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Research article

Biomass productivity and wood chemical composition at different pruning ages of interspecific hybrid Jatrophas

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Abstract

Importance of the work: Interspecific hybridization has the potential to increase the biomass yield of Jatropha hybrid varieties.

Objectives: To assess the biomass yield and wood chemistry composition of interspecific hybrids between *Jatropha curcas* and *J. integerrima*; to evaluate the effect of pruning ages on biomass yield; and to investigate the relationships between the calorific value and chemical composition in the wood of the Jatropha hybrids.

Materials & Methods: In total, 16 genotypes of interspecific hybrids, parental species and a variety commonly found in Thailand were field planted for testing; their pruned biomass yields were harvested for assessment at three different ages.

Results: The pruning age of the Jatropha hybrids influenced their wood biomass yield, chemical composition and calorific value. With increasing pruning age, the hybrids tended to have higher biomass yield, lignin content and wood calorific value. Variability among genotypes was found in all the traits studied. The biomass potential of interspecific hybrids was greater than that of the parent species. The hybrids outperformed *J. curcas* in terms of biomass yield, moisture content, wood density, chemical composition and calorific value. The interspecific hybrid KUBJL 14 had the greatest potential for biomass production. Furthermore, the correlation coefficient (r) averaged across pruning ages indicated highly significant ($p < 0.01$) relationships between the calorific value of wood and its lignin ($r = 0.70$), lignocellulose ($r = 0.74$), ash ($r = -0.92$) and moisture ($r = -0.80$) contents and its density ($r = 0.50$).

Main finding: The pruning age had positive effects on wood biomass yield, chemical composition and calorific value of Jatropha. The wood traits with a significant correlation with calorific value were identified and could be used to improve wood quality in a Jatropha hybrid breeding program.

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Introduction

Jatropha (*Jatropha curcas* L.) is one of the energy crops that has gained worldwide attention by using the oil from its seeds to produce biodiesel (Montes and Melchinger, 2016). Jatropha could also be used as a biomass source because when grown in plantation, it requires annual pruning, with the immediate regrowth producing annual yields (Samsam, 2013). Large amounts of pruned stems and branches could be used as raw material to produce renewable energy. Jatropha is highly adaptable to its environment, fast-growing, drought-tolerant and tolerant to saline and low-fertility soils (Wani et al., 2012). Thus, Jatropha is an ideal fast-growing shrub for use as a biomass feedstock for power plants. However, the wood of Jatropha has a high moisture content and low density that produce a low calorific value when burned, resulting in less electricity generation (Muakrong et al., 2014). The jatropha genotypes should be improved to increase their biomass yield and wood quality for use as a raw material for power plants.

Interspecific hybridization is an approach to broaden the genetic base of plants. Other research has shown that interspecific hybridization increased biomass yields in several fast-growing species, including willow (Gramlich et al., 2018), poplar (Barghini et al., 2015), eucalyptus (Sumathi and Ramasamy, 2017) and leucaena (Brewbaker, 2013). Jatropha has low genetic diversity (Laosatit et al., 2014), making it less likely to produce enough trait variability to select new superior genotypes. However, Jatropha can be cross-pollinated with plants of the same genus, in particular with *J. integerrima* Jacq (Laosatit et al., 2014; One et al., 2014; Fukuhara et al., 2016). This provides opportunities to expand the genetic base of the jatropha hybrids, with useful traits from both species (Muakrong and Srinives, 2020). The interspecific hybrids between *J. curcas* and *J. integerrima* might be used to increase the quantity and quality of Jatropha biomass. However, in order to identify the elite hybrids, their biomass potential and wood quality must be evaluated.

Cultivation of Jatropha hybrids as a feedstock for sufficient and sustainable energy production requires knowledge of appropriate management practices, as well as the wood properties for use as a biomass energy crop. Desirable properties include having a short pruning cycle as well as a high biomass yield so that the biomass could be harvested quickly (Djomo et al., 2015; Bergante et al., 2016). In the Jatropha genotypes where the seeds are used for biodiesel production, the plants are generally pruned annually (Tar et al., 2011; Samsam, 2013). However, the optimal pruning age for hybrids utilized for biomass has never been determined. Pruning age is an important factor in determining biomass production capacity and the harvesting cycle in the Jatropha hybrids cultivation system (Arunyanark et al., 2022). Furthermore, a consistent and sufficient supply of raw materials for industry and power plants might necessitate the use of biomass from multiple harvesting cycles. This requires data on the biomass yield and energy content of jatropha hybrids at various ages.

Wood is an important raw material for producing heat in the energy production process. Yet, wood is a highly volatile material containing a wide range of organic and inorganic compounds in both type and quantity (Nasser and Aref, 2014). Plant genotypes, growing environments and genotype × environment interactions could all explain variations in wood properties. These elements could have significant impacts on the chemical composition and physical properties of the wood, and thus on their use as a material for energy generation (Li et al., 2017; Dadile et al., 2020). In addition, plant age is a significant factor influencing the properties of wood tissue, which has a direct impact on the production and quality of energy-producing raw materials (Silva et al., 2019). The physical and chemical properties of the wood should be considered in the selection of Jatropha hybrid genotypes for use as a feedstock in biomass energy production.

Although jatropha could be used as biomass feedstock, there are few known genotypes with potential for commercial cultivation. Therefore, Jatropha hybrids with high biomass yield and wood quality must be developed. Consequently, the current study aimed to evaluate the biomass yield and wood chemistry composition of interspecific hybrids between *J. curcas* and *J. integerrima*, to assess the effect of pruning ages on biomass yield and to investigate the relationships between the calorific value and chemical composition in the wood of the hybrids.

Materials and Methods

Experimental design and treatments

The research was carried out at the Department of Agronomy, Kasetsart University, Kamphaeng Saen Campus, Thailand, in a Jatropha research field (14.01°N, 99.58°E). The soil was a sandy clay loam with a pH of 6.88, normal electrical conductivity (2.39 dS/m), moderate organic matter (1.64%) and low total nitrogen (0.073%). In contrast, there were high levels of phosphorus (35.3 mg/kg), potassium (263.9 mg/kg), magnesium (144.2 mg/kg) and calcium (2,948 mg/kg). The field experiment was conducted for 2 yr (April 2013–March

2015). Climatic data for the site were obtained from the Kasetsart University Kamphaeng Saen campus weather station. The rainy season generally began in June and lasted until the end of November. Between April 2013 and March 2014, there was 981 mm of rain and between April 2014 and March 2015, there was 761 mm of rain. During the 2 yr of the experiment, the average air temperature was in the range 15.5–37.4°C.

The experiment was laid out in a split-plot, randomized, complete block design with four replications. The main plots were three different pruning ages (12 months after planting (MAP), 18 MAP and 24 MAP) while the subplots were 16 jatropha genotypes. There were 13 F_1 interspecific hybrids (KUBJL 1, KUBJL 2, KUBJL 3, KUBJL 4, KUBJL 5, KUBJL 6, KUBJL 7, KUBJL 8, KUBJL 10, KUBJL 11, KUBJL 12, KUBJL 13 and KUBJL 14—there was no KUBJL 9). *J. curcas* (JcM10), which had a large canopy size, was the female parent, while *J. integerrima* (Ji 2), which was tall and bush-shaped, was the male parent. A *J. integerrima* (Ji 1) which is commonly found in Thailand was also planted as a control for comparison.

All the Jatropha clones were propagated by cutting in a nursery until 2 mth before being transplanted into the field. The spacings were 1 m between plants and 1.5 m between rows, which corresponded to a planting density of 6,666 plants/ha. Before transplanting, 200 g of commercial compost was applied to each plant. A 15:15:15 ($N:P_2O_5:K_2O$) compound fertilizer was applied at 20 g/plant, at 4 mth and 8 mth after transplanting. Hand weeding was done twice a year during the planting season. The field was furrow-irrigated twice a month during 1–4 MAP. The plants were watered when necessary to supplement the natural rainfall.

Measurement of biomass yield, moisture content and wood density

The Jatropha hybrids were harvested for the above-ground parts from two plants randomly selected per subplot at 12 MAP, 18 MAP and 24 MAP to determine the biomass yield and wood traits. Plants were pruned at 30 cm above the ground and separated into leaves and wood (stem and branches). The separate fresh weights of the wood and leaf sections were measured immediately after harvest. The above-ground biomass per plant was calculated as the biomass yield per hectare. Stems and branches with their diameters in the range 1.5–2.5 cm were cut into pieces 15 cm long, with three pieces randomly taken from each plant for the measurement of wood moisture and density. A 500 g subsample of the total leaf weight from each plot was used to determine the leaf moisture content. The wood and leaf samples were weighed separately and dried for 72 hr at 105°C to obtain constant weight values. The moisture percentages of the fresh weight of the wood and leaves were calculated based on the formula [(fresh weight - dry weight) / fresh weight] × 100. The volume of each wood sample was determined using the water displacement method and the dry wood density was calculated using the oven-dry weight per dry volume.

Measurement of chemical composition and heat value in wood

The whole wood yield from each plot was chopped into small pieces; a 2 kg subsample of fresh wood was taken from each plot and oven-dried at 105°C for 72 hr. Then, wood samples were randomly selected to assess for chemical composition and heat value. The fiber content was separated into neutral detergent fiber, acid detergent fiber and acid detergent lignin and used to calculate the cellulose, hemicellulose, lignin and lignocellulose contents using the methods in Van Soest et al. (1991). The crude ash content was determined following the method of Association of Official Analytical Chemists (1990). A standard bomb calorific combustion method was used to determine the heat value (calorific value) of the wood (Association of Official Analytical Chemists, 1990).

Statistical analysis

All data were subjected to analysis of variance appropriate for a split-plot, randomized, complete block design. Duncan's multiple range test was used for mean comparisons and the significance level was tested at $p < 0.05$ (*) or $p < 0.01$ (**). Simple Pearson correlations (r) were calculated between the calorific value, moisture content, density and chemical composition of the wood yield.

Results

Effect of pruning age on biomass yield and wood quality

The analysis of variance revealed that pruning age had significant or highly significant effects on wood fresh weight, leaf fresh weight, total fresh weight, and leaf moisture content (Table 1), but not on wood moisture content and dry wood density. The effect of pruning age was observed for the wood contents of cellulose, hemicellulose, lignin and ash, but not for the lignocellulose. Pruning age also affected the calorific value. All parameters were highly influenced by genotypic variation. Furthermore, the pruning age × genotype interaction effect was significant or highly significant for all parameters except for dry wood density, ash content and calorific value.

Table 1 Mean square values for three different pruning ages from analysis of variance in split-plot design of biomass fresh weight, moisture content, dry wood density and wood chemical composition of interspecific hybrids

Source of variance	df	Fresh weight			Moisture content		Dry wood density
		Wood	Leaf	Total	Wood	Leaf	
Replication	3	1,767 ns	51.55 ns	2,187 ns	237.05 ns	49.99 ns	0.012 ns
Pruning age	2	11,527**	64.41*	11,897**	9.34 ns	617.40**	0.023 ns
Error A	6	127 ns	9.93 ns	182 ns	180.50 ns	40.44 ns	0.015 ns
Genotype	15	8,841**	222.34**	11,761**	138.70**	16.17**	0.046**
Pruning age × Genotype	30	799**	21.62**	1,029**	22.84*	13.03**	0.003 ns
Error B	135	267 ns	8.28 ns	335 ns	14.59 ns	5.40 ns	0.003 ns
	df	Cellulose	Hemicellulose	Lignin	Lignocellulose	Ash	Calorific value
Replication	3	17.24 ns	0.50 ns	8.87 ns	32.36 ns	4.67 ns	24,170 ns
Pruning age	2	205.94**	143.02**	39.06*	22.01ns	3.27*	503,729**
Error A	6	1.80 ns	2.57 ns	3.66 ns	6.98 ns	0.48 ns	1,557 ns
Genotype	15	15.48**	3.47**	10.34**	33.10**	10.69**	73,638**
Pruning age × Genotype	30	6.50**	3.13**	1.96**	10.34**	0.47 ns	4,118 ns
Error B	135	3.18 ns	1.15 ns	1.01 ns	4.80 ns	0.41ns	4,149 ns

df = degrees of freedom; ns, *, ** = not significant ($p \geq 0.05$), significant ($p < 0.05$) and highly significant ($p < 0.01$), respectively.

Pruning age had a significant effect on the biomass production of Jatropha hybrids. Biomass production was higher in older plants. The total biomass weight increased from 41.14 t/ha at 12 MAP to 62.35 t/ha at 18 MAP and to 66.59 t/ha at 24 MAP (Table 2). The wood fresh weight increased from 34.08 t/ha at 12 MAP to 59.76 t/ha at 24 MAP, while the leaf fresh weight remained relatively constant within the range 6.83–8.68 t/ha. The average proportion of total biomass yield could be divided into 86.74% wood yield and 13.26% leaf yield. The age-related increase in the biomass yields of the Jatropha hybrids was due to an increase in the wood component rather than the leaf component. Notably, the total biomass yield of the Jatropha hybrids was not significantly different between the ages of 18 MAP and 24 MAP. The Jatropha hybrids had a 52% increase in biomass weight from 12 MAP to 18 MAP. The increase in the biomass weight of the Jatropha hybrids from 18 MAP to 24 MAP was only 7%. As a result of its high yield and short period for biomass production, the optimum pruning age of the Jatropha hybrids was 18 MAP.

The pruning age had an effect on the biomass quality of the Jatropha hybrids. The study revealed the effect of pruning age on leaf moisture content of the Jatropha hybrids. At 24 MAP, the highest leaf moisture content was 80.90% (Table 2). However, there was no effect of pruning age on the moisture content of fresh wood or on the density of the dried wood. The average fresh wood moisture content was 56.80% and the dry wood density was 0.59 g/cm^3. In addition, pruning age affected the contents of cellulose, hemicellulose, lignin and ash in the wood. At 12 MAP and 24 MAP, the Jatropha hybrids had the highest cellulose contents (44.61% and 44.09%, respectively). At 18 MAP, the highest hemicellulose content was 16.89% and the lowest ash content was 4.17%. The lignin content increased from 16.38% at 12 MAP to 16.74% at 18 MAP and to 17.88% at 24 MAP. The Jatropha hybrids accumulated more lignin in the wood with increasing plant age; however, there was no difference in the content of lignocellulose (the sum of the cellulose, hemicellulose and lignin contents) in the wood based on the pruning age. The heat value of

Table 2 Effects of different pruning ages on means of biomass fresh weight, moisture content, wood density and wood chemical composition of interspecific hybrids

Pruning age	Fresh weight (t/ha)			Moisture content (%)		Dry wood density (g/cm^3)
	Wood	Leaf	Total	Wood	Leaf	
12 MAP	34.08^c	7.07^b	41.14^b	56.96	75.59^b	0.61
18 MAP	53.68^b	8.68^a	62.35^a	56.37	75.45^b	0.60
24 MAP	59.76^a	6.83^b	66.59^a	57.08	80.90^a	0.57
F test	**	*	**	ns	**	ns
Mean	49.17	7.52	56.69	56.80	77.31	0.59
	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Lignocellulose (%)	Ash (%)	Calorific value (cal/g)
12 MAP	44.61^a	14.93^b	16.38^b	75.92	4.62^a	4,406^c
18 MAP	41.28^b	16.89^a	16.74^b	74.91	4.17^b	4,516^b
24 MAP	44.09^a	13.95^c	17.88^a	75.92	4.43^{ab}	4,581^a
F test	**	**	*	ns	*	**
Mean	43.33	15.25	17.00	75.58	4.41	4,501

MAP = months after planting; ns = not significant ($p \geq 0.05$); * = significant ($p < 0.05$); ** = highly significant ($p < 0.01$).
Means in same column with different lowercase superscripts are significantly ($p < 0.05$) different within each trait.

the wood was also affected by the pruning age. The calorific value increased from 4,406 cal/g at at 12 MAP to 4,516 cal/g at 18 MAP and to 4,581 cal/g at 24 MAP. The calorific value of the Jatropha hybrids increased with plant age. Furthermore, before reaching the harvest age of 24 MAP, the Jatropha hybrids were subjected to drought and aphid infestation, resulting in many leaves falling and the new leaves had not yet fully developed at harvest. Thus, at 24 MAP, the Jatropha hybrids had a lower leaf weight and a higher leaf moisture content than at the other ages.

Biomass production of interspecific jatropha hybrids

Genotypic differences were observed for wood, leaf, and total fresh weights at 12 MAP, 18 MAP and 24 MAP (Table 3). The interspecific hybrids had higher biomass production than their parent species at all pruning ages. Biomass yield production was ranked in the order interspecific hybrids > *J. curcas* (JcM10) > *J. integerrima* (Ji1 and Ji2). The biomass fresh weights of the interspecific hybrids were in the ranges 24.54–79.28 t/ha at 12 MAP, 29.74–122.17 t/ha at 18 MAP and 28.39–131.44 t/ha at 24 MAP. KUBJL 14, 13, 5, 6, 1 and 3 were the hybrids with the highest biomass production. Notably, KUBJL 14 consistently had the highest biomass yield across all pruning ages; at 12 MAP, 18 MAP and 24 MAP, it produced the yields of 79.28 t/ha, 122.17 t/ha and 131.44 t/ha, respectively. Furthermore, comparable results were obtained for both wood and leaf fresh weights. Other interspecific hybrids performed differently at different pruning ages, which signified the genotype × pruning age interaction effect. For example, the fresh weight of KUBJL 3 was among the highest at 12 MAP but not at 18 MAP, while KUBJL 5 had the highest biomass yields at 18 and 24 MAP but not at 12 MAP.

At all studied ages for the jatropha hybrids, the wood and leaf moisture contents and the dry wood density were significantly different between genotypes, except at 24 MAP, when there was no significant difference in the leaf moisture content between genotypes (Table 4). In general, the wood moisture content could be ranked as *J. curcas* > interspecific hybrids > *J. integerrima*, while the dry wood density was as *J. integerrima* > interspecific hybrids > *J. curcas*. There was no significant difference in leaf moisture content between interspecific hybrids and parent species. When the moisture and wood density of the interspecific hybrids were compared across the three pruning ages, the hybrids had wood moisture contents of 48.77–59.19%, leaf moisture contents of 72.94–81.96% and dry wood densities of 0.54–0.67 g/cm^3. Of the interspecific hybrids, KUBJL 4 had the lowest leaf moisture content at the three pruning ages, ranging from 48.77% to 56.73%. KUBJL 11 had the lowest leaf moisture content, ranging from 71.86% to 78.05%, and KUBJL 4 had the highest dry wood density, ranging from 0.60 g/cm^3 to 0.67 g/cm^3. Consequently, this hybrid had a lower wood moisture content and a higher wood density than *J. curcas*.

Table 3 Wood fresh weight, leaf fresh weight and total fresh weight of interspecific hybrids between *Jatropha curcas* and *J. integerrima* at different pruning ages of 12 mth after planting (MAP), 18 MAP and 24 MAP

Genotype	Fresh weight (t/ha) at 12 MAP			Fresh weight (t/ha) at 18 MAP			Fresh weight (t/ha) at 24 MAP		
	Wood	Leaf	Total	Wood	Leaf	Total	Wood	Leaf	Total
KUBJL 1	47.97^{bcd}	7.83^{bcd}	55.81^{bcd}	68.95^{bcd}	8.17^{cde}	77.11^{cd}	100.76^{ab}	10.52^{bcd}	111.25^{ab}
KUBJL 2	50.56^{abc}	8.81^{bcd}	59.39^{bc}	67.88^{bcd}	15.48^{a}	83.36^{bcd}	76.28^{cd}	11.00^{bc}	87.28^{bcd}
KUBJL 3	60.20^{ab}	11.92^{ab}	72.13^{ab}	59.89^{cde}	7.41^{de}	67.30^{cde}	85.28^{bc}	10.91^{bc}	96.19^{bc}
KUBJL 4	28.64$^{f\text{-}i}$	5.34^{def}	33.99$^{e\text{-}h}$	43.39$^{d\text{-}g}$	7.84^{de}	51.22^{def}	60.47^{de}	5.92^{efg}	66.38^{cd}
KUBJL 5	32.06$^{d\text{-}h}$	6.59^{cde}	38.64$^{d\text{-}g}$	95.77^{ab}	16.83^{a}	112.59^{ab}	110.84^{a}	13.91^{b}	124.75^{a}
KUBJL 6	44.47$^{b\text{-}f}$	8.67^{bcd}	53.13$^{b\text{-}e}$	98.53^{a}	12.83^{abc}	111.36^{ab}	71.95^{cd}	8.92^{cde}	80.86^{cd}
KUBJL 7	26.89^{ghi}	4.91^{def}	31.81^{fgh}	46.97$^{d\text{-}g}$	6.00^{def}	52.97^{def}	36.74^{fg}	3.75^{fgh}	40.47^{f}
KUBJL 8	39.08$^{c\text{-}g}$	9.55^{bc}	48.63$^{c\text{-}f}$	24.41^{gh}	5.33^{def}	29.74^{fg}	29.96^{g}	1.58^{h}	31.56^{fg}
KUBJL 10	29.99$^{e\text{-}i}$	5.13^{def}	35.08^{efg}	45.30$^{d\text{-}g}$	7.17^{de}	52.47^{def}	40.31^{efg}	2.31^{gh}	42.63^{ef}
KUBJL 11	19.39^{hij}	5.16^{def}	24.54^{ghi}	34.81^{efg}	8.67^{bcd}	43.48^{ef}	26.16^{gh}	2.23^{gh}	28.39^{fgh}
KUBJL 12	30.58$^{e\text{-}h}$	8.00^{bcd}	38.56$^{d\text{-}g}$	53.58$^{c\text{-}f}$	7.50^{de}	61.08$^{c\text{-}f}$	59.05^{def}	6.83^{def}	65.86^{cd}
KUBJL 13	45.97$^{b\text{-}e}$	10.41^{abc}	56.38^{bcd}	80.19^{abc}	12.5^{abc}	92.69^{abc}	100.34^{ab}	11.48^{bc}	111.84^{ab}
KUBJL 14	65.13^{a}	14.17^{a}	79.28^{a}	105.52^{a}	16.66^{a}	122.17^{a}	113.34^{a}	18.08^{a}	131.44^{a}
JcM10	13.42^{ij}	1.92^{f}	15.34^{hi}	28.91^{fgh}	3.84^{efg}	32.73^{fg}	33.73^{g}	0.66^{h}	34.38^{f}
Ji 1	5.76^{j}	2.11^{f}	7.88^{i}	0.69^{h}	0.83^{g}	1.50^{g}	3.31^{i}	0.69^{h}	4.00^{h}
Ji 2	5.13^{j}	2.55^{ef}	7.68^{i}	4.08^{h}	1.75^{fg}	5.84^{g}	7.59^{hi}	0.48^{h}	8.09^{gh}
F test	**	**	**	**	**	**	**	**	**
Mean	34.08	7.07	41.14	53.68	8.68	62.35	59.76	6.83	66.59

* = significant ($p < 0.05$); ** = highly significant ($p < 0.01$).

Means in same column with different lowercase superscripts are significantly ($p < 0.05$) different.

Table 4 Moisture content and dry wood density of interspecific hybrids between *Jatropha curcas* and *J. integerrima* at different pruning ages of 12 mth after planting (MAP), 18 MAP and 24 MAP

Genotype	12 MAP			18 MAP			24 MAP		
	Moisture content (%)		Dry wood	Moisture content (%)		Dry wood	Moisture content (%)		Dry wood
	Wood	Leaf	Density (g/cm^3)	Wood	Leaf	density (g/cm^3)	Wood	Leaf	Density (g/cm^3)
KUBJL 1	58.87^{bc}	75.29^{bcd}	0.54^{ef}	53.37^{cde}	76.48^{a-e}	0.60^{cde}	59.17^{b}	80.16	0.53^{c}
KUBJL 2	57.91^{bcd}	79.27^{a}	0.64^{bcd}	59.19^{bc}	74.92^{c-g}	0.58^{cde}	59.16^{b}	80.66	0.54^{bc}
KUBJL 3	57.57^{bcd}	74.53^{cde}	0.59^{cde}	54.72^{cde}	75.46^{b-f}	0.61^{b-e}	56.93^{b-e}	81.49	0.63^{b}
KUBJL 4	52.39^{d}	74.41^{cde}	0.67^{abc}	48.77^{e}	74.68^{d-g}	0.60^{cde}	56.73^{b-e}	79.61	0.61^{bc}
KUBJL 5	56.55^{bcd}	75.31^{bcd}	0.61^{cde}	55.80^{bcd}	75.34^{b-f}	0.57^{cde}	57.68^{bcd}	79.99	0.55^{bc}
KUBJL 6	54.92^{bcd}	75.15^{bcd}	0.56^{de}	53.17^{cde}	76.74^{a-d}	0.62^{bcd}	56.13^{c-f}	80.00	0.54^{bc}
KUBJL 7	56.87^{bcd}	77.56^{abc}	0.64^{bcd}	56.05^{bcd}	77.40^{ab}	0.60^{cde}	56.48^{cde}	80.98	0.59^{bc}
KUBJL 8	57.63^{bcd}	75.92^{a-d}	0.61^{cde}	54.18^{cde}	73.62^{fgh}	0.64^{bc}	54.42^{ef}	81.27	0.57^{bc}
KUBJL 10	56.11^{bcd}	76.92^{abc}	0.59^{cde}	58.93^{bc}	73.88^{fgh}	0.55^{de}	57.58^{bcd}	81.96	0.55^{bc}
KUBJL 11	55.25^{bcd}	75.81^{a-d}	0.56^{def}	56.37^{bcd}	71.86^{h}	0.54^{e}	58.62^{bc}	78.05	0.56^{bc}
KUBJL 12	55.62^{bcd}	77.00^{abc}	0.63^{cd}	52.49^{de}	72.94^{gh}	0.61^{b-e}	58.07^{bcd}	81.15	0.58^{bc}
KUBJL 13	54.11^{bcd}	72.96^{de}	0.59^{cde}	52.82^{cde}	78.50^{a}	0.60^{cde}	55.53^{def}	81.69	0.59^{bc}
KUBJL 14	58.44^{bcd}	72.95^{de}	0.56^{de}	57.82^{bcd}	77.27^{ab}	0.60^{cde}	58.11^{bcd}	81.36	0.57^{bc}
JcM10	66.02^{a}	78.94^{ab}	0.48^{f}	71.61^{a}	76.97^{abc}	0.40^{f}	64.90^{a}	85.43	0.41^{d}
Ji 1	59.79^{ab}	76.43^{a-d}	0.74^{a}	62.06^{b}	74.33^{efg}	0.68^{ab}	53.63^{f}	79.93	0.73^{a}
Ji 2	53.34^{cd}	70.94^{e}	0.72^{ab}	54.58^{cde}	76.87^{a-d}	0.73^{a}	50.22^{g}	80.65	0.62^{b}
F test	*	**	**	**	**	**	**	ns	**
Mean	56.96	75.59	0.61	56.37	75.45	0.60	57.08	80.90	0.57

ns = non-significant ($p \geq 0.05$); * = significant ($p < 0.05$); ** = highly significant ($p < 0.01$).
Means in same column with different lowercase superscripts are significantly ($p < 0.05$) different.

Chemical composition and calorific value in the wood of interspecific Jatropha hybrids

There were significant differences in the cellulose, hemicellulose, lignin, lignocellulose and ash contents, as well as in the wood calorific values, between genotypes at 12 MAP, 18 MAP and 24 MAP (Tables 5 and 6). The interspecific hybrids had relatively higher contents of cellulose and hemicellulose than *J. curcas* at 18 and 24 MAP (Table 5). At all pruning ages, the lignin content was clearly ranked as *J. integerrima* (Ji 2) > interspecific hybrids > *J. curcas*. At all three pruning ages, the interspecific hybrids had ranges in the cellulose content of 39.81–46.98%, in the hemicellulose content of 13.06–18.14%, and in the lignin content of 15.22–18.67%. There were similar results for the lignocellulose contents in the wood at 18 and 24 MAP that could be clearly sequenced as *J. integerrima* (Ji 2) > interspecific hybrids > *J. curcas* (Table 6). However, the ash content of the wood was arranged in the opposite order as *J. curcas* > interspecific hybrids > *J. integerrima* (Ji 2). At every pruning age, the calorific value of the wood could be clearly classified as *J. integerrima* (Ji 2) > interspecific hybrids > *J. curcas*. Considering only the interspecific hybrids, at all three pruning ages, the interspecific hybrids had ranges in the lignocellulose content of 72.54–78.69%, in the ash content of 3.09–5.17% and in the calorific value of 4,344–4,644 cal/g. Furthermore, the chemical composition of the wood revealed a pruning age × genotype interaction effect. The interspecific hybrids with the highest cellulose content at 12 MAP were KUBJL 14 and KUBJL 1 (Table 5), while KUBJL 3 had the highest content at 18 MAP and KUBJL 5 had the highest content at 24 MAP. In terms of hemicellulose content, KUBJL 13 had the highest content at 12 MAP, KUBJL 5 had the highest at 18 MAP and KUBJL 8 had the highest at 24 MAP. KUBJL 10 had the highest lignin content at 12 MAP; however, KUBJL 6 had the highest at 18 MAP and KUBJL 11 and KUBJL 10 had the highest at 24 MAP. In the interspecific hybrids, KUBJL 14 had the highest lignocellulose content at the three pruning ages, ranging from 77.32% to 78.34% (Table 6). KUBJL 8 had the lowest ash content, ranging from 3.09% to 4.21%. KUBJL 8 had the highest calorific value between 4,480 cal/g and 4,621 cal/g, followed by KUBJL 6 (4,464–4,644 cal/g). The results revealed that the hybrids outperformed *J. curcas* in terms of chemical composition and calorific value of the wood.

Relationships among calorific value, chemical composition and quality traits of wood

Correlation coefficients between calorific value, chemical composition, moisture content, and wood density were calculated for each pruning age and averaged (n=16). A significant positive correlation was found between calorific value and lignin content at all pruning ages when separated by pruning age (r = 50*–0.74**) (Table 7). At 18 MAP and 24 MAP, there was a positive correlation between calorific value and lignocellulose content (r = 0.72** and 0.77**, respectively).

Table 5 Cellulose, hemicellulose, and lignin contents in the wood of interspecific hybrids between *Jatropha curcas* and *J. integerrima* at different pruning ages of 12 mth after planting (MAP), 18 MAP and 24 MAP

Genotype	Cellulose (%)			Hemicellulose (%)			Lignin (%)		
	12 MAP[1/]	18 MAP	24 MAP	12 MAP	18 MAP	24 MAP	12 MAP	18 MAP	24 MAP
KUBJL 1	46.43^{a}	42.17^{a-d}	45.45^{a-d}	13.59^{e}	17.72^{abc}	13.14^{cd}	15.88^{de}	16.87^{abc}	16.44^{f}
KUBJL 2	43.84^{a-d}	40.36^{de}	43.46^{ef}	13.90^{de}	16.38^{bcd}	13.35^{cd}	16.12^{cde}	17.01^{abc}	17.81^{cde}
KUBJL 3	44.03^{a-d}	43.75^{a}	46.51^{ab}	13.91^{de}	16.21^{cd}	13.99^{bcd}	16.79^{a-e}	16.78^{bcd}	18.19^{cd}
KUBJL 4	44.91^{abc}	41.48^{a-e}	43.43^{ef}	13.86^{de}	17.39^{abc}	14.64^{bc}	15.88^{de}	15.96^{c-f}	16.59^{ef}
KUBJL 5	44.82^{a-d}	41.19^{cde}	45.59^{abc}	15.10^{bcd}	18.14^{a}	15.09^{ab}	15.53^{ef}	16.78^{bcd}	16.64^{ef}
KUBJL 6	45.88^{ab}	40.60^{de}	46.98^{a}	14.11^{de}	16.67^{a-d}	13.06^{cd}	15.92^{de}	18.13^{ab}	18.31^{bcd}
KUBJL 7	42.87^{bcd}	41.37^{b-e}	42.16^{fg}	15.87^{abc}	16.56^{bcd}	14.01^{bcd}	16.83^{a-e}	15.26^{def}	16.61^{ef}
KUBJL 8	42.25^{cd}	40.03^{de}	43.53^{def}	15.06^{bcd}	17.69^{abc}	16.30^{a}	17.24^{a-d}	16.94^{abc}	17.94^{cde}
KUBJL 10	43.70^{a-d}	40.72^{cde}	44.50^{cde}	14.11^{de}	17.34^{abc}	13.64^{bcd}	17.52^{ab}	16.96^{abc}	18.59^{bc}
KUBJL 11	41.66^{d}	39.86^{de}	43.52^{def}	14.70^{cde}	16.34^{bcd}	13.98^{bcd}	17.30^{abc}	17.38^{abc}	18.65^{bc}
KUBJL 12	44.78^{a-d}	39.81^{e}	44.07^{c-f}	15.29^{bcd}	17.52^{abc}	13.70^{bcd}	16.71^{b-e}	15.22^{ef}	16.99^{def}
KUBJL 13	43.86^{a-d}	43.57^{ab}	43.46^{ef}	16.31^{ab}	17.82^{ab}	13.91^{bcd}	16.10^{cde}	16.62^{b-e}	17.89^{cde}
KUBJL 14	46.66^{a}	43.04^{abc}	45.66^{abc}	15.69^{abc}	16.21^{cd}	13.61^{bcd}	16.00^{cde}	18.07^{ab}	18.67^{bc}
JcM10	45.05^{abc}	40.12^{de}	41.30^{g}	16.88^{a}	15.44^{d}	12.64^{d}	14.33^{f}	14.59^{f}	16.34^{f}
Ji 1	46.24^{a}	40.48^{de}	40.92^{g}	15.77^{abc}	15.46^{d}	13.77^{bcd}	15.82^{e}	16.9^{abc}	19.55^{ab}
Ji 2	46.85^{a}	41.92^{a-e}	44.94^{b-e}	14.68^{cde}	17.27^{abc}	14.39^{bc}	18.16^{a}	18.4^{a}	20.87^{a}
F test	*	**	**	**	*	*	**	**	**
Mean	44.61	41.28	44.09	14.93	16.89	13.95	16.38	16.74	17.88

* = significant ($p < 0.05$); ** = highly significant ($p < 0.01$).

Means in same column with different lowercase superscripts are significantly ($p < 0.05$) different.

Table 6 Lignocellulose and ash content, and calorific value in the wood of interspecific hybrids between *Jatropha curcas* and *J. integerrima* at different pruning ages of 12 mth after planting (MAP), 18 MAP and 24 MAP

Genotype	Lignocellulose (%)			Ash (%)			Calorific value (cal/g)		
	12 MAP	18 MAP	24 MAP	12 MAP	18 MAP	24 MAP	12 MAP	18 MAP	24 MAP
KUBJL 1	75.90^{b-f}	76.77^{ab}	75.02^{d-g}	4.11^{bcd}	3.87^{cde}	4.07^{de}	4,394^{b-e}	4,572^{bc}	4,582^{bcd}
KUBJL 2	73.87^{ef}	73.75^{bcd}	74.61^{efg}	5.07^{bc}	4.15^{cde}	4.41^{cd}	4,344^{def}	4,492^{cd}	4,545^{cde}
KUBJL 3	74.73^{def}	76.75^{ab}	78.69^{ab}	4.30^{bcd}	3.72^{def}	3.94^{de}	4,372^{cde}	4,516^{bcd}	4,577^{bcd}
KUBJL 4	74.65^{def}	74.83^{a-d}	74.65^{efg}	4.46^{bc}	4.40^{cd}	4.68^{cd}	4,372^{cde}	4,447^{d}	4,530^{de}
KUBJL 5	75.45^{c-f}	76.11^{abc}	77.32^{a-f}	4.32^{bcd}	3.45^{efg}	4.11^{de}	4,427^{a-d}	4,560^{bc}	4,586^{bcd}
KUBJL 6	75.92^{b-f}	75.40^{a-d}	78.34^{abc}	4.06^{cd}	4.08^{cde}	3.99^{de}	4,464^{abc}	4,590^{b}	4,644^{b}
KUBJL 7	75.57^{c-f}	73.19^{cde}	72.77^{gh}	4.69^{bc}	4.11^{cde}	4.22^{de}	4,403^{b-e}	4,533^{bcd}	4,603^{bcd}
KUBJL 8	74.54^{def}	74.66^{a-d}	77.77^{a-e}	4.21^{bcd}	3.09^{fg}	3.54^{ef}	4,480^{ab}	4,604^{b}	4,621^{bc}
KUBJL 10	75.33^{c-f}	75.03^{a-d}	76.73^{b-f}	4.93^{bc}	4.58^{c}	4.13^{de}	4,463^{abc}	4,524^{bcd}	4,630^{b}
KUBJL 11	73.66^{f}	73.57^{b-e}	76.15^{b-f}	5.17^{b}	4.36^{cd}	5.17^{bc}	4,408^{b-e}	4,485^{cd}	4,599^{bcd}
KUBJL 12	76.78^{bcd}	72.54^{de}	74.76^{d-g}	4.31^{bcd}	4.03^{cde}	4.58^{cd}	4,461^{abc}	4,509^{bcd}	4,583^{bcd}
KUBJL 13	76.27^{b-e}	78.01^{a}	75.26^{c-g}	4.51^{bc}	3.67^{def}	4.15^{de}	4,443^{abc}	4,542^{bcd}	4,598^{bcd}
KUBJL 14	78.34^{ab}	77.32^{a}	77.94^{a-d}	4.87^{bc}	3.49^{efg}	4.14^{de}	4,374^{cde}	4,508^{bcd}	4,565^{b-e}
JcM10	76.26^{b-e}	70.16^{e}	70.28^{h}	7.17^{a}	7.48^{a}	7.52^{a}	4,254^{f}	4,209^{e}	4,410^{f}
Ji 1	77.83^{abc}	72.84^{cde}	74.25^{fg}	4.49^{bc}	5.49^{b}	5.52^{b}	4,319^{ef}	4,454^{d}	4,482^{ef}
Ji 2	79.68^{a}	77.58^{a}	80.19^{a}	3.33^{d}	2.77^{g}	2.73^{f}	4,516^{a}	4,706^{a}	4,747^{a}
F test	**	**	**	**	**	**	**	**	**
Mean	75.92	74.91	75.92	4.62	4.17	4.43	4,406	4,516	4,581

* = significant ($p < 0.05$); ** = highly significant ($p < 0.01$).

Means in same column with different lowercase superscripts are significantly ($p < 0.05$) different.

Table 7 Correlation coefficients (n = 16) between calorific value with wood chemical composition, wood moisture content and wood density of interspecific hybrids at different pruning ages of 12 mth after planting (MAP), 18 MAP and 24 MAP

Calorific value	Cellulose	Hemicellulose	Lignin	Lignocellulose	Ash	Wood moisture content	Dry wood density
12 MAP	-0.10^{ns}	-0.29^{ns}	0.74**	0.15^{ns}	-0.74**	-0.73**	0.25^{ns}
18 MAP	0.26^{ns}	0.60*	0.67**	0.72**	-0.92**	-0.70**	0.80**
24 MAP	0.57*	0.35^{ns}	0.50*	0.77**	-0.88**	-0.69**	0.24^{ns}
Average	0.36^{ns}	0.33^{ns}	0.70**	0.74**	-0.92**	-0.80**	0.50*

^{ns} = non-significant ($p \geq 0.05$); * = significant ($p < 0.05$); ** = highly significant ($p < 0.01$)

Furthermore, there was a strong negative correlation between calorific value and ash content (r = -0.74** to -0.88**), as well as between calorific value and wood moisture content (r = -0.69** to -0.73**). At 18 MAP, there was a positive correlation between calorific value and dry wood density (r = 0.80**) across the average of all pruning ages. The calorific value had strong positive correlations with lignin content (r = 0.70**), lignocellulose content (r = 0.74**) and dry wood density (r = 0.50*). Furthermore, a strong negative correlation was observed between calorific value and ash content (r = -0.92**), as well as between calorific value and wood moisture content (r = -0.80**). However, when the total correlation for all pruning ages (n = 48) was calculated, there was a low and unstable correlation between calorific values with cellulose and hemicellulose contents. The calorific value and lignin content had a strong positive correlation (r = 0.70**), as shown in Fig. 1A, while there was a significant negative correlation between calorific value and ash content (r = -0.70**), as shown in Fig. 1B. The findings revealed a good and consistent relationship between calorific value and lignin, as well as between calorific value and ash content in wood. Furthermore, a negative correlation (r = -0.61**) was found between wood moisture content and dry wood density (Fig. 2), indicating that the two traits were inversely related.

Discussion

Interspecific hybridization helps to increase genetic variability by improving certain traits and taking advantage of hybrid heterosis (Muakrong and Srinives, 2020). *J. curcas* can be cross-pollinated with many plant species in the same genus, more popularly with *J. integerrima* (Laosatit et al., 2014; One et al., 2014; Fukuhara et al., 2016) to produce plants with better wood properties than *J. curcas* (Muakrong et al., 2014). The current research revealed that the F1 hybrid plants of *J. curcas* × *J. integerrima* at pruning age had a higher biomass yield than their parent species. In addition, the hybrids had better wood properties than *J. curcas*, specifically a lower moisture content and higher density of the wood, indicating that the hybrid had inherited good physical characteristics of the wood from the male parent, *J. integerrima*. Wood with a lower moisture content and higher density produces a higher heat energy when burned (Al-Sagheer and Prasad, 2010).

Breeding Jatropha hybrids for biomass yield traits is not easy because the biomass yield traits of fast-growing trees are quantitative and regulated by multiple genes. In addition, there have been reported effects of environment and genotype × environment interactions (Sixto et al., 2016). The current findings revealed a genotype × pruning age interaction effect for biomass yield and wood chemical composition. The genotypes with the best biomass yield and wood chemical composition varied according to pruning age. However, differences in biomass yield traits were found between genotypes of interspecific hybrids. There were several genotypes of interspecific hybrids capable of producing biomass yields greater than 50 t/ha within the first year after planting, with KUBJL 14 having the highest biomass production potential of 79.28 t/ha or a dry weight of up to 48.40 t/ha (data not shown). Raising fast-growing trees is an option to produce a stable level of biomass energy that is greater than

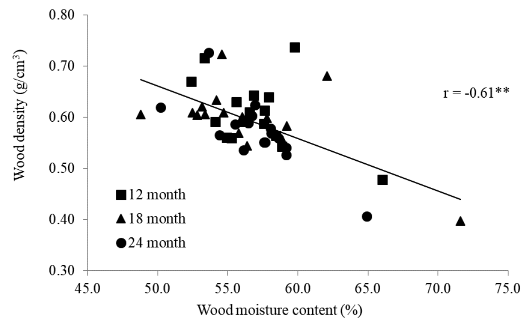

Fig. 2 Correlation between dry wood density and wood moisture content across three pruning ages (12 mth after planting, 18 mth after planting and 24 mth after planting), where r = correlation coefficient (n = 48) and ** = highly significant ($p < 0.01$)

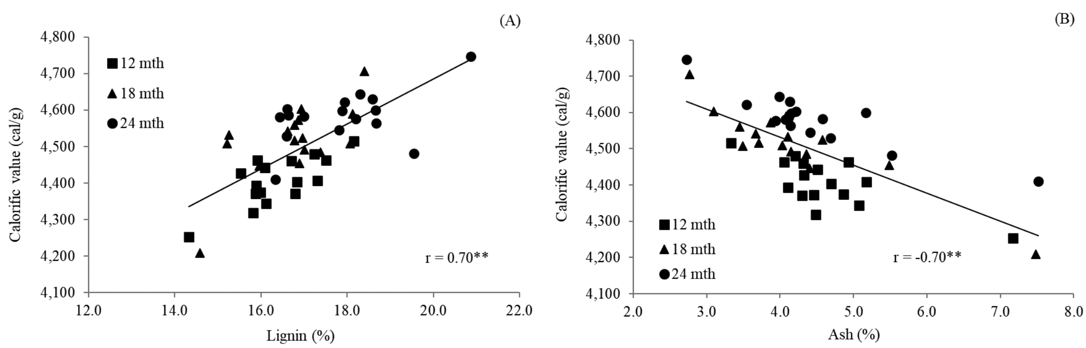

Fig. 1 Correlations based on traits measured across three pruning ages (12 mth after planting, 18 mth after planting and 24 mth after planting) between calorific value and: (A) lignin content; (B) ash content, where r = correlation coefficient (n = 48) and ** = highly significant ($p < 0.01$)

for most other agricultural residues. Currently, there are several types of fast-growing trees used as biomass sources, including species of the genera *Populus*, *Salix*, *Leucaena*, *Acacia* and *Eucalyptus*, which have been developed to produce higher yields using agricultural technology (Aref et al., 2003; Prasad et al., 2011; Djomo et al., 2015). The current study found that the jatropha interspecific hybrids had a high biomass yield potential, with a short duration between pruning cycles. However, the current experiment was carried out on only a small scale. It is necessary to evaluate the hybrids in large field tests across various environments.

Fast-growing trees with short growing harvesting cycles are ideal for use as energy crops (Djomo et al., 2015; Bergante et al., 2016). From the first year, the interspecific hybrids produced high biomass yields. Although the hybrids showed an increase in biomass yield with increasing age, the optimum age for biomass harvesting was 18 MAP, based on the highest rate of biomass increase per period and the proportion of biomass of the hybrids with a large amount of wood. Furthermore, post-pruning regrowth ability is an important characteristic for raising fast-growing trees for biomass energy crops, as it is related to the ability to harvest multiple biomass yields without requiring any replanting investment (Pleguezuelo et al., 2015; Arunyanark et al., 2022). Therefore, jatropha hybrid plantations as a biomass energy crop should be evaluated for biomass yield recovery and stability after pruning.

As an alternative energy source, fast-growing trees with a high biomass per area should be planted to grow wood having a high density and lignin content and low moisture and ash contents to produce a high calorific value product (Demirbas, 2002; Nasser and Aref, 2014; Börcsök and Pásztory, 2021). Based on the current study, the jatropha interspecific hybrids had a better chemical composition and higher calorific values than *J. curcas* because the wood of the jatropha hybrids contained more cellulose, hemicellulose, lignin and lignocellulose than *J. curcas*, while having less ash. The good chemical composition levels and high calorific values of the hybrids were greater than those of *J. curcas*, since they had inherited these desirable traits from *J. integerrima* (Ji 2) that was used as the male parent species. Notably, the chemical composition and calorific value of Ji 2 were superior to Ji1, which showed similar wood properties to the interspecific hybrids and *J. curcas*. Thus, it is necessary to evaluate the phenotypes of both *J. curcas* and *J. integerrima* for the desired characteristics before using them as parental lines.

The calorific value is an indicator in choosing a raw material for energy production (Domingos et al., 2020). The chemical composition of the wood, including the contents of cellulose, hemicelluloses, lignin and ash, were related to the heat energy of the wood (Börcsök and Pásztory, 2021). The current study found that the wood calorific value of the jatropha hybrids was related to the chemical composition of the wood, specifically the lignin, lignocellulose and ash contents. The wood of the hybrids had a high calorific value due to the high lignocellulose and lignin contents coupled with the low ash content. Furthermore, the heat value of the wood was related to its moisture content and density. The low moisture content and high density of the wood of the Jatropha hybrids contributed to their high calorific value. Therefore, these wood traits could be used to indicate the quality of the wood and in the selection of Jatropha hybrid genotypes for high calorific value. In addition, there was an inverse relationship between the moisture content of the wood and the density of the dry wood; thus, one of these traits might be used for selection of superior Jatropha hybrid plants. These two traits can be measured easily and correlated well with the calorific value of the wood, making them useful in a large-scale plant breeding project.

In conclusion, the age of pruning showed an effect on the biomass yield and wood quality of Jatropha interspecific hybrids, whereby biomass yield increased with age. The age of the pruning did not affect the moisture content or the density of the wood. In addition, the pruning age influenced the chemical composition of the wood, including the cellulose, hemicellulose, lignin and ash contents, but not the lignocellulose content. The pruning age influenced the calorific value of the wood. With increasing plant age, the Jatropha hybrids had a higher lignin content and a higher calorific value of wood. Variability between genotypes was observed in all the traits investigated. Interspecific hybrids outperformed parental species in terms of biomass potential. The hybrids outperformed *J. curcas* in biomass yield and wood density, with lower wood moisture content. The wood of the hybrids contained higher cellulose, hemicellulose, lignin and lignocellulose contents, with a higher calorific value than *J. curcas*, while having a lower ash content. Based on these results, the KUBJL 14 hybrid had the greatest potential for biomass production. Furthermore, the calorific value of the wood from the Jatropha hybrids was related to the chemical composition (the lignin, lignocellulose and ash contents). There were significant relationships between the calorific value, moisture content and wood density, revealing that these wood traits could be used to determine the wood quality of the jatropha hybrids.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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