrid clone $U \times G$ significantly showed the lowest compared to other genotypes. This negative value signifies a decline or shrinkage in volume rather than growth. $U \times G$ is the clear underperformer in annual volume, exhibiting a significant decrease compared to all other genotypes. While the genotypes SSB17040, EP03, and EP11 excelled in volume growth, others such as 21041 and SSB17038 balanced volume and other traits.

Selecting genotypes for *E. pellita* plantations requires careful consideration of desired outcomes, whether maximising total volume or prioritising a balance with different growth characteristics. Several factors can contribute to its declining growth performance. Firstly, the age of this genotype may have reached its physiological maturity, leading to reduced growth and increased susceptibility to stress. This is because during the first month of analysis, many trees of this genotype have shown the initial stage of poor phenotypic characteristics such as leaf wilt and brittle trunks (Silva *et al.* 2020). This suggests that this genotype may have matured after two years of planting. There could be inherent genetic factors within the $U \times G$ genotype that make it less resilient to environmental stressors or more prone to disease. Furthermore, environmental stress, such as insufficient water availability, can lead to wilting, leaf drop, and overall growth reduction (McKiernan *et al.* 2017).

Additionally, the management of this plantation did not provide additional watering apart from rainfall, no fertilisation, and pest control, which is likely to cause a decline in the growth performance (Nasholm *et al.* 2014). To understand the causes of $U \times G$'s decline, additional analysis and actions are needed, such as assessing soil nutrient content, pH, and structure, which can provide insights into potential nutrient deficiencies or imbalances. Analysing leaf and stem samples also can help identify nutrient deficiencies or the presence of toxic elements. Thorough inspection for pests, diseases, or pathogens should also be conducted to determine if they contribute to its decline in growth (Römheld 2012).

Then, analysing more detailed growth measurements of $U \times G$, including leaf area, biomass accumulation, and root development, can also help quantify the extent of growth reduction and identify specific growth stages affected. Additionally, implementing different management practices like irrigation, fertilisation, and pest control on a small scale can assess their impact on $U \times G$'s health and growth (Nasholm *et al.* 2014).

Future research on the exceptional performance of clones EP03 and EP11 should focus on several key areas to optimize *E. pellita* plantations. First, genetic studies are needed to identify the specific genetic markers responsible for their superior growth rates, which can then be used in targeted breeding programs. Second, it is crucial to investigate their environmental adaptability by assessing their response to different soil types and climate variations, which will help determine their suitability for diverse planting regions. Third, long-term monitoring of these clones is necessary to understand their performance across different growth stages and to evaluate their overall sustainability. Finally, a thorough assessment of their ecological impact is essential to ensure that introducing these high-performing genotypes does not negatively affect local biodiversity. By pursuing these lines of research, the wood industry can refine its tree planting strategies, leading to increased wood production and more sustainable forest management practices.

CONCLUSIONS

1. The findings demonstrated that genotypes EP03 and EP11 exhibited superior growth compared to other *E. pellita* genotypes. Quantitatively, they achieved higher height, DBH, RCD, and volume. Qualitatively, they displayed better crown health, fewer multiple leaders, and lower incidence of leaf disease. Importantly, these results are specific to the local growth conditions of Puchong, Selangor (rainfall ~3200 mm/year, 25 to 33 °C, Bungor soil type). While wood characteristics were not directly measured, previous studies indicate that *E. pellita* possesses favorable mechanical properties; future work will confirm this in these genotypes. Overall, EP03 and EP11, particularly as *in vitro* regenerated clones, hold strong potential for timber production. These results provide practical guidance for plantation managers in selecting high-yielding, disease-tolerant genotypes for sustainable forestry applications.
2. The findings suggest that specific *E. pellita* genotypes, particularly EP03 and EP11, derived from *in vitro* cultivation, exhibit genetic traits that significantly enhance growth performance and field adaptability when compared to genotypes propagated from seedlings (SSB17038, SSB17040, and SSB18001). This highlights the potential of EP03 and EP11 as highly valuable candidates for timber production due to their superior growth rates. While wood characteristics were not assessed in this study, future research should investigate their wood quality attributes to further substantiate their industrial suitability. The *in vitro* technique provides a decisive advantage in replicating and proliferating these superior genotypes, offering a promising approach for forestry applications that maximise growth and productivity.

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