Transactions on Science and Technology Vol. 11, No. 4, 214 - 227, 2024

Resin profile of gaharu stands in research plantation sites using the Aggregated Assessment Index (IV)

Richard Joseph Majapun#, Chen Thau En, Ian Brandon John, Mohd Jumri Abd. Hamid, Pang Kat Nyen Kelvin
Forest Research Centre, Sabah Forestry Department, P.O. Box 1407, Sandakan 90715, Sabah, MALAYSIA.
Corresponding author. E-Mail: richard.majapun@gmail.com; Tel.: +6089-531-522; Fax.: +6089-531-068.

ABSTRACT This study evaluated resin formation in *Aquilaria malaccensis* Lamk. and *Aquilaria beccariana* Tiegh. plantations in Sabah, Malaysia. Non-destructive methods based on colour and fragrance assessments using the Aggregated Assessment Index (IV) were applied to examine the effects of inoculation segmentation, location, diameter at breast height (DBH), and stand age on resin profiling. A total of 70 trees, aged 7 to 29 years, were assessed across multiple research plantation sites within the Forest Reserves (FR.), with resin inducement carried out by drilling segmented holes and applying locally sourced inoculum. Results after six months showed that inoculation segmentation had minimal impact on resin formation, with slightly higher resin formation found in the middle section for *Aquilaria beccariana* compared to *Aquilaria malaccensis*, though differences were not statistically significant. Resin formation varied by location, with older trees at Segaliud Lokan FR. and Sook FR. producing slightly more resin index than younger trees at Mile 9 and Gum-Gum FR. However, the Kruskal-Wallis H test confirmed that the IV index across locations were not statistically significantly in resin formation. Stand age showed a slightly stronger correlation with resin formation ($r_s = 0.24$, $p = 0.043$) than DBH ($r_s = 0.17$, $p = 0.166$), though both were weak predictors. These findings suggest that resin formation is generally associated by multiple factors beyond tree size and age, including environmental conditions, genetics, and management practices. Despite the limitation of the IV method, it provides a useful baseline for resource-limited settings, with the potential for refinement through detailed grading with modern methods at later stages.

KEYWORDS: *Aquilaria malaccensis*; *Aquilaria beccariana;* aggregated assessment Index; non-destructive; resin profiling.
Received 29 November 2024 **Revised** 20 December 2024 **Accepted** 23 December 2024 **In press** 26 December 2024 **Online** 27 December 2024

Original Article

INTRODUCTION

In Sabah, *Aquilaria malaccensis* Lamk. and *Aquilaria beccariana* Tiegh., are both from the family Thymelaeaceae, are commonly found in lowland montane forests up to 1,700 meters above sea level. These trees can grow up to 40 meters tall and reach diameters of 60 cm. *A. beccariana* thrives in well-drained soils with consistent rainfall, contributing significantly to forest biodiversity. Meanwhile, *A. malaccensis* grows upright and often develops fluted trunks or buttresses up to 10 cm wide and 2 meters high. It occurs in both primary and secondary forests, from plains to hillsides and ridges at altitudes up to 750 meters. In Malaysia, *A. malaccensis* is the primary agarwood-producing species. Natural *Aquilaria* trees can take 20 to 50 years to produce high-quality resin (Turjaman *et al*., 2016; Lim *et al*., 2007; Chakrabarty *et al*., 1994), and only 10% of wild trees develop resin, typically confined to isolated parts of the tree (Persoon, 2007; Gibson, 1977). It is estimated that the aromatic oil from gaharu fetching prices between USD 126 and USD 633 per tola (12 millilitres) (Hashim *et al*., 2016; Nor Azah *et al*., 2008). However, debates persist about the quality of artificially induced agarwood compared to natural resin. While some experts argue that natural agarwood produces a more refined aroma, others believe that well-managed inoculation techniques can yield resin of similar quality in shorter time (Herath *et al*., 2023; Huang *et al*., 2023; Jong *et al*., 2016).

Conservation efforts have helped increase the popularity of gaharu plantations as an investment in Sabah. Campaigns promoting artificial resin induction methods have sparked further interest.

However, the industry still faces challenges with resin quality, production, and harvesting. Traditionally, assessing resin formation requires destructive methods, forcing growers to fell inoculated trees. Unfortunately, many treated trees fail to produce enough resin, resulting in wasted resources and financial losses (Putri *et al.*, 2017). Gaharu harvesting continues to be largely trial-and-error, with growers testing different inoculation techniques and extraction methods to assess resin quality. The high costs of maintaining agarwood plantations, coupled with unpredictable results, add financial risks. Factors such as environmental conditions, inoculation methods, and biotic and abiotic influences all affect resin production, making it difficult to achieve consistent outcomes (Ramli *et al.*, 2022; Turjaman *et al.*, 2016). These ongoing challenges hinder the industry's ability to meet the growing demand for gaharu-based products.

The Forest Research Centre (FRC) of the Sabah Forestry Department (SFD) initiated a project to study resin formation through inoculation trials, using the Aggregated Assessment Index IV to link color grading with olfactory analysis. Most of the trees involved were planted in the 1990s and early 2000s as part of previous FRC plantation efforts. The goal of the project is to develop quicker and more cost-effective assessment methods, while providing baseline data on how resin formation varies with site conditions, stand age, and species type. These findings will help support the growth of sustainable gaharu production in Sabah's plantation sector.

AGARWOOD GRADING SYSTEM

Malaysia's agarwood industry uses the 'ABC' grading system, where the quality of agarwood is determined by the darkness of its resin (Azah *et al.*, 2013; Mazlan & Dahlan, 2010; Lim *et al.*, 2007). In addition, the Forest Department of Peninsular Malaysia (FDPM) has introduced its own grading system, which focuses on the color of the agarwood resin and its intended end use (JPSM, 2015). This grading framework, outlined in Table 1, offers a detailed breakdown of the various grades used in the Malaysian agarwood industry.

Table 1. Agarwood grading system by FDPM

Grade	Resin color	Potential used
Super A	All colors with attractive shape	Decoration or esthetical value
A	Black or shiny black	Aromatherapy or burnt for fragrance
B	Brown or dark brown	Aromatherapy or burnt for fragrance
C	Whitish or yellowish	Essential oil.

This study used the FDPM grading system to assess resin formation, applying non-destructive methods to evaluate the resin's colour and fragrance. The Aggregated Assessment Index IV was employed to analyse standing *Aquilaria* trees in research plantations across Sabah. The goal was to gain insights into resin formation six months after inoculation without the need to fell the trees. The following research questions guided the study:

a) How does inoculation segmentation associated with resin formation in trees?
b) What is the impact of locality on variations in resin formation?
c) How do DBH (diameter at breast height) and stand age associated with resin formation?

METHODOLOGY

Study Site

Between March and May 2017, we initiated the resin inducement process on 70 gaharu trees, focusing on two species: *A. malaccensis* and *A. beccariana*. The inducement of *A. malaccensis* was conducted across five research plantation plots of gaharu; four in the Sandakan district and one in the

Sook district of Keningau (Figure 1). Additionally, a collaborative experiment took place at a private smallholder's site in Mile 9, Sandakan. For *A. beccariana*, the resin inducement activities were carried out at two research sites in the Sandakan district, specifically the Gum-Gum Forest Reserves (FR.) and Kolapis FR. The selected trees, aged between 7 and 29 years, were measured for their diameter at breast height (DBH), as illustrated in Table 2.

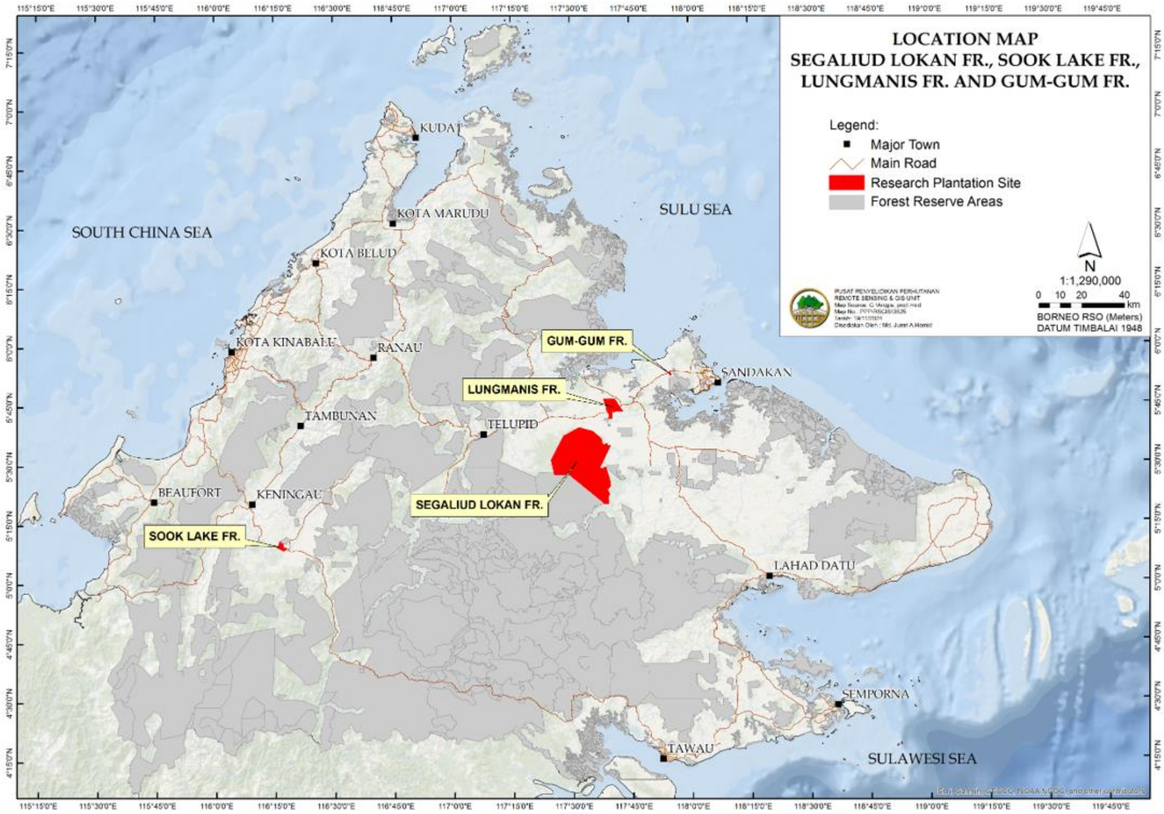

Figure 1. Location map of research plantation site in Sabah.

Table 2. Profile of Agarwood research plantation in Sabah.

District	Sandakan				Keningau
Plantation Research Sites	Segaliud-Lokan FR.	Gum Gum FR.	Kolapis FR.	*Mile 9	Sook FR.
Year planted	1988a	2008ab	2008ab	2010a	2000a
Number of trees, a + b	210	98	300	>1000	200a
Spacing (m x m)	4 x 4	3 x 4ab	4 x 4ab	3 x 3	3 x 4a
Ha / plot, a + b	0.18	0.11	0.48	Na	0.24a
Survival, (%)	Na	77.6a / 93.9b	68.7a / 42b	Na	84a
Mean Ht, (m)	Na	9.2a / 8.19b	5.98a / 7.29b	Na	11.74a
Mean DBH, (cm)	37.43a	11.66a / 13b	6.25a / 1.3b	Na	19.1a
MAI DBH, (cm/year)	Na	1.67a / 1.86b	0.89a / 0.19b	Na	1.47a
Reference	Unpublished	SFD, 2015, p. 433		Na	Pang *et al*., 2016
Soil Association of Sabah	Lokan	Silabukan	Kretam	Rumidi	Brantian
Soil description	Sandstone, Mudstone	Mudstone, Alluvium	Mudstone, Sandstone, MR	Mudstone, Sandstone, MR	Alluvium
Altitude, m a.s.l.	60	35	50	10	360
Mean Annual Rainfall (mm)	228	329	228	329	
Relative Humidity, (%)	80.0 - 86.3				63.2 - 74.8

Note. * Private land, MR = Miscellaneous rock, a = *Aquilaria malaccensis*, b = *Aquilaria beccarina*, SFD = Sabah Forestry Department, Na = Not available. Mean annual rainfall and RH were recorded to the nearest weather station setup by the departmental

Stand Density

The gaharu research plantations are situated at Segaliud-Lokan FR, Kolapis FR, and Gum Gum FR in the Sandakan district, as well as Sook FR in Sook, Keningau (Table 2). Segaliud-Lokan FR, the oldest stand at 29 years, recorded the highest mean DBH (37.43 ± 6.76 cm) during the inducement process, with fewer than 20 trees remaining in the stand. In comparison, the 9-year-old gaharu plantations at Kolapis FR. and Gum Gum FR., which together consist of approximately 400 trees, feature both *A. malaccensis* and *A. beccariana*. For *A. malaccensis*, these stands exhibited mean heights ranging from 6 m to 9.2 m, DBH values between 6.25 cm and 11.6 cm, survival rates of 69% to 78%, and Mean Annual Increment (MAI) values for DBH ranging from 0.89 cm/year to 1.67 cm/year (Sabah Forestry Department, 2015). In contrast, *A. beccariana* demonstrated mean heights of 7.29 m to 9.69 m, DBH values ranging from 1.3 cm to 13 cm, survival rates between 42% and 94%, and MAI values for DBH from 0.19 cm/year to 1.86 cm/year (Sabah Forestry Department, 2015).

The 15-year-old gaharu plantation at Sook FR. includes around 200 *A. malaccensis* trees, which have an average height of 11.7 meters and a DBH of 19.1 cm. The plantation has a survival rate of 84%, and the mean annual increment (MAI) for DBH is 1.47 cm per year (Pang *et al.*, 2016). These results demonstrate how different site conditions can affect growth. For example, *A. beccariana* at Kolapis FR. showed slower growth than the same species at Gum Gum FR.

Inducement process

The resin inducement process followed the method developed by Blanchette and Van Beek (2005), designed to stimulate gaharu resin production for agarwood plantations (Figure 2). Ten holes were drilled into each tree, segmented into three regions—lower, middle, and upper—starting 10 cm above the ground, with each hole spaced 10 cm apart in a spiral pattern. The depth of the holes varied based on the tree's DBH, ranging from 7.5 cm to 12 cm. Plastic PVC tubes (10–12 cm in length and 2.5 cm in diameter) were inserted into the drilled holes, and each tube was filled with 20 ml of locally sourced inoculum using a syringe. To ensure sterility and prevent contamination, the tubes were securely capped after filling.

A B **C**

D E **F**

Figure 2. A - Drilling setup for PVC tube. B - Installation of PVC tube. C - 20 mL of inoculum was injected into the PVC tube using a syringe. D - Capped tube after inoculation. E - Increment borer used to extract core samples, F. Core sample underwent assessments (color and olfactory analysis).

Environmental Conditions

Table 1 provides insights into the soil association in Sandakan which is mainly formed by mudstone and sandstone, namely Silabukan, Rumidi, Kretam, and Lokan, with an altitude ranging from 10 m to 60 m. The mean annual rainfall is between 2500 mm and 2999 mm, with a percentage relative humidity of 80.0% to 86.3%. In Sook, Keningau, the soil association is Brantian which is solely formed by alluvium. The mean annual rainfall ranges from 1000 mm to 1499 mm, with a percentage relative humidity of 63.2% to 74.8% and the altitude is about 360 m.

Data Collection

Six months after inoculation, between September and November 2017, an in-depth assessment of resin formation was conducted on the 70 treated gaharu trees. A specialized increment borer (300 mm in length, 5.15 mm in diameter) was used to extract three core samples from each tree, taken from the lower (between hole 1 & hole 2) middle (between hole 5 & hole 6) and top (between hole 9 & hole 10) sections. These samples underwent two key assessments; color grading and olfactory analysis and evaluated through the LMT Index (low, mid, and top sections). This is also referred to Aggregated Assessment Index IV (Table 3).

Table 3. Aggregated Assessment Index IV Calculation

Color / index	Smell / index	IV	Resin profile
Pale / 0	No / 0	0	No resin
Brown / 1	Slight / 1	1	Slight resin
Dark / 2	Slight / 1	2	Moderate resin
Dark / 2	Distinct / 2	3	Good resin
No match		0	No resin

The index, adapted from the FDPM agarwood grading system, assigned values based on resin color and fragrance intensity: 0 for pale resin with no smell, 1 for brown resin with a slight smell, 2 for dark resin with a slight smell, and 3 for dark resin with a distinct smell (Table 4).

Table 4. Grading assessment index

Detection Method	Description	Index
Color Grading Analysis	Samples were categorized based on observed colors, ranging from darker to lighter hues.	
	i. Pale	0
	ii. Brown	1
	iii. Dark	2
Olfactory Assessment Analysis (Smell)	Samples were classified into olfactory profiles, providing insights into the aromatic characteristics of the induced agarwood resin	
	i. No	0
	ii. Slight	1
	iii. Distinct	2

Color grading involved visually inspecting the resin to assess its maturity and quality, performed consistently by the same personnel to minimize bias. Darker hues indicated more mature, potentially higher-quality resin, while lighter colors suggested lesser maturity. For olfactory assessment, samples were burned to release their fragrance, allowing a qualitative evaluation of the resin's aromatic properties. The intensity and distinctiveness of the aroma served as key indicators of resin quality, with stronger, more distinct fragrances signifying higher value.

Statistical Analysis

The agarwood resin formation data was analyzed using MS Excel (MS Office Professional Plus 2019) to summarize the color and olfactory assessments. The normality of the dataset was evaluated using the Shapiro-Wilk test in PAST 3.22 software (Hammer *et al*., 2001) to determine whether the data followed a normal distribution. Additional statistical analyses were performed using the DATAtab Statistics Calculator (DATAtab e.U., Graz, Austria). Descriptive statistics were calculated, followed by the Friedman test to assess differences in resin formation across tree segments (low, mid, top) for *A. beccariana* and *A. malaccensis*. The Mann-Whitney U test was employed to compare resin production between the two species across the same indices. A comparative analysis was also conducted to examine variability in resin formation across different locations. Lastly, Spearman's rank correlation was used to explore the relationships between tree DBH, stand age, and resin production. All charts were generated by free online graph maker, at https://piktochart.com/graph-maker/.

RESULT AND DISCUSSION

Resin formation by tree segment

Resin formation in *A. beccariana* was minimal across all tree sections (Table 5). The Low Index, and the Top Index similarly indicated no resin presence. However, the Mid Index exhibited a slight resin presence in a few cases, with a value of 0.15 ± 0.37. The overall LMT Index was 0.05 ± 0.12, indicating minimal resin production across tree sections. The Friedman test revealed a borderline significant difference in resin formation across segments ($\chi2$ =6.00, p = 0.050), suggesting that resin production varies, with the middle section showing slightly higher resin formation than the lower and upper sections. In contrast, *A. malaccensis* exhibited slightly more resin formation, though still limited. The Low Index remained low (0.02 ± 0.14), and the Mid Index indicated minimal resin formation (0.04 ± 0.28). However, the Top Index showed slightly higher values, with some trees reaching up to 0.14 ±

0.45, indicating moderate resin formation in a few cases. The overall LMT Index for *A. malaccensis* was 0.07 ± 0.19, indicating more variability in resin formation compared to *A. beccariana*, particularly in the top sections of the tree. The Friedman test indicated no statistically significant difference in resin formation across the Low, Mid, and Top segments ($\chi 2 = 5.33$, $p = 0.069$).

The Shapiro-Wilk test showed deviations from normality for *A. malaccensis* in Low_Index (W = 0.125, $p < 0.001$) and Top_Index (W = 0.346, $p < 0.001$). For Mid_Index and LMT_Index, both species violated normality (p < 0.001), while *A. beccariana* had zero variance in Low_Index and Top_Index (W = 1.000, $p = 1.000$). Hence, Mann-Whitney U test was applied to these indices since it does not rely on assumptions of normality. The Mann-Whitney U test revealed significant differences in resin formation for Mid_Index (U = 563.5, $p = 0.042$), where *A. beccariana* (0.15 ± 0.37) had higher resin formation than *A. malaccensis* (0.04 ± 0.28). For Low_Index (U = 490.0, $p = 0.548$), Top_Index (U = 450.0, $p = 0.149$), and LMT_Index (U = 509.0, $p = 0.849$), no significant differences were observed between the species. The IV Index described that both species exhibit none to slight resin profiles. These findings suggest that *A. malaccensis* demonstrates consistent resin formation across all tree sections, whereas *A. beccariana* shows marginally significant variation, particularly in the middle section. The middle section may provide a more favourable environment for resin production in *A. beccariana*, while resin formation in *A. malaccensis* appears uniformly distributed throughout the tree.

Table 5. Resin formation indices (Low, Mid, Top, LMT and IV) between *A. beccariana* and *A. malaccensis*

Index/Species	**Normality Test**		**Post-hoc Test**	
	A. beccariana	*A. malaccensis*	*A. beccariana*	*A. malaccensis*
Low_Index	W = 1.000, p = 1.000	W = 0.125, p = 0.000	0.0 ± 0.0^{a}	0.02 ± 0.14^{b}
Mid_Index	W = 0.433, p = 0.000	W = 0.125, p = 0.000	0.15 ± 0.37^{a}	0.04 ± 0.28^{b}
Top_Index	W = 1.000, p = 1.000	W = 0.346, p = 0.000	0.0 ± 0.0^{a}	0.14 ± 0.45^{b}
LMT_Index	W = 0.433, p = 0.000	W = 0.382, p = 0.000	0.05 ± 0.12^{a}	0.07 ± 0.19^{b}
IV Index (Resin profile)			0.06 ± 0.17 (No resin to slight resin)	

Note: W = Shapiro-Wilk test; Values are presented as mean ± standard deviation. Different superscripts (a, b) within each row indicate significant differences between species at p < 0.05 as determined by the Mann-Whitney U test.

Pooled Indices for Both Species to Determine Resin Profile of Tree Segmentation

The pooled indices were analysed to determine the resin profile of tree segmentation. The Top_Index had the highest average (0.100 ± 0.386), followed by the Mid_Index (0.071 ± 0.310) and the Low_Index (0.014 ± 0.120). This suggests that the top section of the tree may have greater resin formation compared to the middle and lower sections. The Shapiro-Wilk normality test indicated that none of the indices were normally distributed with Low_Index (W = 0.10, $p < 0.001$), Mid_Index (W = 0.24, $p < 0.001$), and Top_Index (W = 0.28, $p < 0.001$). A non-parametric statistical using Friedman test revealed that no significant differences between the three indices (X^2 (2) = 2.89; $p = 0.236$). The lack of significant variation across the indices may be due to the interpretation by using aggregated index of non-destructive method used to assess resin production, which relies on predictors such as color and smell. This method does not capture real-time resin formation or accurately measure resin density for each segment.

Resin Formation Across Different Locations

The assessment of *A. malaccensis* (Table 6) reveals resin profiles IV differ across the sites: both Sook FR. (0.13 ± 0.23) with a stand age of 17 years and Segaliud Lokan FR. (0.13 ± 0.28) exhibit the highest mean resin levels, while Kolapis A FR. (0.05 ± 0.16) with a stand age of 9 years shows a slightly lower value. Gum-Gum (0.03 ± 0.1) and Mile 9 (0) recorded very low or no resin formation, with both sites having younger stand ages of 9 and 7 years, respectively. For *A. beccariana*, both study locations (Gum-Gum FR. and Kolapis A FR.) have resin formation that remains consistently low across both sites, with Gum-Gum having an IV of 0.03 ± 0.1 and Kolapis A FR. showing a marginally higher IV at 0.05 ± 0.16 (Table 6).

The Kruskal-Wallis H test confirmed that differences in the IV Index across locations were not statistically significant for either species (*A. beccariana*: H(2) = 0.37, $p = 0.542$; *A. malaccensis*: H(2) = 6.01, $p = 0.198$). However, the observed variations in resin production indicate that factors beyond location, such as stand age and management practices, play a critical role. Older trees, like those in Segaliud Lokan FR. and Sook FR., demonstrated higher resin production, while younger trees in Gum-Gum FR. and Mile 9 showed minimal to no resin formation. These findings highlight the importance of environmental conditions and management practices in promoting resin production. Factors such as inoculation methods, stand age and soil conditions likely play a crucial role in influencing resin yields in different plantation settings.

Table 6. Resin Profiles Across Locations for *A. malaccensis* and *A. beccariana*

Site (Year planted)	Stand age (year)	DBH, cm				Resin profile	
		Freq.	Min	Max	Mean ± Std.	NR_tree	IV
A. malaccensis							
Kolapis A FR. (2008)	9	10	13.5	17	15.08 ± 0.9	1	0.05 ± 0.16
Segaliud Lokan FR. (1988)	29	10	25.8	47.5	37.43 ± 6.76	2	0.13 ± 0.28
Sook FR. (2000)	17	10	16.1	17.9	17.29 ± 0.54	3	0.13 ± 0.23
Gum-Gum FR. (2008)	9	10	14.1	15.6	15 ± 0.44	0	0.03 ± 0.1
Mile 9 (2010)	7	10	14.4	15.9	14.97 ± 0.48	0	0
mean	14.2	10	16.78	22.78	19.954		0.068
Std	8.16	0	4.59	12.38	8.78		0.05
A. beccariana							
Gum-Gum FR. (2008)	9	10	14.2	15.9	14.92 ± 0.63	2	0.03 ± 0.1
Kolapis A FR. (2008)	9	10	13.5	16.4	14.7 ± 0.85	1	0.05 ± 0.16
mean	9	10	13.85	16.15	14.81		0.04
Std	0	0	0.35	0.25	0.11		0.01

Note. DBH = Diameter at breast height, Freq. = number of treated trees, Min = Minimum, Max = Maximum, (±, Std = Standard deviation), NR_tree = Number of resin-producing trees, IV = Mean Resin index described from LMT Index.

Stand Age on Tree Size and Resin Production

The analysis shows that stand age has a significant impact on tree size, with older trees exhibiting larger DBH. A strong positive correlation was found between stand age and DBH ($r = 0.90$, $p < 0.001$; Figure 3), confirming that as trees age, their diameter tends to increase. However, the effect of stand age on resin production is more limited. Although a weak positive correlation was observed ($r = 0.24$, $p = 0.043$; Figure 3), this suggests that while older trees may produce slightly more resin, other factors beyond age likely more correlated with resin formation.

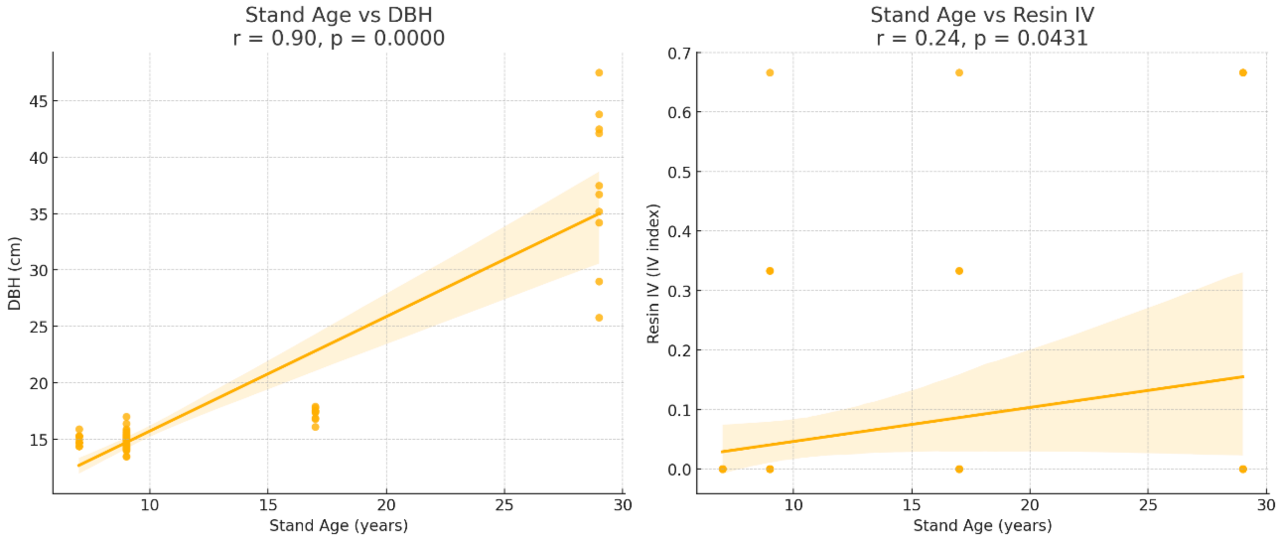

Figure 3. Correlation Between Stand Age and Resin Formation (IV Index) in Aquilaria Species.

DBH on Resin Formation

Resin formation in *Aquilaria* species appears to be associated by tree size, with larger, older trees generally formed more resin. Observations suggest that younger trees with smaller DBHs (14–15 cm), such as those at Mile 9 and Gum-Gum FR., show little to no resin formation. Trees with moderate DBHs (15–17 cm), like those at Kolapis A FR. and Sook FR., exhibit some resin production, although at low levels. In contrast, larger trees with DBHs above 30 cm, such as those in Segaliud Lokan FR., demonstrate higher resin formation. However, statistical analysis using Spearman's rank correlation indicates a weak positive relationship between DBH and resin formation (rs = 0.17, *p* = 0.166; Figure 4). This weak correlation suggests that while there is an observed trend linking larger trees with increased resin production, DBH alone is not a statistically significant predictor of resin yield. Other factors, such as genetic variation, environmental conditions, and stress responses, likely have a more significant correlation. Therefore, DBH should not be considered in isolation when assessing the potential for resin formation in *Aquilaria* species.

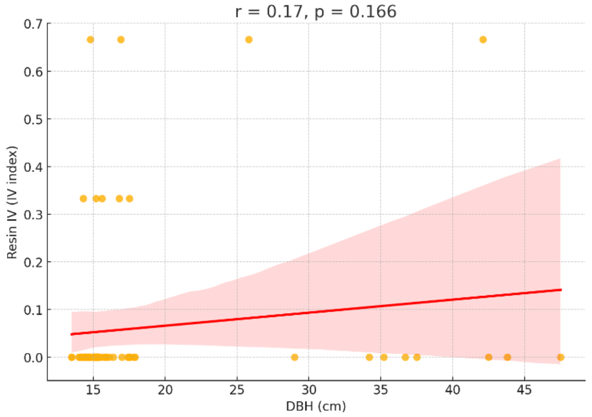

Figure 4. Relationship Between DBH and Resin Formation (IV Index) in *Aquilaria* Species.

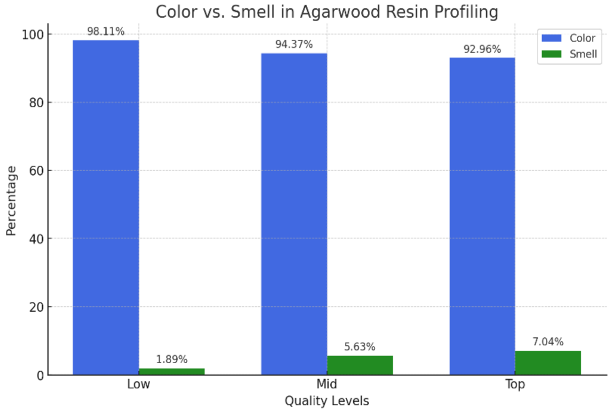

Figure 5. Color versus smell in gaharu resin profiling.

Stand Age versus DBH in Determining Resin Production

Both stand age and DBH showed weak positive correlations with resin production. Stand age had a slightly stronger and statistically significant correlation (rs = 0.24, *p* = 0.043; Figure 3), while DBH had a weaker, non-significant correlation (rs = 0.17, *p* = 0.166; Figure 4). These results suggest that older trees are somewhat more likely to produce resin, but neither stand age nor DBH alone is a strong predictor of resin yield. Although both factors are linked to resin production, their effects differ. Stand age showed a stronger relationship with resin yield, suggesting it may be a better predictor. However, not all trees of the same age have the same DBH due to differences in genetics, environmental conditions, and resource availability, such as sunlight and nutrients. Additionally, factors such as soil fertility, water availability, and silviculture management could positively impact the rate of tree growth in diameter. Trees in optimal conditions tend to develop larger DBHs at a younger age, whereas those in suboptimal environments may exhibit slower growth, taking longer to reach the same size.

ISSUES AND RECOMMENDATIONS

This study uses the simple Aggregate Assessment Index (IV), a conservative method that combines indicators to assess standing agarwood trees based on observable traits like colour and smell. This approach provides an efficient, cost-effective, and straightforward tool that fieldworkers, smallholders, and companies can easily adopt to evaluate gaharu plantation trees without the need to fell them for further inspection. Hence, it enables multiple tests of commercial or new inoculants on individual trees, providing a practical way to gauge initial results. Furthermore, the method can be standardized across different sites, allowing for consistent comparisons between plantation locations.

Despite these advantages, the IV method lacks the depth needed for detailed chemical analysis and resin quality assessment. Advanced techniques like gas chromatography-mass spectrometry (GC-MS), sonic tomography, Fourier-transform infrared spectroscopy (FTIR), and liquid chromatography-mass spectrometry (LC-MS) are essential for obtaining precise data on chemical composition and resin quality, which the IV method cannot achieve. For example, gas chromatography-mass spectrometry (GC-MS) is instrumental in identifying volatile and semi-volatile compounds in agarwood, aiding in more accurate quality grading (Li *et al.*, 2024; Kao *et al.*, 2018; Lee *et al.*, 2016; Jong *et al.*, 2014). Sonic tomography provides a non-destructive method to evaluate the internal structure of trees, offering insights beyond surface-level indicators (Jalil *et al.*, 2022). Fourier-transform infrared spectroscopy (FTIR) enables the chemical fingerprinting of agarwood species and ages, facilitating precise species identification and quality assessment (Yao *et al.*, 2022; Adi *et al.*, 2020). Liquid chromatography-mass spectrometry (LC-MS) allows for detailed profiling of sesquiterpenes, which are essential for determining resin quality and market value (Tran & Hoang, 2021; Hashim *et al.*, 2016).

Inconsistencies in applying the IV method may arise due to differences in individuals' sensory perceptions. For example, if different people are responsible for assessing factors like smell, it can affect the accuracy of the evaluations. To minimize this, the assessment should be assigned to a single person, as was done in this study, to reduce variability. Despite this limitation, the IV method remains valuable, particularly in resource-limited settings where advanced techniques are not accessible. It serves as a useful baseline for initial evaluations, with the potential for more detailed and thorough grading through modern methods to be applied in later stages.

Color vs. Smell: The Final Determinant in Agarwood Resin Profiling

The analysis reveals a notable disparity between the contributions of color and smell in resin profiling across different quality levels: Low, Mid, and Top (Figure 5). At each level, color consistently dominates the scoring, making up 98.11% at the Low level, 94.37% at the Mid-level, and 92.96% at the Top level. In contrast, smell contributes only 1.89%, 5.63%, and 7.04% at the respective levels. When pooled across all levels, color accounts for 94.87% of the total score, while smell constitutes just 5.13%.

Higher color scores are often associated with prolonged resin accumulation, resulting in a dense, darker appearance traditionally linked to high-quality agarwood (Faizal *et al.*, 2020). However, color alone is an unreliable indicator of resin formation, as advanced wood decay can darken wood without enhancing its aromatic properties. Effective fungal inoculation and sufficient maturation time are essential for substantial resin biosynthesis (Lee *et al.*, 2016). Short inoculation periods or weak fungal doses may result in underdeveloped resin with suboptimal aromatic profiles (Turjaman *et al.*, 2016). Excessive decay, even when resin production is triggered, can degrade aroma and reduce market appeal (Yagami *et al.*, 2013). Therefore, while color is a useful preliminary indicator, it must be complemented by smell testing for accurate resin quality assessment.

Does Optimal Gaharu Growth Correspond to Enhanced Resin Formation?

Tree health, age, and soil nutrients are critical factors in resin production. Healthy, mature gaharu trees, ideally aged 7 to 15 years, respond more favourably to fungal inoculation, whereas unhealthy trees may fail to produce adequate resin (Subasinghe *et al.*, 2019). Optimal growth, supported by nutrient-rich, well-draining soils and favourable climates, generally improves tree health and increases the likelihood of resin formation (Hamdan *et al.*, 2021; Hamzah *et al.*, 2021). However, this study found weak correlations between stand age and resin production (rs = 0.24, $p = 0.043$) and an even weaker, non-significant link with DBH (rs = 0.17, $p = 0.166$). While older trees are more likely to produce resin, neither age nor DBH reliably predicts yield. Trees in nutrient-poor soils may have smaller diameters but still produce resin, while larger trees in better soil conditions may not. This finding underscores the limitations of DBH as a consistent indicator of resin potential in this study.

Optimal growth conditions are important for tree health, but they don't directly affect resin formation. Resin production in gaharu trees is more influenced by stress responses than by factors like age, DBH, or nutrient levels alone. This makes it difficult to predict resin yield based only on growth parameters. Instead, it is the combination of environmental factors and stress induced by inoculation that primarily triggers resin biosynthesis (Singh *et al.*, 2017).

Harvesting Gaharu: Timing, Factors, and Environmental Considerations

Apart from timing, environmental conditions are also strong factors in resin formation. Key environmental factors influencing gaharu harvesting include humidity and rainfall. Subasinghe and Hettiarachchi (2013) reported that inoculating trees during rainy seasons or periods of high humidity promotes fungal growth and induces a stronger defence response, resulting in greater resin accumulation. However, harvesting during dry conditions can hinder fungal activity, leading to a decrease in resin production (Herath & Jinendra, 2023). Additionally, harvesting gaharu in warmer temperatures, combined with high humidity, boosts the tree's metabolic processes. This is why harvesting is generally conducted during the rainy season to maximize resin yield (Zhang *et al.*, 2024).

Tree age is considered an important factor in resin production. Older tree stands tend to respond better to fungal inoculation and yield higher amounts of resin compared to younger trees. Conversely, younger or less healthy trees often struggle to produce sufficient resin within the recommended timeframe (Liu *et al.*, 2024; Subasinghe *et al.*, 2019). In terms of management, maintaining tree health through proper cultivation practices, such as pruning and fertilization, enhance tree growth and development. More importantly, these practices increase resin biosynthesis and reduce the time needed for harvesting (Hamdan *et al.*, 2021). Given the variability of environmental factors in the gaharu harvesting process, site-specific monitoring is crucial. It helps identify the optimal harvesting times for each plantation. This ensures consistency and efficiency in resin production (Naziz *et al.*, 2019).

CONCLUSION

Inoculation segmentation had minimal impact on resin formation, with slightly higher formation observed in the middle section for *A. beccariana*, though these differences were not statistically significant. Likewise, locality did not significantly associated with resin formation, although older plantations such as Segaliud Lokan FR. and Sook FR. could produce more resin compared to younger sites like Mile 9 and Gum-Gum FR. Stand age showed a slightly stronger correlation with resin formation than DBH, but both factors demonstrated weak positive relationships, suggesting that neither is a reliable predictor in resin production. These findings highlight that while stand age and environmental conditions play a role in resin formation, achieving optimal results requires refined inoculation techniques and site-specific management practices.

ACKNOWLEDGEMENTS

We sincerely thank the former Deputy Chief Conservator of Forests (R&D), Dr. Lee Ying Fah, and the former Head of the Plantation Programme, Anuar Mohammad, for their guidance and approval of this study. Special thanks were to Maria Ajik (Head of Forest Plantation Programme, FRC), and field staff (Mapuin Rumegap, Mail Garuak and Baraham Buhari) for their pivotal contributions to the fieldwork and data collection at the study sites. We also wish to acknowledge the Chief Conservator of Forests, Datuk Frederick Kugan, and the Deputy Chief Conservator of Forests (R&D), Dr. Arthur Chung, for their unwavering support and encouragement in the successful completion of this study.

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