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Research article

Evaluation of four *Melaleuca* species for wood and non-wood production in Thailand

Eakpong Tanavat[a,*], Kasem Haruthaithanasan[a,†], Tepa Phudphong[a,†], Pussadee Sukpiboon[a,†], Pavina Badan[a,†], Pattama Tongkok[a,†], Khongsak Pinyopusarerk[b,†], John Doran[b,†]

[a] *Kasetsart Agricultural and Agro-industrial Product Improvement Institute, Kasetsart University, Bangkok 10900, Thailand*

[b] *CSIRO Australian Tree Seed Centre, GPO Box 1600, Canberra, ACT 2601, Australia*

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Abstract

Importance of the work: Melaleucas are used for a range of purposes, including land reclamation and wood and non-wood products. Evaluation of species performance to determine its potential for revegetation is important for successful planting on degraded peat swamp forest in Thailand.

Objectives: To assess a range of quantitative and qualitative traits of *Melaleuca* species to determine their potential as revegetation species in southern Thailand.

Materials & Methods: Four *Melaleuca* species (*M. alternifolia*, *M. cajuputi*, *M. leucadendra* and *M. quinquenervia*) were assessed for growth and survival, aboveground biomass, tree form and foliar essential oils on a site affected by seasonal waterlogging in Thailand.

Results: Assessment at 45 mth after field planting revealed considerable variation in all growth parameters among the species and to some extent between provenances within species. None of the species was superior overall, as individual species possessed certain characteristics either superior or inferior to the others. *Melaleuca alternifolia* had the highest mortality and was the least vigorous of the four species; however, it had a high foliar oil concentration and terpinen-4-ol level that was coupled with low 1,8-cineole that qualified it for essential oil markets. Further testing of this species on alternative sites is warranted. *Melaleuca cajuputi* survived and grew well with a reasonable bole length. In addition, its abundant leaf mass and acceptable oil yield and 1,8-cineole level in the *M. cajuputi* provenances tested qualified them for planting for wood and leaf oil production. *M. leucadendra* and *M. quinquenervia* had good growth and survival but their oil yields and concentrations were well below the levels required for economic production of essential oils, making them suitable for wood production only.

Main finding: These four *Melaleuca* species have potential either for wood or foliar essential oil production in Thailand. None of the species was superior overall because individual species possessed certain characteristics either superior or inferior to the others.

† Equal contribution

* Corresponding author
E-mail address: aapept@ku.th (E. Tanavat)n)

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Introduction

The genus *Melaleuca* (Myrtaceae) comprises nearly 300 tree and shrub species distributed naturally in Australia, with a small number of species also found in Papua New Guinea, New Caledonia and some Southeast Asian countries (Doran and Turnbull, 1997; Brophy et al., 2013). Species of this genus are highly adaptable and can tolerate a wide range of site conditions from low to high rainfall and acid to saline soils, as well as being tolerant to seasonal or even continuous waterlogging (Marcar and Crawford, 2004; Carter et al., 2006). One of the species, *M. quinquenervia,* was introduced to Florida, USA as early as 1900 and has now occupied 200,000 ha of wetlands in the southern part of the state (USDA Agricultural Research Service, 2018). The strong adaptability and regenerative capacity of melaleucas suggest caution is required in their deployment as they can become weeds.

Melaleucas are used for a range of purposes, including land reclamation and wood and non-wood products and their ability to coppice vigorously after harvesting or stem damage is advantageous to survival and cropping (Brophy et al., 2013). The wood is heavy, with an air-dry density up to 1,000 kg/m^3 in some species (Doran and Turnbull, 1997). The reported calorific values for melaleuca wood range from 18.4 MJ/kg to 18.8 MJ/kg (Wang et al., 1981; Kasetsart Agricultural and Agri-Industrial Product Improvement Institute, 2014) making many melaleuca species, including the four in the current study very suitable for bioenergy use. The wood of a small number of melaleuca species may be difficult to burn and is very smoky. In addition, several species such as *M. alternifolia* and *M. cajuputi*, are important source material for commercial foliar essential oil production. Through well-planned, systematic evaluation, it is feasible to identify and select *Melaleuca* species suitable for specific purposes.

Recent research in Vietnam has revealed considerable genetic variation in the leaf oil concentration and chemical compounds in *M. alternifolia*, *M. cajuputi* and *M quinquenervia* introduced from Australia; it was concluded that commercial production of essential oils from these species was feasible (Le, 2017). In Thailand, leaf samples of *M. cajuputi* subsp. *cumingiana* growing naturally along the south and east coasts had low oil concentrations with the majority of the samples recording < 1% concentration and only a few samples recording > 1.5% (Haruthaithanasan et al., 2015). Subspecies *cumingiana* is known to have a low oil yield; furthermore, the oils have a chemical composition not viable for commercial production (Brophy et al., 2013).

Thailand has a vast area classified as degraded land, of which approximately 700,000 ha has been set aside under the Agricultural Land Reform Program for fast-growing tree plantations for pulpwood and biomass for bioenergy use (Haruthaithanasan et al., 2014). *Melaleuca* species are recommended for planting on degraded peat swamp forest in the southern region (Haruthaithanasan et al., 2014), where other main species, such as acacias and eucalypts, do not perform well due to waterlogging (Doran and Turnbull, 1997). The current study was conducted on a site representative of the degraded land available for revegetation in southern Thailand. It examined the performance of a limited number of provenances of three broad-leaved species of the *M. leucadendra* complex, namely *M. cajuputi* subsp. *cajuputi*, (hereafter referred to as *M. cajuputi*), *M. leucadendra* and *M. quinquenervia*. These species were selected because they have a propensity to grow to large, single-stemmed trees with timber producing potential. *M. alternifolia*, although shorter-growing and not noted for wood production, was included as it is a renowned source species for high quality leaf oils. These species were subjected to assessment of a range of quantitative and qualitative traits, such as growth and survival, tree form and leaf oil contents, to determine their potential as revegetation species in southern Thailand.

Materials and Methods

Plant material

Two seed lots (provenances) of each of four *Melaleuca* species (*M. alternifolia*, *M. cajuputi*, *M. leucadendra* and *M. quinquenervia*) were obtained from the CSIRO Australian Tree Seed Centre. An additional seed-orchard seed lot of *M. cajuputi* was supplied by the Centre for Forest Biotechnology and Tree Improvement, Indonesia (Table 1). This seed orchard was converted from a first-generation provenance/progeny trial, consisting of 20 families from 11 provenances in which some of the provenances were represented by one or two families only (Susanto et al., 2003). Seedlings were raised as tube stock in a nursery at Kasetsart University in Bangkok, Thailand. When the seedlings were aged 6 mth, they were transported to the trial site.

Table 1 Mean values for growth, aboveground biomass, tree form and leaf oil concentration at age 45 mth of four *Melaleuca* species in trial in Thailand

Species	CSIRO seed lot No.	Provenance	Survival (%)	Height (m)	DBH (cm)	Aboveground biomass per tree (kg)				AP (1-6)	BD (1-3)	CR	Leaf oil (%)
						Stem	Branch + twig	Leaf	Total				
M. alternifolia	18234	Devils Pulpit, NSW	62.7±23.4	4.51±0.70	6.08±1.56	9.28±3.91	4.54±2.08	2.74±1.07	16.61±7.10	2.50±0.69	1.14±0.31	0.52±0.11	3.12±0.22
	20093	Candole, NSW	66.7±12.2	3.99±0.49	5.48±1.14	6.08±2.61	2.82±1.39	1.86±0.72	10.73±4.73	2.41±0.70	1.01±0.25	0.48±0.11	3.18±0.07
	Species mean		$64.7±16.9^{b}$	$4.25±0.63^{d}$	$5.78±1.32^{c}$	$7.68±3.45^{c}$	$3.68±1.84^{c}$	$2.30±0.95^{b}$	$13.67±6.27^{b}$	$2.45±0.70^{b}$	$1.08±0.28^{b}$	$0.50±0.11^{a}$	$3.15±0.15^{a}$
M. cajuputi	19572	Wangi Station, NT	90.7±2.31	7.63±0.90	10.06±2.74	21.56±8.29	11.82±5.62	6.60±2.41	40.36±16.00	2.89±1.13	2.07±0.53	0.67±0.07	1.15±0.14
	19580	Berry Springs, NT	97.3±2.31	8.03±0.82	10.15±2.09	21.76±7.05	12.34±4.48	6.66±2.05	40.76±13.60	2.33±0.78	2.13±0.41	0.66±0.08	1.76±0.15
	–	SSO Paliyan, Indonesia	98.7±2.31	7.17±1.12	10.93±2.67	22.20±9.69	12.07±6.16	6.54±2.82	39.93±18.70	2.34±0.87	1.77±0.56	0.65±0.08	1.22±0.91
	Species mean		$98.0±4.22^{a}$	$7.60±0.97^{b}$	$10.54±2.44^{b}$	$21.98±8.39^{b}$	$12.21±5.45^{a}$	$6.60±2.44^{a}$	$40.35±16.20^{b}$	$2.34±0.96^{b}$	$1.95±0.53^{a}$	$0.66±0.07^{b}$	$1.49±0.32^{b}$
M. leucadendra	13532	Iron Range, Qld	100.0	8.78±5.66	10.89±5.40	29.29±9.01	9.00±2.37	5.13±1.02	43.42±12.40	2.81±0.98	2.27±0.48	0.68±0.08	0.59±0.59
	20673	Bensbach, PNG	100.0	10.12±7.50	12.36±7.60	38.62±11.00	11.46±2.90	6.18±1.24	56.25±15.20	3.25±1.21	2.33±0.50	0.68±0.08	0.53±0.38
	Species mean		100.00^{a}	$9.45±1.12^{a}$	$11.63±2.37^{a}$	$33.96±11.1^{a}$	$10.23±2.91^{a}$	$5.65±1.25^{a}$	$49.84±15.20^{a}$	$3.03±1.12^{a}$	$2.30±0.49^{a}$	$0.68±0.08^{b}$	$0.56±0.09^{d}$
M. quinquenervia	15869	Rokeby, Qld	82.7±4.62	6.29±4.18	7.98±4.10	13.83±6.19	5.81±2.71	4.48±1.34	23.92±10.40	2.72±0.91	1.81±0.60	0.65±0.08	1.01±0.93
	17517	Bribie Island, Qld	97.3±2.31	7.33±5.62	9.31±5.30	19.01±9.60	7.96±4.28	5.14±1.65	32.63±16.10	2.94±1.04	2.03±0.53	0.66±0.07	0.86±0.50
	Species mean		$90.0±8.67^{a}$	$6.81±1.02^{c}$	$8.65±2.37^{b}$	$16.42±8.68^{b}$	$6.89±3.84^{b}$	$4.81±1.56^{a}$	$28.28±14.60^{a}$	$2.83±0.98^{a}$	$1.92±0.57^{a}$	$0.66±0.07^{b}$	$0.93±0.22^{c}$
	p value (species)		< 0.001	< 0.001	< 0.001	<0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
	p value (provenance)		NS	< 0.001	0.024	<0.001	0.011	0.008	< 0.001	0.023	NS	NS	< 0.001
	s.e.d. (provenance)		–	0.23	0.55	1.65	0.81	0.32	2.46	0.19	–	–	0.20

DBH = diameter at breast height (1.3 m above ground); NS = not significantly ($p < 0.05$) different between provenances;

NSW = New South Wales; NT = Northern Territory; Qld = Queensland; PNG = Papua New Guinea. All seed lots were from Australia except *M. cajuputi* from Indonesia and *M. leucadendra* from Papua New Guinea

Mean values (± SD) of a species in the same column superscripted with different lowercase letters are significantly ($p < 0.05$) different.

Experimental site

The trial site belongs to Lad Krating Plantation Station of the Forest Industry Organization (13° 51' N, 101° 53' E, altitude 45 m above mean sea level). Data from Thai Meteorological Department (Climatological Center, 2020) showed that the mean annual temperature is 28 °C (22.8–33.0 °C) and the mean annual rainfall is 1,300 mm, with three months of dry season. The soil is a loam to sandy clay loam and acidic (pH 4.2). The experimental area was subject to seasonal waterlogging for several months each year during the rainy season. The site was disc ploughed twice in perpendicular directions prior to field planting.

Experimental design and layout

The trial was laid out in a randomized complete block design with 3 replicates and 25 trees per plot. Spacing was 2 m × 3 m. One guard row of mixed *M. cajuputi* was planted surrounding the trial.

Data collection

Growth and aboveground biomass

The height (H, measure in meters) and diameter at breast height measured at 1.3 m above ground (DBH, measured in centimeters) were measured at 45 mth after planting. The DBH of multiple-stemmed trees was calculated as the quadratic mean using Equation 1:

$$d = \sqrt{d_1^2 + d_2^2 + d_n^2} \quad (1)$$

where $d_1, d_2, \ldots, d_n$ are the DBH values of each of the multiple stems. The estimated diameter was deemed to approximate that of a single stem with the same cross-sectional area.

Allometric equations were constructed to estimate the biomass of aboveground tree components (stem, branch + twig, leaf and their total) based on the diameter at breast height (D in the equation) and total tree height (H) data. The model consisted of $y = a(D^2H)^b$, where y is the biomass of the total aboveground tree components, D is the diameter at breast height, H is the tree height and a and b are parameter estimates. These equations and relevant coefficient values were derived based on measured values of the tree component weight related to its DBH and height from 20–30 sample trees per species following the methods described in Ounban et al. (2016). Biomass data were presented as mean per tree.

Biomass estimation equations for *M. alternifolia:* Stem $y = 0.0426x + 0.2873$, coefficient of determination (R^2) = 0.84; Branch+twig $y = 0.0214x - 0.2205$, $R^2 = 0.84$; Leaf $y = 0.0117x + 0.2638$, $R^2 = 0.82$; Total $y = 0.0758x + 0.2802$, $R^2 = 0.92$

Biomass estimation equations for *M.* cajuputi: Stem: $y = 0.0206x + 2.7801$, $R^2 = 0.84$; Branch+twig: $y = 0.0126x + 0.4102$, $R^2 = 0.75$; Leaf: $y = 0.006x + 1.1327$, $R^2 = 0.72$; Total: $y = 0.0392x + 4.323$, $R^2 = 0.91$

Biomass estimation equations for *M. leucadendra*: Stem: $y = 0.0186x + 8.777$, $R^2 = 0.90$; Branch+twig: $y = 0.0038x + 4.4729$, $R^2 = 0.49$; Leaf: $y = 0.0021x + 2.8121$, $R^2 = 0.80$; Total: $y = 0.0245x + 16.062$, $R^2 = 0.89$

Biomass estimation equations for *M. quinquenervia*: Stem: $y = 0.0238x + 1.7144$, $R^2 = 0.88$; Branch+twig: $y = 0.0104x + 0.5349$, $R^2 = 0.55$; Leaf: $y = 0.0058x + 1.3123$, $R^2 = 0.65$; Total: $y = 0.04x + 3.5616$, $R^2 = 0.85$

Tree form

Axis persistence (AP) reflected the ability of the tree to retain its primary stem axis. From a timber utilization viewpoint, the longer the main axis, the higher the quality of the resulting log. Axis persistence was categorized into six classes following the method of Pinyopusarerk et al. (2004). The total height of the tree was divided into four equal parts (Fig. 1). The length of the unbroken axis was scored according to the quarter section to which it could be followed. In addition, classes were incorporated at the beginning and the end of the scale, respectively. The scoring grade for each class was: 1 = double or multiple leaders from ground level; 2 = axis loses

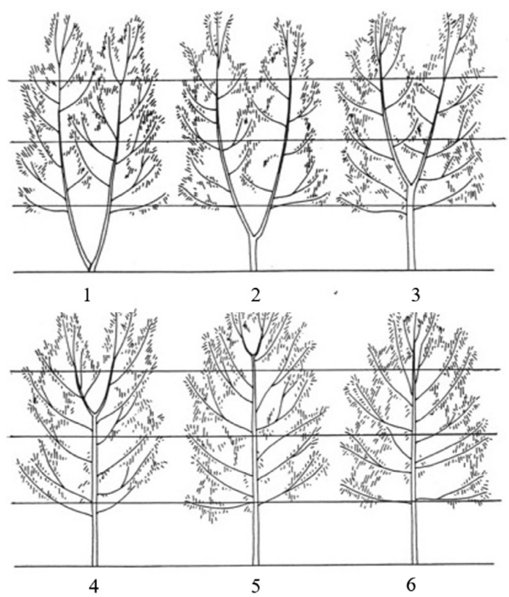

Fig. 1 Guidelines for recording axis persistence (Pinyopusarerk et al., 2004)

persistence in the first (lowest) quarter of the tree; 3 = axis loses persistence in the second quarter of the tree; 4 = axis loses persistence in the third quarter of the tree; 5 = axis loses persistence in the fourth quarter of the tree; and 6 = complete persistence.

Branch density (BD) was divided into three classes based on the internode length of the main branches on the stem: 1) high density, dense branching with internode length mainly < 15 cm; 2) medium density, internode length mainly 15–30 cm; and 3) light density, sparse branching with internode length mainly > 30 cm.

Crown ratio (CR) was the ratio of the crown length to total tree height, where a small ratio implied a longer bole to the crown base relative to total tree height, and vice versa.

Isolation of foliar oils and identification of components

Oil extraction was undertaken using hydro distillation in the laboratory of the Herbs and Bioactive Compounds Technology, Kasetsart University, Bangkok, Thailand. Fresh leaves were collected from the middle section of the crown of nine inner trees in each replicate plot and bulked into a representative sample. The fresh leaves were chopped into small pieces (approximately 1 cm in length) and each sample (100–200 g) was distilled for 6 h. Oil concentrations (measured as fresh weight, weight per weight percentage, w/w%) were derived from a known weight of fresh leaves.

Analyses of the oils were carried out in the laboratory of Thailand Institute of Scientific and Technological Research, Bangkok, Thailand. Qualitative analysis of chemical compositions was based on gas chromatography (GC) with compounds identified by their GC retention time and retention indices relative to *n*-alkanes and by comparison of their mass spectra with either known compounds or published spectra (Adams, 2001). Analytical gas chromatography was carried out using an Agilent Technologies Model 6890 N, Quadrupole Mass Selective Detector Model 5973 inert. The capillary column used was an HP-5MS (30 m × 0.25 mm, film thickness 0.25 μm). The column temperature was programmed from 50 °C to 220 °C at 4 °C/min with helium as the carrier gas (helium 75,911.28 Pascal, flow at 1.0 mL/min and average velocity of 40 cm/s). The injector was mode pulse split 50:1 at 230 °C. Mass spectra were recorded in electron impact mode at 70 eV, with scanning in the range 40–4 00 *m/z*.

Data analysis

Linear mixed models of the general form $y = Xu + Zb + e$ were solved using the restricted maximum likelihood method implemented in Genstat version 18 (VSN International, Hemel Hempstead, UK). This type of model consists of y, a vector of individual-tree observations on each trait; *b*, a vector of fixed-effect estimates, consisting of species, provenance-within-species and replicate; and *u*, a vector of random plot effects, with term e being a vector of random residual effects and X and Z are incidence matrices for fixed and random model terms, respectively. Survival and oil characters were analyzed using plot-mean data in y, dropping the plot term from *u*.

Results

There were highly significant ($p < 0.001$) differences among species in all the traits assessed while the differences between provenances within species were not significant for survival, branch density and crown ratio. Mean values and statistical differences for survival, growth, aboveground biomass, tree form and leaf oils are presented in Table 1. Differences among pair of provenances and species were gauged using the standard error of difference (s.e.d.), with a difference of twice the s.e.d. being considered significant.

Survival and growth

Survival was high to very high in *M. quinquenervia, M. cajuputi* and *M. leucadendra* with means of 90%, 98% and 100%, respectively, and they were not statistically different. It was significantly lower in *M. alternifolia*, (mean 65%). Differences in the survival percentage were not significant between provenances within the species.

Height and DBH growth means ranked similarly: *M. leucadendra* > *M. cajuputi* > *M. quinquenervia* > *M. alternifolia*. The difference between provenances within species was evident with a consistent provenance ranking across the species for both height and DBH.

Aboveground biomass

The total aboveground biomass and tree component biomass for each tree varied considerably among species and provenances within species and generally followed the patterns of height and diameter at breast height (Table 1). In relative terms, the stem component accounted for more than 50% of the total biomass, which together with branches and twigs contributed more than 80%. The leaf component was smallest (11%) in *M. leucadendra* compared to 16–17% in the other three species. In both absolute and relative terms, all three *M. cajuputi* provenances produced more branch and leaf biomass than the other species.

Tree form

The axis persistence scores for *M. leucadendra* and *M. quinquenervia* (3.03 and 2.83, respectively) were significantly ($p < 0.001$) higher than that for *M. cajuputi* and *M. alternifolia* (2.34 and 2.45, respectively). Differences between provenances within species were small but statistically significant and significant differences between the provenance means were observed only within *M. leucadendra* and *M. cajuputi*.

The mean branch density score for *M. alternifolia* was 1.08, indicating very dense branching with an internode length less than 15 cm. The other three species did not differ (based on a comparison of average standard errors of difference) and were significantly ($p < 0.001$) different from *M. alternifolia* and sparsely branched, with mean scores in the range 1.92–2.3. There were no significant differences between provenances within species.

The crown ratio in *M. alternifolia* was significantly smaller than those for the other species, with its mean ratio of 0.50 indicating that half of the total tree height supported foliaged branches. There were no significant differences in the mean crown ratio among the other species (mean 0.66–0.68). The differences between provenances within species were negligible.

Leaf oils

Oil concentration and yield

The leaf oil concentration varied significantly among the species and between provenances within species but the differences between the provenance means were significant only within *M. cajuputi*. The concentration was highest in *M. alternifolia* (mean 3.15%) compared to *M. cajuputi* (1.49%), *M. quinquenervia* (0.93%) and *M. leucadendra* (0.56%). Among the provenances of *M. cajuputi*, the oil concentration of the seed orchard source from Indonesia (1.22%) was lower than that in a natural provenance from Berry Springs, NT (1.76 %) but comparable to that from Wangi Station, NT (1.15%). The oil yield per hectare is an important indicator of the economic value of the crop as a source to produce essential oils. Estimated from species means for survival, leaf mass and oil yield, *M. cajuputi* produced 161 kg of foliar oil/ ha followed by *M. alternifolia* 79 kg/ha, *M. quinquenervia* 67 kg/ha and *M. leucadendra* 53 kg/ha.

Oil composition

The essential oils under study in the current project are classed as medicinal oils, with some also noted for their fragrance. Their differing chemical compositions (Fig. 2) determine their often multiple-end uses (Lassak and McCarthy 2001), as described in the discussion below. The results have been tabulated to show the most commercially important oil constituent expressed as a percentage of total oil for each species and provenance. Table 2 gives the results for the oils of of *M. alternifolia* rich in terpinene-4-ol, Table 3 for the oils of *M. cajuputi* rich in 1,8-cineole, Table 4 for the oils of *M. leucadendra* rich in methyl eugenol and Table 5 for the oils of *M. quinquenervia* rich in 1,8-cineole.

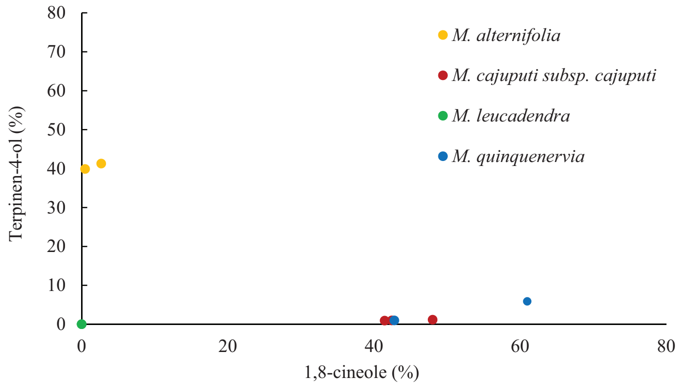

Fig. 2 Oils of studied *Melaleuca* species or provenances in three groups based on chemical composition, for *M. alternifolia* provenances (rich terpinen-4-ol, low 1,8-cineole), *M. cajuputi* and *M. quinquenervia* provenances (rich 1,8-cineole) and *M. leucadendra* oils (neither of these compounds but rich in methyl eugenol)

Table 2 Oil composition (as percentage of total oil) for two provenances of *Melaleuca alternifolia* in trial in Thailand

Oil constituent	Provenance	
	Devils Pulpit, NSW	Candole, NSW
α-Thujene	1.28	0.63
α-Pinene	3.18	2.35
β-Pinene	0.93	0.50
β-Myrcene	0.93	0.73
α-Phellandrene	-	0.45
α-Terpinene	4.35	13.82
p-Cymene	12.52	2.34
β-Phellandrene	-	1.52
limonene	1.27	-
1,8-Cineole	2.69	0.48
ɣ-Terpinene	15.58	24.24
Terpinolene	3.03	4.35
Terpinen-4-ol	41.27	39.88
α-Terpineol	4.98	2.61
Aromadendrene	1.67	-
Ledene	1.25	-
Total (%)	94.93	93.90

Table 3 Oil composition (as percentage of total oil) for three provenances of *Melaleuca cajuputi subsp. cajuputi* in trial in Thailand

Oil constituent	Provenance		
	19572 Wangi Station, NT	19580 Berry Springs, NT	SSO Indonesia
α-Pinene	2.05	1.69	2.68
Sabinene	0.78	0.26	2.34
β-Pinene	1.97	1.68	-
β-Myrcene	2.10	1.48	0.95
α-Terpinene	0.23	-	-
p-Cymene	0.36	0.40	0.61
Limonene	6.13	5.44	6.89
1,8-Cineole	42.45	41.47	48.03
γ-Terpinene	0.55	0.57	0.73
Linalool	-	-	0.56
(Z)-Dihydro-α-terpineol	0.34	0.33	-
Terpinen-4-ol	0.97	0.93	1.17
α-Terpineol	14.57	14.27	16.25
Terpinyl acetate	1.49	2.19	2.57
β-Elemene	0.88	0.69	0.27
Methyl eugenol	-	-	0.59
(E)-Caryophyllene	5.00	7.27	5.97
Aromadendrene	1.91	2.17	-
C15H24	0.35	0.42	-
α-Humulene	1.81	2.87	2.81
Alloaromadendrene	1.04	1.1	-
α-Amorphine	-	0.32	1.07
β-Selinene	1.09	2.58	1.59
β-Guaien	-	0.51	-
Bicyclogermacrene	7.04	-	-
Ledene		5.63	2.23
Spathulenol	2.01	2.04	
Globulol	2.19	2.3	0.82
Viridiflorol	1.28	0.92	1.87
Ledene oxide	-	0.47	-
Ledol	0.59	-	-
β-Eudesmol	0.30	-	-
Total (%)	99.48	100	100

Table 4 Oil composition (as percentage of total oil) for two provenances of *Melaleuca leucadendra* in trial in Thailand

Oil constituent	Provenance	
	13532 Iron Range, Qld	20673 Bensbach, PNG
α-Copaene	0.37	-
Trans-β-ocimene	-	1.59
Methyl eugenol	86.31	94.66
Trans caryophyllene	1.55	0.43
E,E-α-Farnesene	-	2.91
β-Cubebene	1.31	-
Germacrene D	2.23	-
Calamenene	3.36	-
Total (%)	95.13	99.59

Table 5 Oil composition (as percentage of total oil) for two provenances of *Melaleuca quinquenervia* in trial in Thailand

Oil constituent	Provenance	
	15869 Rokeby, Qld	17517 Bibie Island, Qld
α-Thujene	0.59	-
α-Pinene	2.17	8.63
Sabinene	0.61	-
β-Pinene	1.37	3.00
β-Myrcene	1.63	1.57
α-Terpinene	1.78	0.28
p-Cymene	-	0.39
Limonene	6.02	8.63
1,8-Cineole	60.98	42.79
ɣ-Terpinene	3.29	0.89
α-Terpinolene	0.75	-
Terpinen-4-ol	5.87	0.99
α-Terpineol	10.26	16.55
(E)-Caryophyllene	-	3.27
α-Humulene	-	0.58
Aromadendrene	-	0.39
Ledene	-	1.02
Caryophyllene oxide	-	0.68
Viridiflorol	-	9.07
Ledol	-	1.27
Total (%)	95.32	100

In *M. alternifolia*, the levels of terpinen-4-ol in the oils of the Devils Pulpit and Candole provenances were 41.27% and 39.88%, respectively. Both provenances produced oils with low levels of 1,8–cineole at 2.69 and 0.48%, respectively.

In *M. cajuputi*, the oils of the SSO seed lot from Indonesia had the highest 1,8-cineole content at 48.03% compared to 42.45% and 41.47% for the Wangi Station and Berry Springs provenances, respectively.

In *M. leucadendra*, methyl eugenol was the dominant compound with 86.31% from the Iron Range provenance, Queensland, Australia and 94.66% from trees in the Benbach provenance, Papua New Guinea.

In *M. quinquenervia*, 1,8-cineole was the most important oil constituent, with 61.98% for the Rokeby provenance and 42.79% for the Bribie Island provenance, both in Queensland, Australia.

Discussion

Growth and tree form traits among the species

Except for *M. alternifolia*, the three broad-leaved *Melaleuca* species in the study had high survival, indicating good adaptation to seasonal flooding at the trial site. Tolerance of periodic or even continuous waterlogging of these species has also been reported in the studies of Sena Gomez and Kozlowski (1980), Hoang et al. (1996), Yamanoshita et al. (2001) and Brophy et al. (2013). The poorer survival of *M. alternifolia* indicated that the site conditions were not optimal for this species. Nevertheless, the mean survival of 65% nearly 4 yr after field planting was encouraging. Further performance testing of this species is recommended in the northern region of Thailand where temperature is considerably cooler in winter.

The growth rates recorded for height (1–2 m/yr) and DBH (1–3 cm/yr) were consistently within the ranges reported for young trees of these species planted in Australia (Small, 1981), Indonesia (Susanto et al., 2003), Thailand (Kasetsart Agricultural and Agri-Industrial Product Improvement Institute, 2014), Vietnam (Hoang et al., 1996; Le, 2017) and Zimbabwe (Gwaze, 1989). The current results showed the superiority of *M. leucadendra* above other species in growth characteristics. Not only was *M. leucadendra* the fastest growing in the trial, it was also the only species to have maintained 100% survival. Furthermore, this species recorded high scores in axis persistence and low branch densities indicating long clear tree boles, which combined with its fast growth rate, makes *M. leucadendra* very suitable for planting for sawlog and pole production, as is already taking place in the Mekong Delta of Vietnam where farmers have been rapidly replacing local *M. cajuputi* with *M. leucadendra* (Le, 2017).

Variation in the aboveground tree component biomass and tree form among the species found in the current study helps to explain tree appearance and to determine utilization options. For example, *M. leucadendra* may be faster growing with a larger bole component than *M. cajuputi*, but the latter has an economic advantage in that its greater percentage of leaf biomass provides material for oil extraction in addition to its reasonable bole length for wood production.

The crown ratio values of *M. leucadendra* and *M. quinquenervia* (0.66–0.68) indicated that two-thirds of the tree height carried the crown canopy. However, the axis persistence values of these species (2.83–3.03) indicated their clear bole length was about half of the tree height. These two trait values suggested that the species retained a large portion of live branches well below the forking point. Old and mature trees of these species tend to have a long clear bole to three quarters of tree height. However, the shedding characteristics of branches of these species are unknown.

Oil characteristics

The oil concentration levels of the four *Melaleuca* species in the current study were generally within the range reported for these species. However, the oil concentration of *M. cajuputi* trees from a seed orchard in Indonesia was lower than expected, as it was subject to genetic improvement; this should be further investigated. While the oil yield from this source was lower than expected, its 1,8-cineole content was the highest among the three provenances, reflecting its superiority from genetic improvement.

Melaleuca alternifolia: Two of the provenances this species, well-known as being rich in terpinene-4-ol (Baker et al., 2015), one of several chemotypes that occur naturally in this species (Butcher et al., 1994; Homer et al., 2000), were under trial in the current study. *M. alternifolia* oil rich in terpinen-4-ol is an effective antiseptic, anti-bacterial, antiviral, antifungal and anti-inflammatory agent and has been used in a wide range of antimicrobials and cosmetics, as well as being available as crude oil in various concentrations (Rural Industries Research and Development Corporation, 2007). The international market (approximately 1,000 t/yr) for this oil type has been expanding including in Asia and oil prices have been strong (>USD 29/kg) and relatively stable in recent years (Larkman, 2020).

The average foliar oil concentration for this species in the current trial of 3.15% (w/w% on a fresh weight basis; Table 1) was within the normal range for this species. Oils with terpinen-4-ol levels of 40% or more in combination with low levels of 1,8-cineole (3%) are in demand in the principal markets (Brophy et al., 2013) so the two oils here qualify under these criteria.

The oil yield for *M. alternifolia* of 79 kg/ha was low, estimated at 45 mth from planting and at a stocking of 1,084 trees/ha (65% survival). However, notably, this species is usually grown for production of essential oils (not for its wood) and would normally be planted at a stocking of 30,000–35,000 plants/ha. The first harvest for oil production is typically after 18 mth of growth and thereafter, the coppice is harvested every 12 mth. This regime regularly achieves oil yields of 150–250 kg/ha/yr (Colton and Murtagh, 1999). Further trials of this species in Thailand are warranted on different site types and applying silviculture suitable for oil production.

Melaleuca cajuputi: This species occurs as three subspecies, each producing oils of differing compositions (Brophy and Doran, 1996). Subspecies *cajuputi* is the current study is the main source of oil rich in 1,8-cineole, sold commercially as 'cajuput oil'. Cajuput oil is popular in Southeast Asia, particularly Indonesia, as a household medicine used internally to treat coughs and colds and externally for relief of pain, often in the form of ointments and liniments, as well as a fragrance in soaps, cosmetics, detergents and perfumes (Rimbawanto, 2013). Indonesia is the main producer of cajuput oil (> 650 t/yr) from 27,000 ha of plantation, mostly on Java, with the annual production far below the existing demand (Rimbawanto et al., 2021). Vietnam is also a production center of cajuput oil from native stands. The quality of the cajuput oil traded in Indonesia is based on its 1,8-cineole content (premium class > 60% cineole, first class 55–60 %, standard class 50–54.9 %) and meeting various physical attributes, as specified in the Indonesian National Standard, SNI 3954: 2014 (National Standardization Agency, 2014). Oil prices at the farm gate in Indonesia in 2021 were about USD 17/kg (Rimbawanto et al., 2021).

The estimates for oil concentration, oil yield and the percentage of 1,8-cineole from the current study were within the normal ranges found in this species (Rimbawanto, 2013). With an average oil yield of 161 kg/ha in combination with a likely ready market for the oil produced and reasonable production of woody biomass, this species was the best of the candidates in this trial for further testing for the production of both woody biomass for energy and essential oil as a secondary product. The percentage of 1,8-cineole and the oil concentration are known to be amenable to improvement by selection and breeding in this species (Kartikawati et al., 2016), so screening of a wider range of provenances is warranted.

Melaleuca leucadendra: Methyl eugenol is a chemical compound classified as a phenylpropene, a type of phenylpropanoid, with much of the world demand for this chemical met by synthesis of the compound (Tan and Nishida, 2012). However, several essential oils, including some tea tree oils, like those from the more eastern provenances of *M. leucadendra*, contain methyl eugenol as a major component (Brophy and Doran, 1996; Brophy, 1999). These oils have a limited market in aromatherapy, massage oils and alternative medicines, as well as fragrances in consumer products, such as personal care products and household cleaners (Government of Canada, 2010). The extent of the international market for oils of this type and the price paid for such oils is unknown to the authors at this time.

Melaleuca leucadendra was amongst the best producers of leafy biomass in this trial. However, the oil concentration in this biomass, was the poorest of all the species (0.56% on a w/w fresh weight basis) giving an estimated oil yield/ha of only 53 kg. The oil concentration was below what would normally be considered suitable for economic production (> 1% on a w/w fresh weight basis; Brophy, 1999). These factors combined with the uncertainty of the market for such an oil and concerns about its toxicity (Smith et al., 2002) mean that this species has potential for wood production only.

Melaleuca quinquenervia: The leaf oils of *M. quinquenervia* fall into two classes based on their chemical composition (Brophy and Doran, 1996; Brophy et al., 2013); one chemotype is rich in nerolidol (> 90%), while the other is rich in 1,8-cineole (> 15–65 %) and sometimes in viridiflorol (1–80%). In the current study, both provenances were rich in 1,8-cineole (43% and 61%, respectively) which is the source of niaouli oil produced from natural stands of *M. quinquenervia* in New Caledonia and plantations in Madagascar, with the uses of this oil being similar to those of *M. cajuputi* given above (Ramanoelina al et., 2008). Production figures for this oil type are not easily obtained. Trilles et al. (1999) gave estimates of an annual production of 7–10 t for New Caledonia, while Ramanoelina et al. (2008) reported an annual production of 1.5–2 tonnes of niaouli oil in Madagascar.

Melaleuca quinquenervia ranked behind both *M. cajuputi* and *M. leucadendra* in the production of leaves in this trial and averaged below 1% in oil concentration. Its oil yield was a modest 67 kg/ha which combined with the uncertainty of the market for niaouli oil, means that this species has potential for wood production only.

Conclusion

The four *Melaleuca* species, and to some extent their provenances, planted in this trial differed considerably in a range of quantitative and qualitative traits. Overall, none of the species could be deemed superior in all aspects, with individual species having certain characteristics either superior or inferior to the others. Evaluation of the species performance to determine their suitability needs to be weighed against specific objectives and sometimes based on multiple traits rather than one. All four species are suitable for planting in Thailand either for wood or foliar essential oil products.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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