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Three-Strata Agroforestry Enhances Yield and Quality of Multi-Purpose Crops in Post-Taungya Teak Plantations

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ABSTRACT

Limited information on the yield and quality of fodder, fuelwood, and food crops of post-taungya teak plantation systems often hinders further development. Therefore, this study aims to evaluate the yield and quality of fodder, fuelwood, and food crops under teak stands in three-strata agroforestry of post-taungya plantation systems. Fodder and fuelwood species (*Calliandra calothyrsus*) and food crops (*Canna edulis*) were planted in a split-plot design. Main plots consisted of teak at three ages and Relative Light Intensities (RLI), namely four years (RLI: 49.87 ± 28.74%), 11 years (31.25 ± 22.89%), and 16 years (26.77 ± 25.98%). Subplots included border trees, alley cropping, and alternate rows agroforestry planting models, with monoculture in an open field as a control. Evaluations covered fodder (yield, protein, tannin), fuelwood (biomass, caloric value, moisture), and tubers (yield, starch, protein, flavonoid). Fodder yield under four-year-old teak (132.50–137.25 g plant^{-1}) was comparable to the control (161.78 g plant^{-1}) but declined in 11- and 16-year-old stands (69.38–93.75 and 84.88–92.00 g plant^{-1}). Fuelwood biomass showed a similar pattern (101.00–112.25 vs. 137.11 g plant^{-1} in young teak; 38.50–84.22 g plant^{-1} in older stands). Only tuber yield in the alternate-rows model (288.57 g plant^{-1}) matched the control (296.12 g plant^{-1}). In three agroforestry models, fodder protein increased under four-year-old teak (31.01–42.00%), while tannin decreased in four- and 11-year-old stands (20.05–34.66%). Fuelwood caloric value rose slightly in border trees under 16-year-old teak (2.30%), whereas water content decreased under 11-year-old teak (52.23–77.07%). Tuber starch increased with teak age (2.9–22.32%), protein rose under four-year-old teak (32.26–50.00%), and flavonoids tended to decline (3.83–11.28%). Three-strata agroforestry was more productive than monoculture (LER > 1.0), enhancing fodder and tuber (starch and protein) quality while maintaining fuelwood quality. Yield reductions under older teak stands indicate that maintaining adequate light penetration through selective thinning and pruning can help sustain understory productivity.

1. INTRODUCTION

Food and energy remain global issues that threaten the fulfilment of the basic needs of the world's population in the climate change era. As the population grows, increasing demand for food, wood energy, and fodder has accelerated the decline in agricultural land productivity, damaged the environment, and driven the rate of deforestation [1-4]. In addition, the intensification of conventional monoculture to meet food, wood energy, and water security needs has accelerated environmental degradation and triggered social impacts [5, 6]. The unsustainable characteristics of conventional agriculture are causing a shift toward sustainable and multifunctional agriculture. Multifunctional agroforestry can increase food production while remaining positive for social and environmental aspects in line with Sustainable Development Goals [7, 8].

Agroforestry, as a multifunctional agricultural system, can provide food, fodder, biomass energy, and environmental benefits, serving as a form of adaptation and mitigation of climate change, while also preserving biodiversity [9]. In addition, agroforestry has been proven to increase food crop production by 35% on dry land through agrosilvopastoral and agrosilvicultural models [10]. Nevertheless, traditional agroforestry practised by farmers on Java Island, such as intercropping systems on forest land, is generally subsistence-based, with low productivity and unsustainable practices [11, 12]. On the Java Island, there are 1.2 million hectares of social forestry land dominated by teak plantations with intercropping of food crops in teak stands under three years old [13]. However, the food production process in the intercropping system is only temporary and is likely to be terminated or stopped due to competition from teak trees after three years. This period is known as the post-taungya teak plantation system period, which is characterised by a possible decline in food production and other agricultural products.

To reduce the economic and livelihood risks of rural farmers living near forests, a forest land use strategy is needed that integrates fodder, wood energy, and food into a sustainable agroforestry system [14], namely multi-strata agroforestry. In the post-taungya plantation system, it is necessary to optimize the use of land under teak trees through three-strata agroforestry practices to integrate the sustainability of food, fodder, and bioenergy. Under a teak canopy, *Calliandra* (*Calliandra calothyrsus*) is possibly planted in the middle strata as a fast-growing species whose leaves are used as fodder with low tannin content, easy digestibility, and high protein content [15]. *Calliandra*, as a source of wood energy, has a calorific value ranging from 16,000 to 19,000 kJ [16]. In the lower strata, there is edible *Canna* (*Canna edulis*) as a potential tuber crop for alternative staple and functional foods, and a raw material for the pharmaceutical industry [17]. The tuber is rich in starch, which can be used to make flour, biscuits, instant noodles, bread, and kwetiau [18].

Agroforestry with a multistrata configuration integrates complementary tree, shrub, and herbaceous layers that differ in light requirements, photosynthetic capacity, and resource-use strategies [19]. *Calliandra* serves as an effective second stratum because it is a nitrogen-fixing legume that enhances soil fertility [20], performs well under approximately 70% light intensity [21], and supports understory crop growth [22]. Edible *Canna* was selected as the third stratum due to its strong shade tolerance (50–70% light) [23-25], making it ecologically compatible with both teak and *Calliandra*. These complementary niches help stabilize system functioning and improve light-use efficiency [26]. Light availability is a critical factor not only for photosynthesis but also for regulating source–sink dynamics that determine carbon allocation to storage organs [27, 28]. Under reduced light, plants adjust biomass distribution and metabolic activity, influencing the development and chemical composition of tubers [29] and the nutritional quality of fodder [30]. Although shade can limit yield and impose stress [31], it may also alter primary and secondary metabolites, with potential implications for crop quality [32]. These compounds also function as biostimulants that enhance resilience to biotic and abiotic stress [33].

The presence of a tree canopy in agroforestry creates a microclimate, characterised by lower solar radiation and temperature, as well as higher humidity levels. Low evapotranspiration has been hypothesized to have a potential effect on the yield and quality of understory crops [31, 34]. Compared to an open field, the dominant factor that changes due to tree shade is the reduction in the quantity and quality of sunlight, which has the potential to affect crop yield and quality [30, 35]. However, field studies on the impact of tree shade on the production and chemical content of understory crops are still limited [36, 37], both for above-ground production, such as fodder and fuelwood [36, 37], and below-ground production, including tuber food crops [23, 25, 38]. The quality of fodder and tuber crops is determined by the content of primary (protein and starch) and secondary metabolites (flavonoids and tannins) [39, 40], while the quality of fuelwood is determined by its calorific value and moisture content [41]. Therefore, a study is needed to identify the effect of agroforestry planting models with microenvironmental changes on the yield and quality of understory crops [37], particularly those with potential uses as fodder, fuelwood (*Calliandra*), and food (*Canna*) in various age classes of three-strata agroforestry in the post-taungya teak plantation systems. Information on the yield and quality of understory crops in a three-strata agroforestry system provides valuable insights for guiding farmers and managers in the sustainable management of post-taungya teak plantation systems.

2. METHODOLOGY

2.1 Study location

This study was conducted in a teak plantation forest managed by PT Perhutani, in the Ciamis Forest Management Unit (KPH), West Java Province, Indonesia (Figure 1). The study location laid on the altitude of 146 to 250 meters above sea level and had an annual rainfall of 2,137.9 mm, an air temperature of 22.2°C to 36.0°C, with air humidity of 42.8% to 96.8%, and average daily sunshine of 5.85 hours [42]. Ciamis experiences nine wet months and three dry months. Based on the Köppen and Schmidt–Ferguson classifications, the area is categorized as a moist tropical or wet Type B climate [43], while the Köppen–Geiger system further identifies it as an equatorial, tropical-rainforest climate with monthly rainfall consistently exceeding 60 mm [44, 45].

2.2 Study procedure

For the sustainability and integration of food, fuelwood, and fodder production in the post-taung system, *Calliandra* and *Canna* were planted under a teak stand of four-year, 11-year, and 16-year-old trees, representing the 20-year teak cycle. *Canna* seedlings were obtained from community forests of Ciamis, West Java, while *Calliandra* seeds were sourced from Madiun, East Java. Both plant species were planted during the rainy season in December 2022. The planting distance between the plants was 75 cm × 75 cm, with a minimum distance of 75 cm from the center of the teak trees. Teak stands used to represent the entire teak cycle in the post-taungya plantation system were four-year, 11-year, and 16-year-old. The teak plantation was established at an initial spacing of 3 m × 3 m, with 1,111 trees ha^{-1} remaining at four years of age. At 11 years of age, the first thinning was carried out once, leaving 707 trees ha^{-1}, and at 16 years of age, the second thinning was carried out, remaining 425 trees ha^{-1}.

2.3 Experimental design

In this study, a split-plot design was implemented, with three types of teak canopy covered in the main plots: four-year-old (1,111 trees ha^{-1}), 11-year-old (707 trees ha^{-1}), and 16-year-old (425 trees ha^{-1}). The subplot consisted of three agroforestry planting models: border trees, alley cropping, and alternate rows, as shown in Figure 2. This selection represents the predominant agroforestry systems practiced in the region [46]. The control was achieved through the establishment of *Calliandra* and *Canna* monocultures in an open field. Each treatment was arranged in three replications. A total of 33 experimental units were established, consisting of three combinations of agroforestry planting models for four-year-old teak (nine units), 11-year-old teak (nine units), and 16-year-old teak (nine units), as well as *Canna* monoculture (three units) and *Calliandra* monoculture (three units).

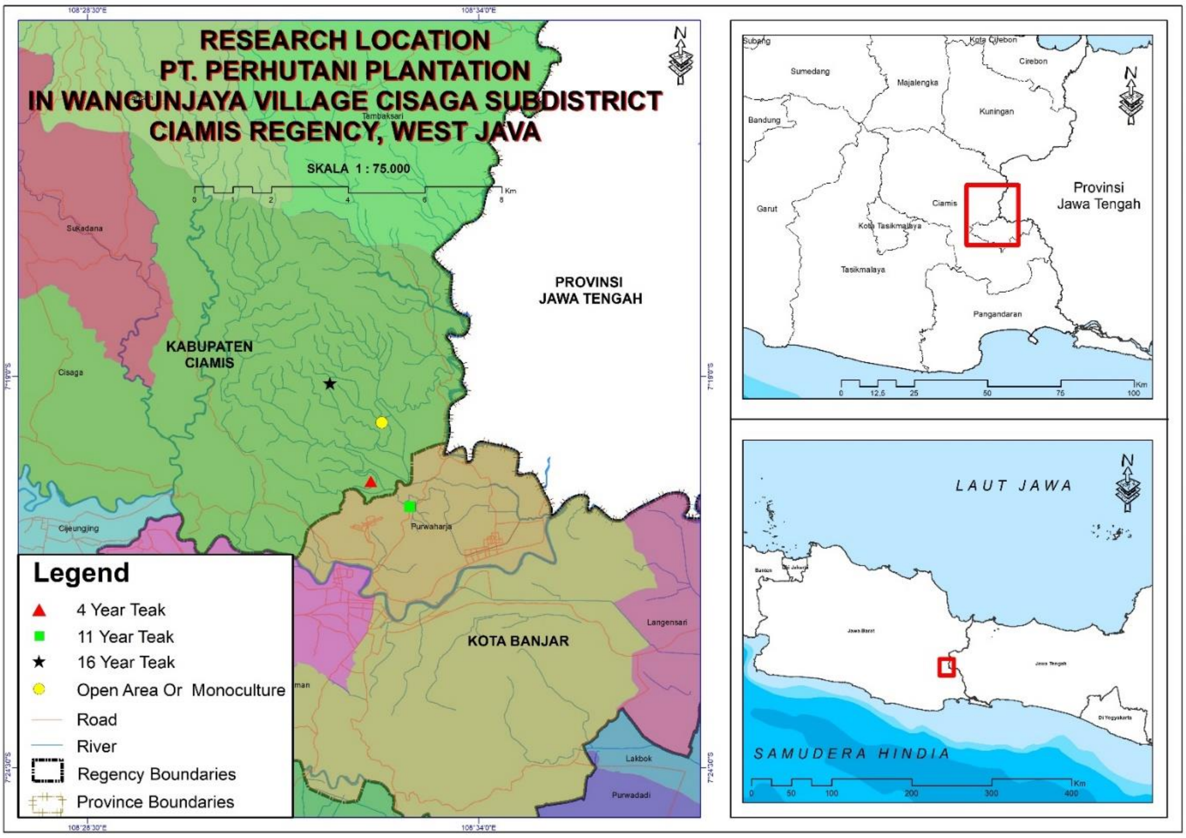

Figure 1. The study location was in teak plantation in the Ciamis forest management unit

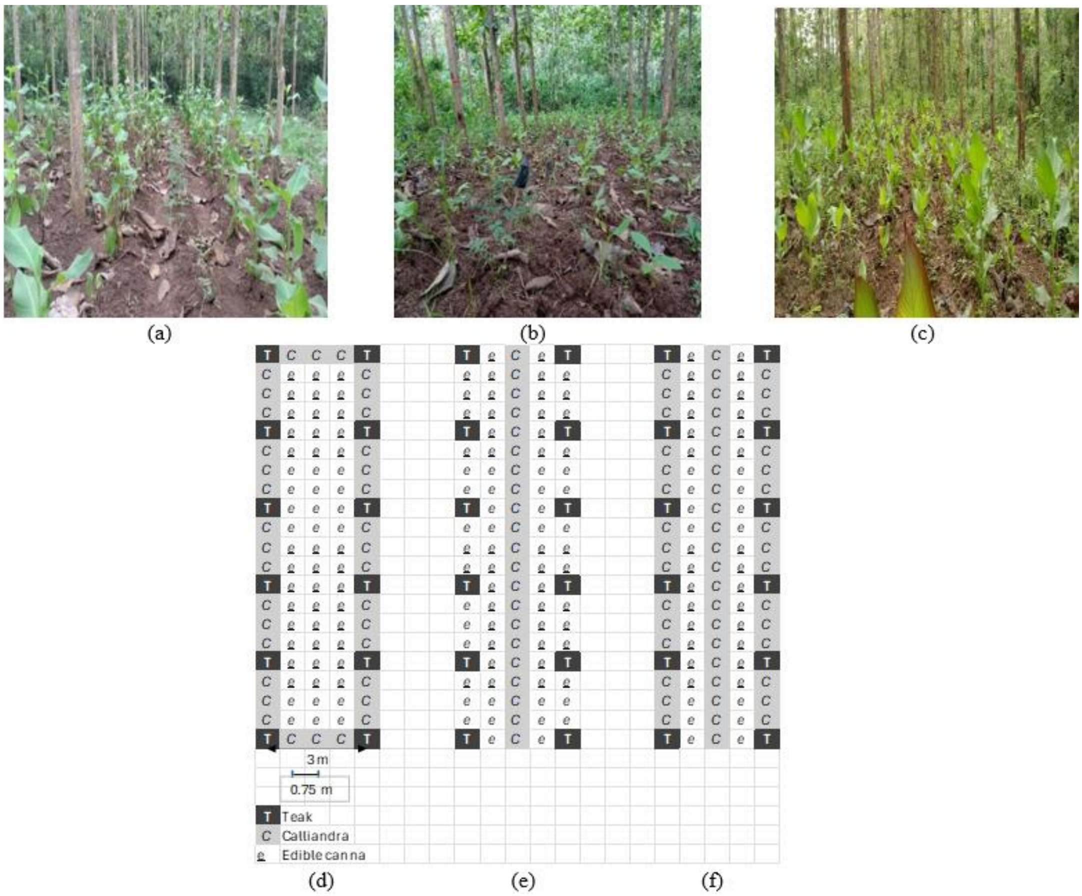

Figure 2. Main plots represent three age classes of teak: (a) four-year-old, (b) 11-year-old, and (c) 16-year-old teak stands. Subplots represent three basic planting models in a three-strata agroforestry system: (d) border planting—*Calliandra* and teak as a border, (e) alley cropping—*Canna* grown in alleys between *Calliandra* and teak, (f) alternate rows—*Canna* and *Calliandra* planted in alternating rows under teak

Table 1. Teak canopy shading in each age class of teak plantation within a three-strata agroforestry model

Measurement	Under Teak Stands					
	4-Year-Old Teak		11-Year-Old Teak		16-Year-Old Teak	
Tree height (m)	13.38 ± 2.22	a.	18.86 ± 2.92	b.	20.16 ± 2.48	c.
Height at crown base (m)	4.91 ± 1.91	ab.	4.53 ± 2.80	a.	5.17 ± 1.91	c.
Thick of shades (m)	8.57 ± 2.66	a.	14.05 ± 4.24	b.	15.13 ± 2.95	c.
Radius of shades (m)	1.70 ± 0.69	a.	2.71 ± 0.66	b.	3.08 ± 0.71	c.
Area of shades (m^2)	10.51 ± 7.78	a.	24.40 ± 11.48	b.	31.30 ± 13.85	c.

Note: Values are expressed as means ± standard deviation (SD). Teak canopy sizes as shade with identical letters in the same line show no significant differences based on Duncan's test at the 95% confidence level.

2.4 Canopy shading and physical environment assessment across age classes of teak

The measurements of teak stands (overall height, bole length, crown thickness, crown height, crown radius, and crown area) influenced alterations in the microclimate of three-strata agroforestry. Furthermore, the crown radius was assessed with a tape measure from the center of the tree toward the canopy growth in four cardinal directions (north, south, east, and west). Tree height and teak canopy development were assessed using a Haga meter from the ground (Table 1).

Light intensity was assessed with a Lutron LX-07 luxmeter from 11:00 a.m. to 1:00 p.m. during peak sunlight at the start of planting (December 2022), three months after planting (March 2023), and six months after planting (June 2023). Relative Light Intensity (RLI, %) or shade was calculated by taking the ratio of the light intensity under the teak canopy to the light intensity in the open field. Temperature and humidity were measured with a thermo-hygrometer in each teak age group and the open field at 07:00–08:00, 12:00–13:00, and 16:00–17:00 during the understory crop cycle. Soil samples were collected from the tillage layer at a depth of 10–20 cm. Five sampling points were taken randomly within each experimental unit, then composited to obtain one representative soil sample per unit. The soil characteristics were categorized according to the age class of the teak stands and the open field. Soil analysis included physical properties (soil texture) and chemical properties such as pH, C-organic, N, P, K, Mg, and Ca. Soil in the location was classified as ultisol soil (USDA Soil Taxonomy) with an argillic horizon, which was predominantly clay and light brown [45]. The detailed physical and chemical properties of the soil condition are presented in Table 2.

Table 2. Soil characteristics at the study site in the teak plantation

Variables	Teak Canopy Shade in Agroforestry Systems						Open Area / Monoculture Crop			
	4-Year-Old Teak		11-Year-Old Teak		16-Year-Old Teak		*Calliandra*		*Canna*	
Soil Physical Properties										
Sand	15.22		14.00		22.44		26.00		19.67	
Dust	39.11		36.67		31.00		30.67		34.33	
Clay	45.67		49.33		46.56		43.33		46.00	
Soil texture	Clay		Clay		Clay		Clay		Clay	
Soil Chemical Properties										
pH (1:5)	5.39	(a)	5.54	(a)	5.46	(a)	5.33	(a)	5.33	(a)
C-Organik (%)	2.06	(m)	2.15	(m)	2.38	(m)	2.04	(m)	1.96	(l)
N total (%)	0.19	(l)	0.20	(l)	0.22	(m)	0.15	(l)	0.20	(l)
Available P (P_2O_5, mg kg^{-1})	1.74	(vl)	3.43	(vl)	5.50	(vl)	1.65	(vl)	2.67	(vl)
Ca (cmol(+) kg^{-1})	4.36	(l)	3.89	(l)	2.63	(l)	8.32	(m)	5.19	(l)
Mg (cmol(+) kg^{-1})	2.60	(h)	2.61	(h)	1.68	(m)	5.89	(h)	3.33	(h)
K (cmol(+) kg^{-1})	0.30	(m)	0.13	(l)	0.19	(l)	0.13	(l)	0.07	(vl)

Remarks: a = acidic; m = medium; l = low; vl = very low; h = high.

2.5 Evaluation of yield and quality

Harvesting of fodder and fuelwood was conducted when the *Calliandra* reached ten months after planting. The technique for harvesting was known as Short Rotation Coppice (SRC) by cutting the plant stems 30 cm above the ground for fodder and fuelwood [47]. Leaves, petioles, and green branches were used as fodder, while the main trunk and old branches were used as fuelwood.

Fresh fodder yield was measured by harvesting the complete net plot of the experimental units. The protein and tannin contents in fodder were derived from 90 samples of the *Calliandra* plant, averaging three samples for each experimental unit. The total protein content was measured using the Kjeldahl macro method with an Omnilab Food ALYT device. Furthermore, the tannin content of fodder was analyzed using a spectrophotometer at a wavelength of 730 nm.

The wood biomass was measured by oven drying at 70°C for 48 hours or until a constant weight was achieved out of 90 plant samples. The moisture content of the wood was measured using the gravimetric method (oven), and its calorific value was determined using a bomb calorimeter (Parr's model 6400 Automatic Isoperibol Calorimeter) by measuring the heat released upon burning the sample. Both main wood and coppice wood produced the same calorific value [16]. The potential yield per hectare was calculated by converting the average yield of fresh fodder and fuelwood biomass per experimental unit to the total crop composition per hectare.

The tubers were collected when the *Canna* plants reached eight months of age. During harvest, the fresh tubers were weighed for each plant, and the contents of starch, protein, and flavonoids were assessed in each sample. For fresh tuber yield, samples weighing 25% of each randomly selected experimental unit were weighed. Potential tuber yield per hectare was calculated by converting the average wet weight of tubers per experimental unit to the number of crops per hectare.

For tuber quality, 90 samples were obtained from the entire experimental unit, or three tubers per experimental unit. Subsequently, the tuber samples were finely chopped with a knife and mixed into a composite per experimental unit and analyzed in the laboratory. Starch content was determined using the Nelson-Somogyi method, while protein content of tubers was determined using the Indonesian National Standard method number SNI 01-2891 [48]. Tuber flavonoids were measured using the Nagy and Grancai method [49].

2.6 Data analysis

Analysis of variance (ANOVA) was used to assess the yield and quality of the crop for each treatment. Subsequently, a post hoc analysis was conducted using Duncan's Multiple Range Test (DMRT) at the 95% confidence level [50]. Productivity comparison between monoculture and three-strata agroforestry was carried out by calculating the Land Equivalent Ratio (LER). These data were incorporated into the Land Equivalent Ratio (LER) calculation to represent the teak component within the three-strata agroforestry system. LERs were obtained from a comparison of the yield of a three-strata teak agroforestry with a monoculture, calculated using one cycle of *Calliandra* and *Canna*. Teak yield was estimated based on the change in stand volume during the intercropping period. Stand volume (V, m³ ha⁻¹) was calculated using an allometric equation [51] derived from tree diameter at breast height (DBH) and total height measurements taken in all sample plots before the establishment of understory crops (*Canna* and *Calliandra*) and immediately after crop harvest. LER was used to determine the effect of interactions between plant species in a three-strata agroforestry planting model using the following formula [52]:

$$\text{LER} = \frac{CF_i}{CF_s} + \frac{CW_i}{CW_s} + \frac{Ct_i}{Ct_s} + \frac{T_i}{T_s} \quad (1)$$

where,

LER = Land Equivalent Ratio
CF_i = Fresh fodder yield of *Calliandra* under agroforestry
CF_s = Fresh fodder yield of *Calliandra* on monoculture
CW_i = Fuelwood yield of *Calliandra* under agroforestry
CW_s = Fuelwood yield of *Calliandra* on monoculture
Ct_i = Fresh tuber yield of *Canna* under agroforestry
Ct_s = Fresh tuber yield of *Canna* on monoculture
T_i = Teak stands yield under agroforestry
T_s = Teak stands yield on monoculture

3. RESULTS

3.1 Microclimate characteristics under teak plantation in a three-strata agroforestry system

Differences in canopy shade treatment for three ages of teak plantation and open field created microclimates with distinctly different light intensity, air temperature, and relative humidity (with respective F = 69.95, P < 0.05; F =3.443, P < 0.05; and F =12.018, P < 0.05) (Table 3). Canopy shading, the site conditions, and crop performance under teak stands are shown in Figure 3. The Relative Light Intensity (RLI) ranked from highest to lowest was open field (RLI = 100%), four-year-old teak shade (RLI = 49.87%), 11-year-old teak shade (RLI = 31.25%), and 16-year-old teak shade (RLI = 26.77%). The microclimate temperatures, listed from highest to lowest, were *Canna* monoculture (33.28℃), *Calliandra* monoculture (32.57℃), four-year-old teak shade (30.63℃), 11-year-old teak shade (30.44℃), and 16-year-old teak shade (30.41℃). Relative humidity, from highest to lowest, was as follows: 11-year-old teak shade (57.88%), four-year-old teak shade (57.10%), 16-year-old teak shade (54.34%), *Canna* monoculture (45.60%), and *Calliandra* monoculture (45%) (Table 3).

(a) (b) (c)

Figure 3. Canopy and site conditions in teak stands of different ages: (a) canopy of teak stand, (b) site conditions, (c) *Calliandra* and *Canna* plant performance under teak

Table 3. Microclimate conditions under the canopy of three teak age classes and in monocultures

Microclimate	4-Year-Old Teak		11-Year-Old Teak		16-Year-Old Teak		Monoculture or Open Field *Calliandra*		Monoculture or Open Field *Canna*	
Relative Light Intensity (RLI) (%)	49.87 ± 28.74	b	31.25 ± 22.89	a	26.77 ± 25.98	a	100 ± 0.00	c	100 ± 0.00	c
Temperature (℃)	30.63 ± 14.37	a	30.44 ± 10.92	a	30.41 ± 3.75	a	32.57 ± 4.70	b	33.28 ± 15.11	b
Air Humidity (%)	57.10 ± 18.92	c	57.88 ± 18.53	c	54.34 ± 18.79	b	45.00 ± 17.17	a	45.60 ± 19.55	a

Notes: Values represented mean ± standard deviation (SD). Microclimate conditions sharing the same letter in the same line were not significantly different at the 95% Duncan level.

Table 4. Fresh fodder and fuelwood biomass yield of *Calliandra*, and fresh tuber yield of *Canna* under different teak stands in a three-strata agroforestry system, compared with monoculture crops in an open field (control)

Treatments		*Calliandra* (Fresh Fodder and Fuelwood) and *Canna* (Tubers)					
		Fresh Fodder Yield (g/plant)		Fuelwood Biomass Yield (g/plant)		Fresh Tuber Yield (g/plant)	
Control in the open field		161.78 ± 78.38	c.	137.11 ± 105.97	d.	296.12 ± 186.52	c.
4-year teak	Border trees	137.25 ± 72.01	bc.	112.25 ± 64.82	cd.	163.68 ± 90.93	b.
	Alley cropping	132.50 ± 59.12	bc.	101.00 ± 27.33	abcd.	148.64 ± 108.55	b.
	Alternate rows	137.14 ± 58.38	bc.	102.43 ± 63.77	bcd.	288.57 ± 166.28	c.
11-year teak	Border trees	69.38 ± 32.82	a.	38.50 ± 25.72	a.	54.28 ± 44.81	a.
	Alley cropping	93.75 ± 61.20	ab.	58.25 ± 54.74	abc.	66.70 ± 50.49	a.
	Alternate rows	71.44 ± 20.97	a.	47.33 ± 24.67	ab.	66.00 ± 56.87	a.
16-year teak	Border trees	92.00 ± 41.84	ab.	65.29 ± 29.02	abc.	74.77 ± 66.25	a.
	Alley cropping	90.56 ± 43.17	ab.	84.22 ± 61.61	abcd.	51.92 ± 41.61	a.
	Alternate rows	84.88 ± 25.06	ab.	58.50 ± 16.28	abc.	61.62 ± 43.79	a.
F and significance		3.30*		2.97*		30.36*	

Notes: The values represent the mean ± standard deviation (SD). The values followed by the same letters within a column do not differ significantly from each other at the 95% Duncan Test.

Table 5. Yield per ha of fresh fodder, fuelwood biomass, fresh tuber, and teak under different teak stands in a three-strata agroforestry system compared with monoculture as control

Treatments		Fresh Fodder Yield (kg ha⁻¹)		Fuelwood Biomass (kg ha⁻¹)		Fresh Tuber Yield (kg ha⁻¹)		Teak Volume Increment (m^3 ha⁻¹) during Crop Rotation
4-year teak monoculture								14.20
11-year teak monoculture								22.10
16-year teakmonoculture								12.14
Crop control in the open field		2875.92 ± 730.21	b.	2437.42 ± 855.89	c.	5410.42 ± 3454.96	b.	-
4-year teak	Border trees	863.34 ± 400.17	a.	715.19 ± 437.37	ab.	1663.75 ± 311.78	a.	11.21
	Alley cropping	486.29 ± 51.56	a.	389.12 ± 34.62	ab.	1954.68 ± 418.61	a.	12.10
	Alternate rows	1273.54 ± 601	a.	960.73 ± 641.56	b.	2176.63 ± 511.65	a.	11.67
11-year teak	Border trees	306.45 ± 116.99	a.	166.08 ± 99.13	a.	667.23 ± 269.38	a.	32.27
	Alley cropping	182.76 ± 128.96	a.	110.83 ± 104.55	a.	1005.57 ± 197.57	a.	24.01
	Alternate rows	639.66 ± 143.42	a.	423.78 ± 196.99	ab.	538.83 ± 129.34	a.	21.64
16-year teak	Border trees	439.99 ± 90.31	a.	322.56 ± 99.36	ab.	934.12 ± 451.26	a.	18.34
	Alley cropping	166.79 ± 59.98	a.	155.13 ± 97.41	a.	793.9 ± 290.63	a.	16.39
	Alternate rows	752.63 ± 256.81	a.	523.41 ± 119.14	ab.	513.36 ± 76.67	a.	15.34
F and significance		15.14*		9.32*		4.76*		

Notes: The values represent the mean ± standard deviation (SD). The values followed by the same letters within a column do not differ significantly from each other at the 95% Duncan Test.

3.2 Fodder and fuelwood yield from *Calliandra*, and food yield from canna tubers

The analysis of variance (ANOVA) results showed that overall treatments (teak age with agroforestry planting models) had significant effects on the fresh weight of fodder yield per plant compared to the control (monoculture crops in open fields) ($F = 3.30$, $P < 0.05$) (Table 4). DMRT showed that although the control had the highest fresh weight of fodder, it was not significantly different from the three agroforestry models under four-year-old teak. The fresh weight of fodder in the three agroforestry planting models with 11-year-old and 16-year-old teak was significantly lower than that of the control. Furthermore, three agroforestry planting models in each teak age class (4, 11, and 16 years) produced relatively the same fresh weight of fodder (Table 4).

The ANOVA results also showed that the overall treatments (teak age with agroforestry planting models) had significant effects on fuelwood biomass yield compared with the open field ($F = 2.97$, $P < 0.05$) (Table 4). DMRT showed that although the control had the highest fuelwood biomass, it was not significantly different from the three agroforestry planting models under 4-year-old teak stands. Fuelwood biomass in most three-strata agroforestry planting models under 11-year-old and 16-year-old teak tended to be significantly lower than in the control (Table 4).

The ANOVA results also showed that the overall treatments (teak age with agroforestry planting models) had significant effects on fresh tuber yield of *Canna* per plant compared to the control ($F = 30.36$, $P < 0.05$) (Table 4). DMRT showed that the control produced the highest fresh tuber yield. This result was not significantly different from the fresh tuber weight in the alternate row under four-year-old teak. In most agroforestry planting models, the fresh weight of *Canna* tubers at 4, 11, and 16 years was significantly lower than that of the control. Fresh tuber yield in the three agroforestry planting models under four-year-old teak was significantly higher than under 11-year-old and 16-year-old teak (Table 4).

3.3 Yield potential of fodder, fuelwood, and tubers per hectare and Land Equivalent Ratio (LER)

The ANOVA results showed that the overall treatments (teak age with agroforestry planting models) had significant effects on the fresh fodder yield per ha, wood biomass per ha, and fresh tuber weight per ha compared to the control, with values of $F = 15.14$, $P < 0.05$; $F = 9.32$, $P < 0.05$, and $F = 4.76$, $P < 0.05$, respectively (Table 5). DMRT showed that fresh fodder weight, fuelwood biomass, and fresh tuber weight per hectare in the control were significantly higher than in the three agroforestry planting models across all teak age classes. The average volume increment of teak stands during the cropping period ranged from 11.21 to 32.27 m³ ha⁻¹ across different age classes. Its inclusion highlights the long-term productivity advantages of the three-strata agroforestry system compared with the monoculture stands (Table 5).

The results of LER showed that the three-strata teak agroforestry planting models produced a value of more than 1.0 (Table 6). This value showed that the three-strata agroforestry planting models were more productive than the monoculture for the cultivated commodities. Although the production of each commodity per hectare in agroforestry planting models was lower than in the monoculture, the land productivity from the total amount of the total agroforestry commodity yields per hectare was higher than the yield of a single commodity in the monoculture of the cultivated crops. The four-year-old teak stand with alternate rows resulted in the highest LER among all treatment combinations (Table 6).

Table 6. Land Equivalent Ratio (LER) under different teak ages in a strata agroforestry system

No.	Treatments	Land Equivalent Ratio (LER)		
		Border Trees	Alley Cropping	Alternate Rows
1	4-year-old teak	1.69	1.54	2.06
2	11-year-old teak	1.76	1.39	1.48
3	16-year-old teak	1.97	1.62	1.83

LER >1.0 shows that the agroforestry system is relatively more productive than monocultures for the cultivated commodities.

3.4 Nutrient content of *Calliandra* fodder, fuelwood moisture, and caloric value

The ANOVA results showed that the overall treatments (teak age with agroforestry planting models) had significant effects on fodder protein of *Calliandra* compared to the control ($F = 20.71$, $P < 0.05$) (Table 7). DMRT showed that the highest or optimal protein content was achieved in the three agroforestry planting models under four-year-old teak compared to other treatments. The protein content of the fodder in agroforestry planting models could still be maintained in 11-year-old and 16-year-old teak, which was equivalent to monoculture in an open field (Table 7).

The ANOVA results also showed that the overall treatments (teak age with agroforestry planting models) had significant effects on the quality of tannin in *Calliandra* fodder compared to the control ($F = 6.33$, $P < 0.05$) (Table 7). DMRT showed that the tannin content of fodder in the three agroforestry planting models planted in four and 11 years of teak was lower (higher quality) than the control. This trend did not continue in the 16-year-old teak, i.e., the tannin content was equivalent to the control in the open field (Table 7).

The ANOVA also results showed the overall treatments (teak age with agroforestry planting models) had significant effects on the calorific value and moisture content of fuelwood compared to the control, with values of $F = 4.95$, $P < 0.05$, and $F = 3.64$, $P < 0.05$, respectively (Table 7). DMRT showed that the calorie value in most agroforestry planting models under the three age classes of teak was not different from the control in the open field. Only the border tree under 16-year-old teak produced a significantly higher calorific value than the control. The moisture content of fuelwood in most agroforestry planting models under four and 16-year teak was not significantly different from the controls in the open field. Consequently, fuelwood moisture content in the agroforestry planting models under 11-year-old teak was significantly lower than in the control (Table 7).

3.5 Tuber quality of *Canna*

The ANOVA results showed that the overall treatments (teak age with agroforestry planting models) exhibited a significant effect on *Canna* tuber starch compared to the control (monoculture crops in open fields) ($F = 36.20$, $P < 0.05$) (Table 8). DMRT showed a tendency for starch content in agroforestry planting models to be significantly higher than in the control, except for alley cropping and alternate rows in four-year-old teak. Moreover, the starch content of tubers in 11-year-old and 16-year-old agroforestry planting models was significantly higher than in four-year-old teak agroforestry and control in the open field (Table 8).

Table 7. Nutritional quality of *Calliandra* fodder (protein and tannin) and fuelwood (calorie and moisture content) under different teak stands in a three-strata agroforestry system compared with monoculture crops in an open field (control)

Treatments		Quality of *Calliandra* Fuelwood and Fodder							
		Protein Content (%)		Tanin Content (mg/g)		Calorie Values (calorie/g)		Water Content (%)	
Control in the open field		12.93 ± 0.38	ab.	56.58 ± 15.09	c.	4564.8 ± 31.23	ab.	36.51 ± 2.79	d
4-year teak	Border trees	17.68 ± 0.38	c.	22.15 ± 16.69	a.	4577.91 ± 63.8	ab	26.32 ± 14.30	bcd
	Alley cropping	18.36 ± 1.53	c.	21.92 ± 20.17	a.	4620.89 ± 54.22	bc	35.42 ± 7.46	d
	Alternate rows	16.94 ± 1.46	c.	30.72 ± 24.28	ab.	4494.80 ± 67.00	a	30.92 ± 6.21	cd
11-year teak	Border trees	13.64 ± 0.92	ab.	30.25 ± 1.80	ab.	4555.52 ± 21.24	ab	13.55 ± 10.83	ab
	Alley cropping	14.44 ± 1.27	b.	36.53 ± 11.99	ab.	4581.92 ± 69.87	ab	8.37 ± 1.67	a
	Alternate rows	13.89 ± 1.20	ab.	28.45 ± 14.32	ab.	4580.92 ± 46.48	ab	17.44 ± 14.72	abc
16-year teak	Border trees	12.53 ± 1.27	a.	42.90 ± 9.41	bc.	4670.01 ± 28.11	c	30.31 ± 5.80	cd
	Alley cropping	12.86 ± 0.84	ab.	59.83 ± 19.49	c.	4599.37 ± 41.26	bc	12.71 ± 3.21	ab
	Alternate rows	13.60 ± 0.40	ab.	60.03 ± 1.62	c.	4624.43 ± 61.03	bc	22.87 ± 15.03	abcd
F and significance		20.71*		6.33*		4.95*		3.64*	

Remarks: The values represent the mean ± standard deviation (SD). The values followed by the same letters within a column do not differ significantly from each other in the 95% Duncan Test.

Table 8. Starch, protein, and flavonoid content of *Canna* tubers under different teak stands in a three-strata agroforestry system compared with monoculture crops in an open field (control)

Treatments		Quality of Tuber					
		Starch Content (%)		Protein content (%)		Flavonoid Content (μg/g)	
Control in the open field		11.38 ± 0.14	a.	1.86 ± 0.22	ab.	492.56 ± 60.45	b.
4-year teak	Border trees	11.99 ± 0.23	b.	2.46 ± 0.20	c.	465.23 ± 31.99	ab.
	Alley cropping	11.71 ± 0.37	ab.	2.79 ± 0.27	d.	437.03 ± 30.55	a.
	Alternate rows	11.79 ± 0.33	ab.	2.72 ± 0.16	d.	439.80 ± 50.85	a.
11-year teak	Border trees	12.53 ± 0.48	c.	1.70 ± 0.09	a.	437.00 ± 58.87	a.
	Alley cropping	13.68 ± 0.81	d.	1.88 ± 0.23	ab.	465.23 ± 40.85	ab.
	Alternate rows	13.72 ± 0.57	d.	1.75 ± 0.10	ab.	586.70 ± 48.83	c.
16-year teak	Border trees	13.90 ± 0.86	d.	1.87 ± 0.15	ab.	437.00 ± 55.12	a.
	Alley cropping	13.80 ± 0.30	d.	1.85 ± 0.19	ab.	473.70 ± 29.36	ab.
	Alternate rows	13.92 ± 0.43	d.	1.94 ± 0.20	b.	459.60 ± 57.05	ab.
F and significance		36.20*		35.87*		7.99*	

Remarks: The values represent the mean ± standard deviation (SD). The values followed by the same letters within a column do not differ significantly from each other in the 95% Duncan Test.

The ANOVA results also showed that the overall treatments (teak age with agroforestry planting models) had a significant effect on protein content compared to the control (monoculture crops in open fields) ($F = 35.87$, $P < 0.05$) (Table 8). DMRT showed that the total protein content of tubers in the three agroforestry planting models under 4-year teak was higher than in the other treatments. The protein content of tubers in agroforestry planting models under 11-year-old and 16-year-old teak was similar to that of the control (Table 8).

The ANOVA results also showed that the overall treatments (teak age with agroforestry planting models) had a significant effect on flavonoids in tubers compared to the control (monoculture crops in open fields) ($F = 7.99$, $P < 0.05$) (Table 8). DMRT showed that tuber flavonoids in most agroforestry planting models across teak age classes were generally the same as or lower than the control, except in alternate rows of 16-year-old teak (Table 8).

4. DISCUSSION

4.1 Yield of fodder crops, fuelwood, and functional food tubers in three-strata agroforestry

Fresh fodder yield per plant could be maintained in agroforestry planting models under four-year-old teak. This showed that *Calliandra*, as an understory crop for fodder, was quite tolerant to light reduction of up to about 49%. However, the decreasing light intensity in 11 and 16-year-old teak caused a significant decrease in the yield of fresh fodder per plant. Most fodder plants maintained or even increased their yield at light intensities of 44-50%, but their yield decreased dramatically in heavy shade with light intensities of 3-17% [53]. This showed that there was an optimal shade limit in agroforestry planting models for maintaining or increasing fodder yield. The sunlight intensity was too low in the increasingly heavy shade, resulting in a significant decrease in yield.

The fuelwood yield of *Calliandra* was maintained under four-year-old teak. The decrease in light intensity under the heavy shade of 11-year-old and 16-year-old teak reduced photosynthesis, resulting in lower fuelwood yield. The alley-cropping under medium and old-aged teak produced relatively higher wood biomass than other agroforestry planting models because it provided more growing space for *Calliandra*. The biomass of wood energy produced was higher with a larger *Calliandra* growing space [16]. *Calliandra* tolerated four years of teak shade with 49.87% RLI or up to 70% under coconut trees [21].

In this study, the fresh weight of *Canna* tubers per plant decreased as shade or teak tree age increased. Tuber yield was comparable to that in the open field only in alternate rows under four-year-old teak trees. Greater shade from teak stands reduced sunlight intensity, which in turn limited photosynthetically active radiation needed for tuber development. Previous research found that *Canna* tuber weight under albizia trees (RLI 58%) was not significantly different from open-field conditions [54]. Other tuber crops like rodent tuber [55], arrowroot [29], and potato [56] also showed reduced yields under heavier shade. Thus, lower sunlight intensity from shading was a key factor in reducing fresh tuber weight, whereas drought stress under full sunlight in open fields did not have the same effect [57].

4.2 Optimal land use with three-strata agroforestry compared to monoculture

Optimizing land use under teak stands produced more commodities in both the short and long terms, with higher productivity (LER > 1.0) than the monocultures. High LER was also found in a three-strata agroforestry system consisting of Manilkara achras + Jatropha curcas + medical herbs [58] and a two-strata agroforestry system consisting of Falcataria molluccana+arrowroot [59] and teak + *Canna* [60]. Although the individual yield per hectare of fodder, wood, and tuber decreased in some agroforestry planting models, the combination of the three commodities in agroforestry planting models still yielded higher results than when planted separately or in monoculture. The cumulative results of the commodities provide greater benefits and resilience in terms of both economic and environmental benefits. This was more beneficial for the livelihood of smallholder farmers in rural areas, as the land accommodated their needs for food, fodder, and wood energy. Land optimization through agroforestry produces higher productivity or profits compared to monoculture agriculture or forestry, and is ecologically positive for adaptation to climate change.

4.3 Primary and secondary metabolites of *Calliandra* for fodder and fuelwood quality

Teak shade or changes in light intensity affected primary metabolite yields of fodder protein, which were optimized under four-year-old teak with an RLI of 49%. This was consistent with a previous study [61], stating that the protein content of woody plant leaves was higher under shade than in the open field. Fodder yield per plant in the four-year-old teak plantation was not significantly different from that in the monoculture, but the quality of the protein content produced was significantly higher or the highest. Previous studies show that *Calliandra* maintains high leaf productivity at ~70% light [21]. Our results further indicate that it enhances fodder quality by increasing protein content even under 49% light. *Calliandra* grows optimally at temperatures below 30°C [62], and teak shade reduces understory temperatures compared with open areas that often exceed 32°C. Consistent with earlier findings, fodder quality improves under shaded agroforestry conditions [15]. Under teak shade, where humidity is higher, *Calliandra* remains evergreen, supporting sustained leaf production and improved fodder quality. The accumulation of N as a protein-forming element in fodder leaves was higher under agroforestry shade than in an open field [63]. Even N leaves could elevate with increased shade or decreased light intensity [64]. In this study, N induction in protein formation was optimal under moderate light intensity conditions (RLI 49%) in four-year-old teak. Previous studies also showed that [65] fodder protein (beans and legumes) increased by under 50% shade compared to the open field. At lower light intensities below 11 years (RLI 26%) and 16 years (30%) of teak, protein formation did not differ significantly from the control in the open field. While previous studies had shown that limited light increased protein content [66]. This study showed that fodder protein increased only under optimal shade in four-year-old teak (RLI 49%) and declined with greater shading.

Differences in microclimate between agroforestry planting models and open field affected the yield of tannin as a secondary metabolite. Even changes in temperature and humidity generally affected the tannin content of *Calliandra* fodder [37]. Tannins, as secondary metabolites, tend to increase under hotter and drier conditions associated with full sunlight in open fields. In contrast, the lower temperature and higher humidity under the 4-year-old teak canopy (49% RLI) reduced tannin levels. This was consistent with previous studies showing that shade or changes in light intensity influenced the yield of secondary metabolites in leaves [67]. In an open field, most woody plant leaves produced greater amounts of tannin than in a shaded field [61]. Even the yield of secondary metabolites of Vitis vinifera tannins could increase in response to stress caused by excessive ultraviolet light intensity in the open field [68]. Improving the quality of fodder by reducing tannin can be achieved by planting *Calliandra* in four-year teak agroforestry planting models with moderate light intensity (± 49%). However, lower light intensity in 11-year-old teak (RLI 30%) tended to increase tannin levels, which continued to rise until 16-year-old teak (RLI 27%). Ultimately, heavy shading under 16-year-old teak resulted in tannin levels comparable to those of the control. This increase in secondary metabolite yield also played a role in increasing tolerance to low light and resistance to biotic and abiotic stresses [32, 33]. When sunlight was too low (5-15% and 5-25%), it increased the yield of secondary metabolites [69, 70]. This result was consistent with the previous results [66] that the quality and digestibility of fodder (beans and legumes) could be improved by reducing tannins if planted in optimal shade of ± 50% RLI.

The caloric value of fuelwood in most agroforestry planting models generally remained the same as in an open field, except for border trees under 16-year-old teak. Under the teak, *Calliandra* produced less fuelwood but compensated with denser wood of higher calorific value. Denser wood provides greater energy per gram due to reduced air spaces and increased solid material content. According to study [61], plants under shade invested more extractives, which were high-energy compounds. The calorific value of *Calliandra* fuelwood produced in agroforestry planting models and open field still met the standard (SNI 8675:2018), which was above 3,941 calories/gram [71].

Most of the moisture content of fuelwood under four-year-old and 16-year-old teak stands was similar to that of the control in the open field. Calorific value and moisture content were negatively correlated in wood energy [72]. Lower moisture content increased calorific value, as less energy was expended in evaporating water during combustion. Only the alley cropping under 11-year-old teak stands produced a moisture content of less than 12%, which met the wood energy standard requirements of SNI 8675:2018 [71]. This showed that agroforestry planting models could maintain or improve the quality of the produced wood energy.

4.4 Primary and secondary metabolites of canna tubers for functional food quality

Different microenvironmental conditions affected the primary metabolite yield in the form of starch content in tubers [73]. *Canna* is a C3, shade-tolerant species that grows optimally near 28°C [74] and under 68–80% relative humidity [24], making it sensitive to heat stress and only moderately photosynthetic. These traits explain its weaker starch accumulation under full-sun conditions. Although full sunlight in open fields increased gene expression for photosynthesis and sucrose, and starch metabolism [75], and increased the solubility of sugar and starch in leaves [76], semi-tolerant or tolerant plants were sensitive to drought stress [77]. C3 plants with slow photosynthesis rates in shaded conditions were inhibited from producing primary starch metabolites in dry, open conditions [74]. Although light was abundant, under higher temperature and drier conditions in the open field, semi-tolerant or tolerant plants produce lower concentrations of soluble carbohydrates [78]. Plants lose non-structural carbohydrates in the form of starch, sucrose, and hexose during the tuber filling process, which is a form of protection against drought stress [56]. Although shade can also reduce NSC, it was not as significant as the reduction in NSC caused by drought in the open field [79]. In an open field, there was an increase in cell wall content (fibre), which was accompanied by a decrease in NSC due to dry conditions and relatively higher temperatures [78]. Starch synthesis, which mainly occurs in the roots, is strongly affected by enzyme activity [80]. High light intensity and temperature in open fields can inhibit the enzymes that produce amylose and amylopectin [81]. In contrast, shade with higher humidity can increase starch content [82]. In tubers, starch increased under shade for *Canna* [60] and arrowroot [83], fluctuated in yams [40], and showed no significant change in potato [56].

Compared to the open field, protein content in *Canna* tubers increased under four-year-old teak shade (RLI 49%) but declined under 11 and 16-year-old stands as light intensity decreased. Because *Canna* is a semi-tolerant C3 species that grows best at ~28°C [74] and 68–80% relative humidity [24], it is less adapted to the hotter and drier conditions of open fields. Consequently, optimal tuber protein was achieved at

49% RLI, with protein content declining as shading increased and RLI decreased. A previous study [84] showed that there was an increase in total protein at 60% light intensity. The greater the shade, the lower the protein and N content of rodent tubers [32, 55]. Furthermore, the adaptation of tolerant or semi-tolerant plant species to low sunlight intensity was shown by changes in their nitrogen and protein content [32]. Shade could increase nitrogen production, but heavy shade disrupted protein synthesis, resulting in low protein levels [85]. In an open field with higher air temperatures, protein synthesis initially functioned well, but due to low total N levels, total protein levels were also suboptimal. Four-year-old teak shade (49% RLI) provided optimal conditions for total N accumulation and sufficient solar energy for protein synthesis, resulting in the highest protein content.

In agroforestry, flavonoid content in *Canna* tubers tended to decrease or remain stable compared to the open field. An increase in flavonoids in the open field was because flavonoid synthesis increased when plants were exposed to full sunlight and relatively high air temperatures [86, 87], as well as the period or duration of exposure, tended to increase the total flavonoid content [88]. This was because flavonoids appeared as a pre-adaptation of plants to full UV-B radiation, which was relatively harmful to plants in an open field [89]. Plant stress due to high exposure to full sunlight and relatively high air temperatures in the open field promoted an increase in flavonoids [90]. Under tree shade, understory crops were relatively protected from UV-B radiation. Therefore, the plant's defense mechanism of producing flavonoids decreased. Shade affected the regulation of gene expression, including secondary metabolism, particularly flavonoids [91]. Previous studies had shown differences in secondary metabolite production due to increased air temperature or drought stress in the open field [92]. The secondary metabolites in the form of phenolic arrowroot tubers were greater in the open field than under agroforestry shade [59]. Meanwhile, study [93] reported that 50% shade was optimal for obtaining the highest secondary metabolite yield, which reduced as light intensity decreased (RLI 10%-30%).

Light intensity is a major driver of plant competition and regulates physiological and biomass responses [94]. Because radiant energy fuels both heat balance and biochemical processes [95], the reduced light intensity under teak canopies directly limits photosynthesis and crop yield [96, 97]. The study site's wet climate and clay-rich soils provide high water-holding capacity [98], suggesting that soil moisture stress was likely minimal compared with light limitation. Shading can also reduce surface evaporation, helping maintain soil moisture comparable to or even higher than in open areas [99, 100]. Overall, these conditions indicate that limited light, rather than soil moisture, was the primary constraint on crop performance under teak, although microclimatic interactions cannot be fully ruled out.

4.5 Advancing three-strata agroforestry practices of the post-taungya teak plantation system

In medium-aged and mature teak stands, the potential sustainability of understory crop cultivation is compromised by rapid canopy growth, which intensifies shading and limits light availability. In plantation forests, canopy density after thinning depended mainly on crown development and the intensity and frequency of thinning [101]. Teak preferred a light ambient, ensuring the canopy grew rapidly after thinning, which had the potential to cause canopy closure within a short period [102]. This suggested that thinning must be integrated with planting understory crops as part of silviculture practices in agroforestry. Therefore, to maintain crop yield throughout the teak cycle, integrated pruning and thinning frequency and intensity were required to provide space for teak and understory crops in an agroforestry system. The first thinning was recommended when teak trees were five years old, while 50% pruning was performed when teak trees were three years old [103]. Thinning can be performed every three to five years until the end of the cycle (20-25 years) at a rate of 20-50% [104], and pruning could be performed every five years [105]. Thinning to leaving 217 trees ha^{-1} in an 11-year-old teak plantation [106] and 156 trees ha^{-1} at the end of the teak cycle [105] was carried out to maintain the required light intensity for the understory (± 50%). These silvicultural practices had proven beneficial for the remaining teak trees and the yield of food crops under the canopy [105].

Planting and maintaining the understory had a positive effect on teak growth [105]. Leguminous plants (Fabaceae) such as *Calliandra* could form a symbiotic relationship with rhizobium bacteria to fix nitrogen (N_2). This proved that planting leguminous plants could improve soil nutrients [107] and the growth of teak trees [108] as well as food crops [22]. *Canna* can serve as a cover crop to reduce runoff and nutrient leaching. Compared to monoculture, agroforestry remains productive in obtaining long-term (teak wood) and short-term (fodder, wood energy, and food) yields, while also maintaining soil fertility. This contributed to the food and energy security of smallholder farming communities living around forests through social forestry programs for the sustainable teak forest management.

5. CONCLUSIONS

Three-strata agroforestry model under teak can enhance land-use efficiency, as indicated by LER values greater than 1.0. In four-year-old teak stands, the system maintained understory crop yield and improved fodder quality (higher protein and lower tannins) as well as tuber quality (higher starch and protein), while fuelwood quality remained stable. In general, tubers grown under the agroforestry planting model exhibited lower flavonoid concentrations than those produced in open-field conditions. Across teak age classes, the three planting arrangements produced similar fodder yields, with alley cropping yielding more fuelwood in medium and older stands and alternate-row planting supporting higher fresh tuber yields in young stands.

Thinning and pruning can enhance understory light, yet the integration of complete teak silviculture—across the full rotation—with agroforestry systems needs further study. Overall, the findings provide practical guidance for three-strata teak agroforestry in post-taungya systems, but long-term productivity and sustainability will require verification through extended multi-year evaluation.

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