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Enhancing bioenergy and feed production in Southern Thailand: An approach through *Leucaena* cultivation and hydrothermal carbonization

Pimpaporn Pengpit [a], Songyos Chotchutima [b], Sumate Chaiprapat [c], Sucheewan Yoyrurob [d], Boonya Charnnok [a,*]

[a] *Energy Technology Program, Department of Interdisciplinary Engineering, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla 90110, Thailand*
[b] *Department of Agronomy, Faculty of Agriculture, Kasetsart University, Bangkok 10900, Thailand*
[c] *Department of Civil and Environmental Engineering, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla 90110, Thailand*
[d] *Faculty of Science and Technology, Songkhla Rajabhat University, Mueang Songkhla, Songkhla 90000, Thailand*

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ABSTRACT

This study addresses sustainability challenges in Southern Thailand, particularly the scarcity of biomass fuel and animal feed. It investigates the integration of *Leucaena leucocephala* cultivation with hydrothermal carbonization. The research compares the biomass yield and economic feasibility of growing *Leucaena* as a sole crop versus intercropping it with *Para* rubber trees. Sole cropping *Leucaena* produces higher biomass yields and is more economically viable. The wood stem of *Leucaena* is competitive with other biomass fuels used in local power plants, while its leaves, with over 14 % protein content, meet local animal feed market standards. Additionally, branches, which constitute 15.15 %–30.58 % of the total biomass, are usually left as residue but can be used for hydrochar production. The study examines the effects of temperature (235 °C and 265 °C) and retention time (1, 2, and 3 h) on hydrochar properties. Optimal condition (265 °C for 1 h) produces hydrochar with high heating value and energy yield. Using these branches for hydrochar can significantly boost total revenue, with hydrochar contributing 54.9 % to overall revenue (4522.00 USD/ha). Integrating *Leucaena* cultivation with hydrothermal carbonization offers a sustainable solution, enhancing revenue, supporting local energy and feed needs, and promoting environmental sustainability.

1. Introduction

Thailand aims for net-zero emissions by 2065, focusing on renewable energy. In 2022, 13.38 % of its energy came from renewables, with a goal to reach 30 % by 2037 (Thai Alternative Energy Development Plan 2018–2037). The country's tropical climate and large agricultural sector produce significant biomass, totaling 59.54 million tons in 2021. As of 2023, Thailand hosts 241 biomass power plants, with 42 located in the southern region, highlighting its commitment to leveraging domestic renewable resources for energy production.

In Southern Thailand, rubber tree (2220691.36 ha) and oil palm plantations (881366.24 ha) dominate the agricultural sector, as reported by the Thai Office of Agricultural Economics in 2022. Residues from oil palm and rubber trees serve as key biofuel sources for biomass power plants. The government's initiative to increase the number of biomass power plants has led to a surge in demand for these resources, notably causing rice husk prices to rise to 42 USD/ton, which in turn has positively impacted farmers' incomes in other regions. However, this surge has also escalated operational costs for power plants, where biomass accounts for 70 % of expenses, potentially affecting electricity pricing for consumers. Furthermore, prioritizing these plantations has restricted land availability for cultivating high-protein animal feed crops, leading to shortages and necessitating expensive feed imports for the livestock industry.

Therefore, *Leucaena* emerges as a viable solution, thriving in tropical and semi-tropical climates, exhibiting resilience to various weather conditions and the ability to flourish in degraded areas. *Leucaena* wood presents potential as a biofuel source with a calorific value of 19.36 MJ/kg [1], closely resembling that of rubberwood at 17.0 MJ/kg [2], *Acacia mangium* Willd at 16.85 MJ/kg [3], rice husks at 17.26 MJ/kg [4] and bagasse at 16.45 MJ/kg [5]. Additionally, the shorter harvesting cycle of *Leucaena*, every 8–12 months, makes it an attractive choice for small farmers compared to other plants like *Acacia auriculiformis* and *Acacia mangium*, which require longer cycles of 3–4 years per crop. Moreover,

* Corresponding author.
E-mail address: boonya.c@psu.ac.th (B. Charnnok).

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Leucaena leaves contain a high protein content of up to 19.53 % [6], making it a valuable resource for animal feed in livestock such as cattle, goats, chicken, and duct. The cultivation of *Leucaena* not only alleviates the issue of biomass fuel scarcity for biomass power plants but also addresses the shortage of animal feed. While research and cultivation have been undertaken in central and northeastern regions, there has been limited investigation in the southern region.

Following the harvest of *Leucaena* biomass, wood stems ranging from 2 to 10 inches in diameter are sold to biomass power plants, while the dried leaves are marketed to animal feed processing facilities. However, branches and other residues, including pods, which constitute 8.9–12.1 % of the yield [1], are often left in the cultivation area, highlighting the need for effective residue management. These lignocellulosic residues, composed of cellulose (37.10 %), hemicellulose (18.4 %), lignin (22.7 %), ash (1.99 %), extractives (1.90 %), and acetyl groups (2.10 %) [7], offer potential for various carbon-based products.

Innovative uses of *Leucaena* residues include converting pods into adsorbents for water purification, where treatment with methanol and nitric acid followed by thermal processing at 300 °C results in significant metformin removal efficiency [8]. Similarly, *Leucaena* bark, a pulping byproduct, can be transformed into biochar through pyrolysis, offering benefits for soil health and carbon sequestration with a long lifespan [9]. Additionally, thermal-chemical pretreatment of *Leucaena* wood produces high concentrations of reducing sugars, demonstrating the potential for bioenergy production [10]. These applications highlight the versatility of *Leucaena* residues, encouraging sustainable practices and value addition in agricultural waste management.

Hydrothermal carbonization (HTC) offers a novel method for converting *Leucaena* branches into stable, carbon-rich hydrochar, utilizing subcritical water conditions (200–300 °C) to ionize water into reactive hydroxide and hydronium ions. This process, enhanced by the catalytic action of hydronium ions from hemicellulose-derived acetic acid, effectively breaks down lignocellulosic materials. HTC's chemical reactions—hydrolysis, dehydration, condensation, and decarboxylation—transform biomass into hydrochar [11], a potential coal power plant fuel that lowers carbon emissions and supports the transition away from fossil fuels [12]. This environmentally friendly approach not only promotes sustainable biomass management but also contributes to cleaner energy production.

The fuel characteristics of hydrochar, such as fixed carbon to volatile solid ratio (FC/VS), higher heating value (HHV) and combustion stability are significantly influenced by the HTC conditions, particularly temperature and retention time. The optimal temperature and retention time for HTC vary depending on the specific feedstock and desired outcomes. For instance, bamboo-derived hydrochar at 260 °C for 1 h yielded 28.29 MJ/kg with an energy yield of 59.77 % and a fixed carbon content of 63.08 % [11]. Wheat straw hydrochar produced under similar conditions for 30 min resulted in 27.90 MJ/kg with an energy yield of 74.74 % and an FC/VS ratio of 0.59 [13]. Corn cob hydrochar at 260 °C for 2 h yielded 29.21 MJ/kg with an energy yield of 74.46 % and an FC/VS ratio of 0.89 [14]. Additionally, while increasing HTC temperature and retention time tends to reduce mass and energy yields, it also significantly improves hydrochar's fuel quality. However, elevating the temperature from 260 °C to 300 °C marginally increased the HHV of bamboo-derived hydrochar but substantially reduced its mass yield, decreasing the energy yield from 59.77 % to 54.41 % [11]. This highlights the need to carefully balance HTC conditions to optimize hydrochar's fuel properties derived from specific feedstock.

Diversifying the utilization of *Leucaena* branch could potentially boost a farmer's income beyond solely selling the co-products of wood stems and leaves. However, it's worth noting that research within this framework remains relatively limited and requires further investigation. Thus, this research was conducted to evaluate the yield of *Leucaena* cultivation in Southern Thailand, comparing sole crop of *Leucaena* (SCL) with intercropping of *Para* rubber with *Leucaena* (IPL). It also investigated the optimal conditions for converting *Leucaena* branches into hydrochar, through HTC with the goal of boosting income from *Leucaena* cultivation. Ultimately, the study incorporated a thorough economic analysis to determine how hydrochar could potentially enhance the overall financial returns from cultivating *Leucaena*.

2. Materials and methods

2.1. Preparation of Leucaena leucocephala germination

Leucaena leucocephala cv. Taramba was used for this study. Laboratory germination tests were conducted with ten replicates over a 14-day incubation period, resulting in a germination rate of 82.0 ± 11.4 %, deemed suitable for the research.

The pilot plant germination took place at Songkhla Biopower in Songkhla, Thailand. *Leucaena* seeds were scarified, inoculated with rhizobium strain 3126 [1], and sown in moistened soil within seedling bags (5.0 cm in diameter and 15.2 cm in length), with two seeds per bag. After seven days, the weaker seedlings were culled, leaving one strong seedling per bag for further growth. Seed propagation proceeded in a nursery for three months, with germination rates monitored every 21 days. The observed germination rate was 76.4 ± 7.6 %, a crucial data point for assessing the economic feasibility of *Leucaena* cultivation. The germinated seeds were subsequently used for cultivation in the designated farmland areas.

2.2. Cultivation of Leucaena leucocephala

Cultivation was conducted on vacant land by a farmer in Khun Tad Wai, Songkhla, Thailand (Table S-1). The study area was flood-free and not previously used for agricultural purposes. As illustrated in Figs. S–1, *Leucaena* with sole crop was arranged with a spacing design of 2 × 1 m (SCL-1, SCL-2, and SCL-3), resulting in a density of 5000 plants/ha. In addition, intercropping of *Para* rubber with *Leucaena* was carried out in a 15-year-old rubber tree plantation, where *Leucaena* was planted between the rows of *Para* rubber trees, maintaining the same 2 × 1 m spacing, equating to 1850 plants/ha. The rubber trees in the plantation were spaced 3 m apart within rows, with a 7-m spacing between the rows (Figs. S–2). Fertilizer dosing included 18-46-0 at 0.08 kg/plant, 0-0-60 at 0.06 kg/plant, and chicken manure at 0.10 kg/plant.

The biomass was harvested twice, during the first and second years of cultivation. The wood stem was cut at a height of 50 cm above ground level. The mass of the wood stem (with a diameter greater than 2 cm), branches, and leaves in each plot was measured and collected for further characterization. In each plot, samples were randomly collected from three different blocks located in the middle of the cultivation area, and each block was analyzed for chemical characteristics in triplicate.

2.3. Hydrothermal carbonization of Leucaena branch

The *Leucaena* branch residues were processed for hydrochar production, initiating with grinding to 1–2 cm size, followed by oven drying at 60 °C to a consistent weight, and storage in plastic bags at ambient conditions. The branches had the following composition: moisture content (4.66 ± 0.44 %), volatile solids (74.24 ± 1.05 %), fixed carbon (17.53 ± 0.32 %), ash (3.56 ± 0.81 %), carbon (46.41 ± 2.57 %), hydrogen (6.07 ± 0.07 %), oxygen (41.95 ± 1.53 %), nitrogen (0.86 ± 0.15 %), sulfur (0.11 ± 0.03 %), potassium (26910 mg/kg), chloride (5160 mg/kg), and a higher heating value (HHV) of 16.84 MJ/kg (dry).

The hydrothermal carbonization experiments, performed in triplicate, explored temperatures of 235 °C and 265 °C across three retention times (1, 2, and 3 h) using a laboratory-scale pressurized reactor with a 250 mL capacity, monitoring internal conditions via temperature and pressure gauges (P.T. SCIENTIFIC CO., LTD, Thailand). Mixing occurred at 100 rpm during the reaction. A unique feature of process was the recirculation of hydrothermal wastewater (HW). This involved three consecutive HTC cycles. In the first cycle, raw biomass was mixed with distilled water at a 1:10 solid-to-liquid ratio. In the second cycle, raw biomass was mixed with retrieval process water, which was a 1:1 mixture of 125 mL of HW from the first cycle and 125 mL of distilled water. In the third cycle, raw biomass was mixed with retrieval process water, consisting of 125 mL of HW from the second cycle and 125 mL of distilled water (Figs. S–3).

Post-HTC, the produced hydrochars were dried, labeled according to their specific process conditions (e.g., HTC235-1 for hydrochar produced at 235 °C for 1 h), and stored for further analysis. Hydrochar yield, energy densification and energy yield were determined based on Eqs (1)–(3).

$$Hydrochar\ yield\ (\%) = \frac{Mass\ of\ hydrochar\ (g)}{Mass\ of\ feedstock\ (g)} \times 100 \tag{1}$$

$$Energy\ densification = \frac{Heating\ value\ of\ hydrochar\ \left(\frac{MJ}{kg}\right)}{Heating\ value\ of\ feedstock\ \left(\frac{MJ}{kg}\right)} \tag{2}$$

$$Energy\ yield\ (\%) = Hydrochar\ yield \times Energy\ densification \tag{3}$$

2.4. Analytical methods

Moisture, volatile solid, fixed carbon and ash contents of hydrochar were determined according to in-house method based on ASTM D7582. C, H, N, and S of the hydrochars were analyzed by a Flash 2000 CHNS/O Analyzer (ThermoScientific, Italy). The O content was determined as the difference between the total CHNS composition and the ash content (Eq. (4)).

$$O[\%] = 100\% - C[\%] - H[\%] - N[\%] - S[\%] - Ash[\%] \tag{4}$$

HHV was calculated using elemental analysis and ash content values by software program of a Flash 2000 CHNS/O Analyzer (ThermoScientific, Italy). To analyze the combustion behavior of the samples, thermal gravimetric analysis was conducted using a TGA 8000 thermogravimetric analyzer from PerkinElmer, USA. The analysis was conducted under atmospheric pressure conditions with nitrogen as the inert gas. The weight (TG) and the derivative weight (DTG) of the samples were continuously monitored over a non-isothermal temperature range of 25 °C–900 °C, with a heating rate of 20 °C/min. The elemental composition was determined using X-ray fluorescence spectrometer, Zetium, PANalyticaln Netherlands. Fourier transform infrared spectrometer, Vertex 70 (Bruker, Germany) with pellet KBr technique was used to identify functional groups of the samples.

The concentration of sugars, furfural, hydroxylmethylfurfural, and organic acids in the hydrothermal wastewater were analyzed using a high-performance liquid chromatograph (HPLC) (Agilent 1100; Agilent Technologies Co., Ltd.) with a diode array detector (DAD) and refractive index detector (RID), equipped with an Aminex HPX-87H (7.8-mm column and 300 mm in length; Bio-Rad Laboratories Ltd.) [2].

Mn, Fe and K contents in *Leucaena* leaves were quatified using Inductively Coupled Plasma - Optical Emission Spectrometer (ICP-OES), PerkinElmer, AVIO 500 model, USA. Crude fiber, neutral detergent fiber (NDF), acid detergent fiber (ADF), and ash were analyzed according to AOAC [15], and protein content was determined following AOAC [16] guidelines.

2.5. Statistic analysis

This study utilized regression analysis using the Data Analysis tool in Microsoft® Excel for Mac version 16.58 (22021501). A significance level of $p < 0.05$ was used to evaluate the statistical analysis results.

3. Results and discussion

3.1. Yield of Leucaena biomass

Leucaena biomass was harvested in the first and second years of cultivation, comprising wood stem, leaves, and branches. The wood stems was sold to a biomass power plant located 1.5 km away from the plantation. Biomass yields on dry mass, including wood stem, leaves, and branches from SCL (SCL-1, SCL-2, and SCL-3 averaged) were 10.1, 2.9, and 2.9 times higher, respectively, than IPL in the first year (Table 1).

In the second year, only data from SCL-1 were reported, as farmers from SCL-2 and SCL-3 did not harvest biomass. The wood stem and leaf yield of SCL-1 were significantly 37.6 % and 10.9 % higher than in the first year, respectively, while the branch was slightly lower. During the first year, *Leucaena* plants focus on establishing a robust root system and acclimating to the environment. In the second year, with a well-

Table 1
Yield of *Leucaena* biomass.

Biomass yield	Woody stem	Branch	Leaves	Total biomass
1st year ton_{fresh}/ha				
IPL (1-year cutting cycle)	0.99 ± 0.11	1.00 ± 0.28	0.84 ± 0.14	2.83 ± 0.53
SCL-1	24.56 ± 5.11	8.63 ± 1.43	5.57 ± 1.58	38.75 ± 5.07
SCL-2	17.77 ± 3.83	7.50 ± 1.70	5.83 ± 1.52	31.10 ± 5.45
SCL-3	18.33 ± 6.55	3.86 ± 1.27	7.36 ± 3.36	29.56 ± 10.79
[1] [a]	26.90 ± 2.26	4.50 ± 0.50	4.50 ± 1.08	35.90 ± 3.37
[17] [b]	2.70	0.40	2.20	5.30
ton_{dry}/ha				
IPL (1-year cutting cycle)	0.44 ± 0.05	0.51 ± 0.14	0.52 ± 0.09	1.47 ± 0.28
SCL-1	16.01 ± 3.33	5.64 ± 0.93	3.66 ± 1.04	25.31 ± 3.31
SCL-2	9.45 ± 2.03	3.99 ± 0.90	3.90 ± 1.02	17.34 ± 3.05
SCL-3	10.41 ± 3.72	2.22 ± 0.73	4.62 ± 2.10	17.25 ± 6.33
[1] [a]	13.70 ± 0.99	2.10 ± 0.29	1.50 ± 0.46	17.40 ± 1.52
[17] [b]	1.40	0.20	0.90	2.50
2nd yearton_{fresh}/ha				
IPL (1-year cutting cycle)	0.96 ± 0.53	0.56 ± 0.25	0.58 ± 0.19	2.09 ± 0.81
IPL (2-year cutting cycle)	3.81 ± 0.34	1.91 ± 0.36	1.15 ± 0.29	6.88 ± 0.98
SCL 1	34.42 ± 4.46	6.64 ± 0.21	6.17 ± 0.80	47.22 ± 4.76
[1] [a]	43.70 ± 2.33	5.30 ± 0.24	5.80 ± 0.31	54.80 ± 2.61
[17] [b]	12.61	1.20	3.50	7.30
ton_{dry}/ha				
IPL (1-year cutting cycle)	0.61 ± 0.34	0.33 ± 0.14	0.36 ± 0.12	1.30 ± 0.51
IPL (2-year cutting cycle)	2.27 ± 0.20	1.15 ± 0.15	0.75 ± 0.19	4.17 ± 0.53
SCL-1	22.03 ± 2.85	4.25 ± 0.13	4.06 ± 0.52	30.34 ± 3.05
[1] [a]	22.30 ± 1.19	2.40 ± 0.11	2.00 ± 0.11	26.70 ± 1.28
[17] [b]	5.70	0.60	1.40	7.70

Note.
[a] *Leuceana* (*Taramba*), sandy loam, pH of soil 6.5, cultivation in Pak Chong, Nakhon Ratchasima, Thailand.
[b] *Leuceana* (*Taramba*), sandy loam, pH of soil 5.2, cultivation in Pakham, Buriram, Thailand.

established root system, the plants are better equipped to absorb nutrients and water, promoting overall growth. Notably, SCL-1 exhibited 1.3 and 5.5 times higher dried total biomass yield compared to cultivation in northeastern Thailand, Pak Chong, Nakhon Ratchasima, and Pakham, Buriram, respectively, over two years. This discrepancy might be due to higher rainfall in Khun Tad Wai's area (3555–5220 mm/year during 2021–2023 reported by Southern Meteorological Center) compared to Pak Chong (1160 mm/year in 2006) and Pakham (1217 mm/year in 2011) reported by Northeastern Meteorological Center. Moreover, the soil characteristics studied in northeastern Thailand were sandy loam, which had lower water-holding capacity compared to clay loam in this study.

Biomass obtained from IPL with a 1-year cutting cycle in the second year showed a slight decrease compared to the first year. Furthermore, when IPL with a 2-year cutting cycle was compared to a 1-year cutting cycle over a 2-year collection period, the wood stem and branch yields from a 2-year cutting cycle were 2.3 and 1.40 times higher, respectively. In IPL systems, where *Leucaena* is grown alongside rubber trees, there might be increased competition for resources such as water, nutrients, and sunlight. Allowing *Leucaena* plants to grow for an additional year in the 2-year cutting cycle provides more time for the plants to develop root systems, enhancing the plant's ability to absorb water and nutrients from the soil, thus supporting robust above-ground growth and reaching a mature stage, which generally results in increased biomass production compared to younger plants. Consequently, the 2-year cutting cycle appears to be more favorable for intercropping *Leucaena* in rubber plantations, offering increased biomass yield and potential economic benefits for farmers aiming to enhance revenue and make efficient use of available land.

In Khun Tad Wai, prevalent vacant lands in low-lying areas face flooding for 2–4 weeks annually, impacting *Leucaena*'s survival when planted early in the rainy season. This challenge hinders the expansion of SCL cultivation. Land leveling and water management improvements are essential for SCL expansion, potentially supported by government or local biomass power plants. For IPL plantations, a minimum 2-year cutting cycle is advised, though the effects on rubber latex productivity remain unexplored, highlighting the need for further research to understand the implications on rubber production.

The fresh wood stems are sold to the power plant immediately after cutting, while the leaves are sold to animal feed factories or farms after drying. Branches constituted 18.15 %–30.17 % of *Leucaena*'s total biomass (Figs. S–4) and were left as residue post-harvest. The RPR (residue to product ratio) of IPL was found to be 1.6–1.8 times higher than that of SCL (Table 2), which may not contribute to the farmer's income. This RPR pattern aligns with findings from *Leucaena* cultivation in Nakhon Ratchasima [1] and is comparable to other biomass crops like rice, corn, and cassava, suggesting a consistent trend across various biomass sources.

Table 2
Residue to product ratio.

Products	Residues	RPR	References
Leucaena (IPL) (1-year cutting cycle)	Branch: Wood stem	0.87 ± 0.37 (0.33–0.88)	This study
	Branch: Leaves	0.92 ± 0.12 (0.77–1.00)	
	Branch: Wood stem + Leaves	0.43 ± 0.13 (0.24–0.47)	
Leucaena (IPL) (2-year cutting cycle)	Branch: Wood stem	0.50 ± 0.03 (0.48–0.54)	This study
	Branch: Leaves	1.56 ± 0.22 (1.42–1.81)	
	Branch: Wood stem + Leaves	0.38 ± 0.01 (0.36–0.39)	
Leucaena (SCL)[a]	Branch: Wood stem	0.32 ± 0.14 (0.16–0.55)	This study
	Branch: Leaves	1.05 ± 0.47 (0.44–2.07)	
	Branch: Wood stem + Leaves	0.24 ± 0.10 (0.13–0.43)	
Leucaena (SCL)	Branch: Wood stem	0.39 ± 0.20 (0.16–0.87)	[1]
	Branch: Leaves	1.13 ± 0.55 (0.44–2.31)	
	Branch: Wood stem + Leaves	0.28 ± 0.13 (0.13–0.54)	
Leucaena (SCL)	Branch: Wood stem	0.11	[1]
	Branch: Leaves	1.13	
	Branch: Wood stem + Leaves	0.10	
Rubberwood	Offcut	75.00	[18]
	Stumps, roots and branches	31.25	
	Sawdust	18.75	
Rice	Straw	0.45–1.75	[18]
	Husk	0.20–0.27	
Maize	Stalk	0.55–4.33	[18–20]
	Cob	0.20–1.80	
	Husk	0.20–0.30	
Cassava	Stalk	0.09–1.00	
	Peel	0.25–0.91	
Sugarcane	Bagasse	0.05–1.16	
	Top and leaves	0.10–0.30	
Oil palm	Empty bunch	0.23–0.43	
	Fiber	0.10–1.14	
	Shell	0.05–0.07	
	Frond	2.60	
	Male bunch	0.23	

Note.
[a] These values were calculation from 1st year (SCL-1, SCL-2 and SCL-3) and 2nd year (SCL-1).

3.2. Characteristics of Leucaena wood stem and leaves

In assessing wood stem fuel characteristics for biomass power plant suitability, it was found that the ash content of wood stems from both IPL and SCL-1 was below 5 %, meeting biomass power plant requirements (Table 3). Additionally, the HHV of wood stems obtained from IPL (17.22 ± 0.17 MJ/kg) and SCL-1 (16.79 ± 0.11 MJ/kg) were similar, indicating that the cultivation practices had no significant impact on the energy content of the wood. This energy content is slightly below that of wood stems from Pak Chong, Nakhon Ratchasima (18.38–19.64 MJ/kg), indicating that *Leucaena* from the southern region can produce energy of a quality comparable to successful cultivations in the northeast. Rainfall and soil type variations did not significantly affect the wood stem's fuel characteristics.

The wood stems' HHV in this study matched those of other woods accepted by biomass power plants, like *Acacia mangium Willd* (16.85 MJ/kg) [3], rambutan wood (16.84 MJ/kg) and *Para* rubberwood (17.00 MJ/kg), which are in limited supply in the southern region. Consequently, some power plants use oil palm empty fruit bunches with a lower HHV (15.38 MJ/kg) [21] due to their availability from palm oil production, despite their higher potassium content (2.26 %) [22] that poses risks of deposition and corrosion during combustion [23]. *Leucaena*, with a potassium content ranging from 1.35 to 1.56 %, offers a sustainable alternative, reducing the need for additives to counteract potassium's harmful effects, thereby addressing both the quality and quantity gaps in biomass feedstock for power generation.

Leucaena leaves, high in protein, are excellent forage for livestock like goats and cows, and can supplement up to 5 % of poultry feed. This study, covering both SCL and IPL scenarios, shows that the leaves' protein, ash, crude fiber, and mineral levels are comparable to those in local Thai markets (Lop Buri and Kamphaeng Phet) and other regions like Indonesia, India, and Sweden (Table 4). This consistency suggests that *Leucaena* leaves from this research could be a competitive animal feed source, both locally and internationally.

Table 3
Chemical and energy characteristics of *Leuceana* biomass.

Parameter	Branch (1st year)		Wood stem (1st year)		Wood stem[a]	
	IPL	SCL-1	IPL	SCL-1	SCL	
Moisture (%)	4.44 ± 0.09	4.88 ± 0.57	4.11 ± 0.18	4.37 ± 0.30	N/A	N/A
Volatile solid (%)	75.19 ± 0.19	73.30 ± 0.39	76.79 ± 0.42	75.14 ± 0.34	N/A	N/A
Fixed carbon (%)	17.40 ± 0.31	17.67 ± 0.32	17.27 ± 0.35	18.12 ± 0.26	N/A	N/A
Ash (%)	2.97 ± 0.45	4.16 ± 0.61	1.83 ± 0.07	2.37 ± 0.42	2.50	1.70
Carbon (%)	47.47 ± 3.51	45.36 ± 0.29	45.81 ± 0.36	46.46 ± 0.29	45.5	46.1
Hydrogen (%)	6.12 ± 0.06	6.02 ± 0.05	6.11 ± 0.06	6.06 ± 0.04	6.7	6.4
Oxygen (%)	40.54 ± 0.37	43.35 ± 0.32	40.63 ± 0.70	43.74 ± 0.79	47.1	46.8
Nitrogen (%)	0.75 ± 0.07	0.98 ± 0.10	0.54 ± 0.26	0.61 ± 0.07	0.60	0.61
Sulfur (%)	0.10 ± 0.04	0.12 ± 0.03	0.03 ± 0.00	0.05 ± 0.02	0.10	0.07
Potassium (%)	2.08	3.30	1.35	1.56	–	–
Chloride (%)	0.30	0.73	0.18	0.42	–	–
Higher heating value (MJ/kg_{dry})	17.22 ± 0.09	16.45 ± 0.09	17.22 ± 0.17	16.79 ± 0.11	19.64	18.38
Lower heating value (MJ/kg_{dry})	15.96 ± 0.06	15.16 ± 0.09	15.91 ± 0.16	15.32 ± 0.10	N/A	N/A
Fixed carbon/ Volatile solid	0.23 ± 0.00	0.24 ± 0.00	0.22 ± 0.01	0.24 ± 0.00	N/A	N/A
O/C	0.65 ± 0.03	0.72 ± 0.00	0.67 ± 0.00	0.71 ± 0.01	N/A	N/A
H/C	1.56 ± 0.09	1.59 ± 0.01	1.60 ± 0.00	1.57 ± 0.02	N/A	N/A

Note.
[a] *Leuceana Taramba* wood stem, 3rd and 4th year, sandy loam, pH of soil 6.5, Pak Chong district, Nakhon Ratchasima province [1].

In Southern Thailand, unlike other regions, there are no buyers for fresh *Leucaena* leaves, making timely drying crucial to prevent fungal growth that can affect marketability, especially during the rainy season (November and December). A hybrid solar dome offers a solution for quick drying within 24 h, reducing fungal growth and dust contamination. Further studies on practical applications and market acceptance are needed for broader utilization.

3.3. Fuel characteristics of hydrochar derived from Leucaena branch

Changes in hydrochar yield and its fuel properties are influenced by the combined effects of temperature and retention time. Lignin, a complex three-dimensional polymer primarily composed of aryl ether and carbonyl linkages, degrades to release phenolic compounds into hydrothermal wastewater. Cellulose, characterized by its linear, crystalline structure formed by β-1,4-glycosidic bonds of glucan, contrasts with hemicellulose, which consists of pentoses, and hexoses linked by glycosidic ether bonds. This gives hemicellulose an amorphous and more hydrolyzable nature compared to the more rigid cellulose and lignin. Additionally, hemicellulose contains carbonyl groups in forms such as acetyl groups or uronic acid residues. According to Table 5, the highest hydrochar yield was observed in HC235-1. An increase in temperature and retention time led to a linear decrease in hydrochar yield, attributed to the degradation of cellulose, hemicellulose, and lignin due to the disruption of C-O-C (ether, wave number range of 1000–1100 cm^{-1}) and C=O (carbonyl, wave number range of 1700–1744 cm^{-1}) linkages (Figs. S–5). Moreover, acetic acid was predominantly found in hydrothermal wastewater, particularly at 265 °C for 1 h (18.92 g/L) (Table S-2), indicating significant degradation of carbonyl groups in hemicellulose, similar to hydrothermal carbonization of bamboo [11]. In contrast, phenolic compounds were present in relatively smaller amounts, not exceeding 1.08 g/L at 265 °C for 3 h. This observation is consistent with the thermal stability of lignin (280–500 °C), which is higher than that of hemicellulose (200–260 °C) and cellulose (240–350 °C), leading to less degradation of lignin within the studied temperature range.

During processing, volatile compounds decrease, improving the fixed carbon to volatile solids ratio (FC/VS). Regression analysis indicates that retention time has a more significant effect on the FC/VS ratio than temperature, as evidenced by its larger coefficient in the statistical

Table 4
Characteristics of *Leuceana* leaves for animal feed.

Parameter	% dw					mg/kg dw		
	Protein	Ash	Crude fiber	Neutral detergent fiber	Acid detergent fiber	Fe	Mn	K
1st year								
IPL (1-YCC)	21.52 ± 1.06	6.47 ± 0.59	22.19 ± 1.29	32.01 ± 1.49	23.50 ± 2.48	111.48 ± 3.37	150.42 ± 2.95	25631.7 ± 388.91
SCL-1	21.74 ± 1.28	8.25 ± 0.49	24.75 ± 1.28	34.81 ± 4.76	20.49 ± 6.89	224.89 ± 16.09	70.97 ± 0.63	25031.1 ± 143.04
SCL-2	23.20 ± 1.61	7.03 ± 0.13	24.78 ± 2.30	35.57 ± 1.61	29.05 ± 2.29	153.38 ± 10.55	390.68 ± 55.88	19278.9 ± 1641.38
SCL-3	24.46 ± 0.74	6.84 ± 0.94	17.19 ± 2.04	43.76 ± 1.41	39.81 ± 1.61	N/A	N/A	N/A
2nd year								
IPL (1-YCC)	20.83 ± 0.67	6.98 ± 0.37	27.56 ± 0.16	29.56 ± 0.56	11.08 ± 0.66	147.31 ± 14.74	134.46 ± 13.91	23508.9 ± 398.11
IPL (2-YCC)	22.08 ± 1.05	6.98 ± 0.58	24.68 ± 0.73	27.57 ± 0.99	10.54 ± 0.42	167.23 ± 14.49	168.67 ± 16.38	25615.6 ± 1440.22
SCL-1	20.15 ± 0.97	7.38 ± 0.28	29.56 ± 1.13	29.56 ± 1.13	10.16 ± 0.16	116.05 ± 8.61	65.31 ± 8.93	25044.4 ± 937.52
Others								
Lop Buri[a]	14.88 ± 0.13	6.35 ± 0.11	37.44 ± 0.59	40.43 ± 0.32	11.20 ± 0.24	N/A	N/A	N/A
Kamphaeng Phet[b]	15.01 ± 0.15	6.17 ± 0.07	36.11 ± 0.35	43.25 ± 0.60	13.46 ± 0.07	N/A	N/A	N/A
Indonesia[c]	25.47 ± 0.25	9.28 ± 0.51	32.89 ± 0.86	25.27 ± 0.95	11.13 ± 3.22	N/A	N/A	N/A
India[d]	24.2	–	–	37.5	22.7	N/A	N/A	N/A
Sweden[e]	14.2	–	–	42.2	2.4	N/A	N/A	N/A

Note.
[a] Dried *Leucaena* leaves are available in the local market in Lop Buri, Thailand.
[b] Dried *Leucaena* leaves are available in the local market in Kamphaeng Phet, Thailand.
[c] [24].
[d] [25].
[e] [26].

Table 5
Characteristics of hydrochar.

Parameter (%)	HC235-1	HC235-2	HC235-3	HC265-1	HC265-2	HC265-3
Hydrochar yield	59.5 ± 0.04	53.5 ± 1.9	49.1 ± 0.92	48.4 ± 0.50	46.1 ± 0.44	44.0 ± 1.2
Moisture	1.81 ± 0.13	1.56 ± 0.15	1.32 ± 0.05	1.30 ± 0.02	1.40 ± 0.24	1.27 ± 0.04
Volatile solid	63.51 ± 0.37	58.61 ± 0.10	55.17 ± 0.07	53.02 ± 0.10	51.17 ± 0.31	49.79 ± 0.24
Fixed carbon	31.17 ± 0.26	35.89 ± 0.17	38.77 ± 0.12	41.36 ± 0.15	41.68 ± 0.28	44.62 ± 0.23
Ash	3.51 ± 0.03	3.94 ± 0.03	4.74 ± 0.07	4.31 ± 0.15	5.75 ± 0.02	4.32 ± 0.06
Carbon	57.04 ± 0.06	60.84 ± 0.03	62.70 ± 0.15	66.19 ± 0.56	64.86 ± 0.09	67.34 ± 0.12
Hydrogen	5.67 ± 0.02	5.63 ± 0.02	5.48 ± 0.07	5.55 ± 0.06	5.30 ± 0.07	5.41 ± 0.03
Oxygen	32.22 ± 0.37	27.85 ± 0.48	25.34 ± 0.36	22.57 ± 0.12	22.31 ± 0.03	20.11 ± 0.04
Nitrogen	1.33 ± 0.00	1.53 ± 0.01	1.56 ± 0.02	1.99 ± 0.03	2.02 ± 0.02	1.89 ± 0.01
Sulfur	0.06 ± 0.00	0.06 ± 0.00	0.06 ± 0.00	0.11 ± 0.00	0.10 ± 0.00	0.11 ± 0.00
Fixed carbon/volatile solid	0.49 ± 0.01	0.61 ± 0.00	0.70 ± 0.00	0.78 ± 0.00	0.81 ± 0.01	0.90 ± 0.01
O/C	0.42 ± 0.00	0.34 ± 0.01	0.30 ± 0.00	0.26 ± 0.00	0.26 ± 0.00	0.22 ± 0.00
H/C	1.19 ± 0.00	1.11 ± 0.00	1.05 ± 0.01	1.01 ± 0.01	0.98 ± 0.00	0.97 ± 0.00
HHV (MJ/kg_{dry})	21.95 ± 0.02	23.98 ± 0.03	24.87 ± 0.12	26.67 ± 0.26	25.89 ± 0.13	27.30 ± 0.06
LHV (MJ/kg_{dry})	20.73 ± 0.02	22.77 ± 0.03	23.69 ± 0.11	25.47 ± 0.25	24.75 ± 0.11	26.14 ± 0.06
Energy densification	1.33 ± 0.00	1.46 ± 0.00	1.51 ± 0.01	1.62 ± 0.02	1.57 ± 0.01	1.66 ± 0.00
Energy yield (%)	77.46	76.45	72.78	77.05	71.19	71.41

Note: Higher heating value of branch was 16.83 MJ/kg; HC235-1 refers to the hydrochar sample produced at a temperature of 235 °C with a retention time of 1 h.

analysis (Table S-3), underlining its importance in achieving combustion stability. This is demonstrated by smoother thermogravimetric analysis curves and more subtle peaks in the derivative thermogravimetric analysis (Fig. 1), indicating a uniform decomposition rate. This stability is beneficial for controlled combustion in industrial settings, with an enhanced FC/VS ratio (minimum of 0.70 in HC235-3) indicative of superior fuel quality.

During HTC, increasing temperature and retention time significantly enhances dehydration and charring, reducing H and O content relative to C (Fig. 2). This process results in H/C and O/C ratios in hydrochar produced at 265 °C for 1, 2, and 3 h being similar to those of Chinese lignites from Inner Mongolia and Yunnan (average O/C = 0.22 and H/C = 0.81), two of the top lignite-producing regions in China [27]. However, in terms of HHV, hydrochar produced at 265 °C for 3 h (27.30 ± 0.06 MJ/kg) is 1.8 % higher than lignite (average 26.83 MJ/kg) [27], indicating that the quality of the hydrochar is slightly better than that of lignite. Additionally, hydrochar produced at 265 °C for 3 h showed the highest HHV, which is 2.4 % higher than hydrochar produced for a

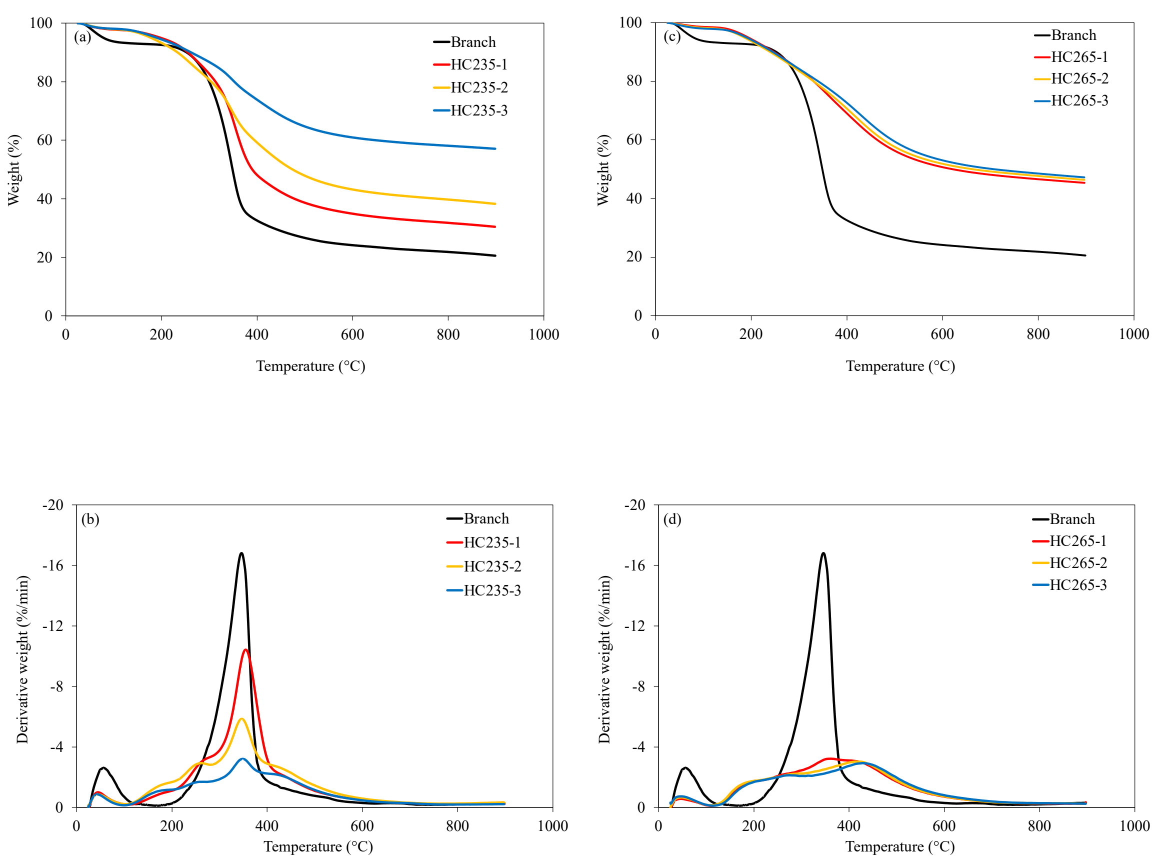

Fig. 1. Differential thermogravimetric analysis profiles of hydrochar: (a) weight at 235 °C (b) derivative weight at 235 °C, (c) weight at 265 °C and (d) derivative weight at 265 °C.

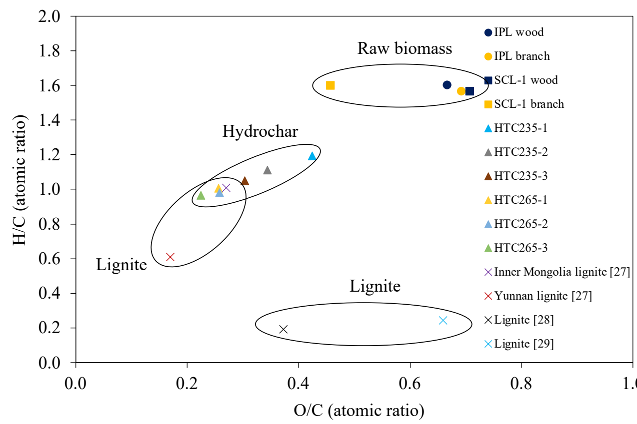

Fig. 2. Atomic ratio of H/C and O/C in raw biomass, hydrochar and coal.
Note: H/C and O/C of lignite [27–29].

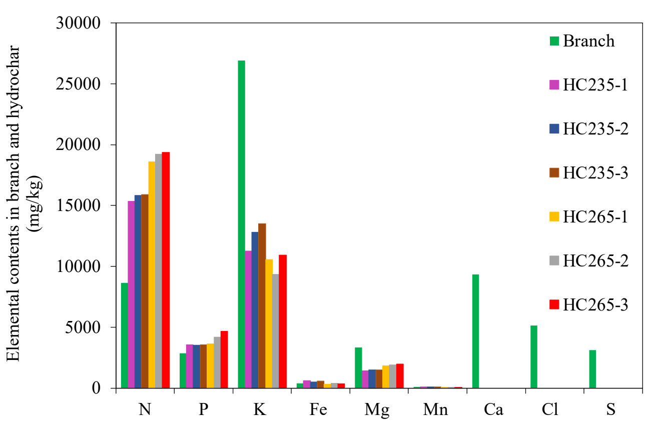

Fig. 3. Elemental content in *Leucaena* branch and hydrochar.
Note: Value of elemental content was averaged of IPL and SCL-1.

shorter duration at the same temperature (HC265-1). This indicates that prolonged HTC treatment times improve the biofuel's quality, making it comparable to traditional coal in terms of carbon content and heating value.(See Fig. 3)

Optimizing HTC conditions for hydrochar involves balancing parameters to enhance the FC/VS ratio, combustion stability, HHV, and energy yield. Higher temperatures and extended retention times improve hydrochar's quality but reduce yield due to volatile solid loss. Producing hydrochar at 265 °C for 1 h, balances fuel properties with a satisfactory energy yield of 77.05 %, offering an energy-efficient and practical fuel solution, considering both quality and yield.

The HC265-1 hydrochar produced has a heating value of 26.67 MJ/kg, which is lower than wheat straw hydrochar (27.90 MJ/kg; 74.74 % energy yield; HTC at 260 °C for 30 min) by 4.4 % [30], corn cob hydrochar (29.21 MJ/kg; 74.46 % energy yield; HTC at 260 °C for 2 h) by 8.7 % [14], and bamboo hydrochar (28.29 MJ/kg; 59.77 % energy yield; HTC at 260 °C for 1 h) by 5.7 % [11]. However, energy yield obtained from HC265-1 is notably higher, surpassing these fuels by 3.1 %, 3.5 %, and 28.9 % respectively, positioning it as a competitive alternative in the solid fuel market.

3.4. Elemental dynamics and optimal conditions in hydrochar production

In *Leucaena* branches, K (26910 mg/kg), Ca (9345 mg/kg), N (8642 mg/kg), Cl (5160 mg/kg), Mg (3355 mg/kg), S (3105 mg/kg), and P (2870 mg/kg) were the most abundant elements. Post-hydrothermal carbonization, the absence of Ca, Cl, and S in the hydrochar highlights their dissolution and removal during processing, offering a clear advantage for using hydrochar as solid fuel by preventing the formation of corrosive compounds.

HTC conditions markedly influenced elemental dynamics: K and Mg were leached due to their solubility, while N and P, less soluble and bonded organically (e.g., proteins, amino acids, nucleic acids), accumulated. Hydrochar production at 265 °C for 1 h resulted in a notable increase in N (21.3 %) and P (2.3 %) accumulation compared to 235 °C for 1 h. Extended reaction times further accentuated these effects, promoting the entrapment of N and P within the hydrochar, thanks to prolonged interactions and chemical transformations within the biomass. Consequently, the highest concentrations of N (19366.7 ± 230.9 mg/kg) and P (4651.0 ± 103.8 mg/kg) were observed at 265 °C over 3 h. When used as solid fuel, hydrochar may increase nitrogen oxide emissions under moderate combustion conditions (300–600 °C) with limited oxygen. To mitigate environmental impacts, a 1-h retention time at 265 °C is advised, balancing environmental concerns with energy yield.

Furthermore, the observed leaching of K (60.8 %) at 265 °C for 1 h, 6.4 % lower than at 235 °C for 1 h, while the slight increase in Mg accumulation (11.6 %) at 265 °C for 1 h reflects its lower solubility compared to K. Higher HTC temperatures particularly promoted the leaching of K because K readily forms ions (K^+) and reacts with anions in the liquid phase, while slightly increasing the Mg content, which has inherently lower solubility at high temperatures. The production of hydrochar at 265 °C for 1 h aids in reducing the accumulation of K and Mg, critical contributors to undesirable effects on combustion systems [23].

Therefore, the production of hydrochar at 265 °C for 1 h represents a balancing act that safeguards combustion systems, environmental concern and delivers high-quality fuel characterized by high FC/VS ratio, high heating values, and elevated energy yield.

3.5. Economic analysis

The cost analysis for cultivating SCL and IPL on a 1-ha plot based on the practices of a small farmer in Thailand included seeding, cultivation, and harvesting costs (Table S-4 and S-5). *Leucaena*, planted once with annual harvests, incurs initial capital investment and operational harvesting expenses in the first year, with subsequent years only incurring harvesting costs. Labor costs for planting were excluded, considering farmer-led efforts. Revenue calculations were based on the wood stem and leaves yield.

The IPL method, both in 1-year and 2-year cutting cycles, was evaluated considering the small annual net cash flow and the substantial initial investment. Although adopting a 2-year cutting cycle improved the benefits by 26 % (Table 6), it may still not be sufficiently advantageous for farmers, as the payback period would exceed the 10-year project duration.

The economic evaluation of sole crop of *Leucaena* cultivation (SCL-1) highlights its viability for small farmers in Southern Thailand. Initially, cultivation demands significant investment, primarily in capital costs, which constitute 79.1 % of total expenses. However, the first year's yield starts to recoup these costs, with a notable reduction in expenses and increase in profit by the second year due to decreased operational costs and higher yield. Remarkably, revenue from *Leucaena* leaves, accounting for 30.7–38.8 % of total revenue, emphasizes the importance of drying and storage to mitigate fungal risks, as there's no direct market for fresh leaves in Southern Thailand. This sustainable agricultural model offers a profitable return on investment, affirming SCL's economic and environmental benefits.

The cost and revenue assessment for hydrochar (HC265-1) production from *Leucaena* branches, following [31], shows a revenue potential of 225.31 USD/ton of feedstock (Table S-6), leading to an expected total revenue of 2484.72 USD/ha over two years of SCL-1 cultivation. With

Table 6
Revenue from *Leucaena* cultivation in an area of one ha.

Cutting		Product[a] (ton)	Price[b] (USD/ton)	Revenue (USD)	Cost (USD)	Profit (USD)
SCL-1						
Year 1	Wood stem	24.56	23.17	569.06		
	Leaves	3.66	86.88	317.98		
	Total	–	–	887.04	1341.58	–
Year 2	Wood stem	34.42	23.17	797.51		
	Leaves	4.06	86.88	352.73		
	Total	–	–	1150.24	80.37	–
Total		-	–	**2037.28**	**1421.95**	**615.33**
IPL						
1-year cutting						
Year 1	Wood stem	0.99	23.17	22.94		
	Leaves	0.52	86.88	45.18		
	Total			68.12	523.87	
Year 2	Wood stem	0.96	23.17	22.24		
	Leaves	0.36	86.88	31.28		
	Total	–	–	53.52	40.15	
Total		–	–	**121.64**	**564.01**	**−442.37**
2-year cutting						
	Wood stem	3.81	23.17	88.28		
	Leaves	0.75	86.88	65.16		
Total				**153.44**	**524.64**	**−371.20**

Note.
[a] The report presents the yield of *Leucaena* as fresh weight for the wood stem and dry weight for the leaves.
[b] The average wood price is referenced from the Songkhla Biopower Plant for fresh hardwood, and the average dry *Leucaena* leaves price is from the local markets in the central region as of November 15, 2023.

HTC costs at 1248.30 USD/ha, the profit stands at 1236.42 USD/ha. Across the two-year SCL project, the total investment is 2670.25 USD/ha, yielding a combined revenue of 4522.00 USD/ha from wood stems, leaves, and hydrochar, with hydrochar accounting for 54.9 % of the total revenue. This increase in value could motivate the expansion of such practices, yet the feasibility of setting up hydrochar production units heavily depends on the local capacity for biomass aggregation and the volume of production, necessitating further investigation.

4. Conclusion

This research demonstrates that integrating *Leucaena* cultivation with hydrothermal carbonization presents a viable solution to the sustainability challenges in Southern Thailand. Cultivating *Leucaena* as a sole crop yields higher biomass and proves more economically feasible than intercropping with *Para* rubber trees. The study highlights the competitive quality of *Leucaena* wood stem as a biomass fuel and its leaves' suitability for the animal feed market. Notably, the typically discarded branches can be effectively utilized for hydrochar production, significantly enhancing total revenue. Thus, this integrated approach not only supports local energy and feed needs but also offers a sustainable agricultural practice that boosts economic returns.

CRediT authorship contribution statement

Pimpaporn Pengpit: Writing – original draft, Visualization, Methodology, Investigation. **Songyos Chotchutima:** Writing – original draft, Methodology, Conceptualization. **Sumate Chaiprapat:** Resources. **Sucheewan Yoyrurob:** Resources, Investigation. **Boonya Charnnok:** Writing – review & editing, Writing – original draft, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2024.121673.
Data will be made available on request.

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