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Research Article

Comparative life cycle assessment of pelletized biomass fuels from corncobs and rubberwood sawdust

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Abstract. This study investigates and compares the environmental impacts of pelletized biomass fuel production from corn cobs and rubberwood sawdust using the Life Cycle Assessment (LCA) methodology across the entire cradle-to-grave process. The assessment encompasses raw material acquisition, production, industrial use, and transportation. Data were collected on resource usage, energy consumption, water usage, and greenhouse gas (GHG) emissions, with the functional unit set as 1 ton of steam generated by a steam generator. Environmental impacts were evaluated using the CML (baseline) 2015 method in openLCA software, with data drawn from the Ecoinvent 3.4 database. Comparisons with other biomass types were also included. The findings indicate that corn cobs are a preferable raw material for pelletized biomass production compared to rubberwood sawdust, as they require less electricity and fewer resources across the lifecycle due to a simpler production process. The study reveals that the highest environmental impacts occur during biomass pellet production, particularly in rubberwood processing, which is energy intensive. Climate change impacts are most significant in the steam production stage, attributed to GHG emissions from biomass pellet combustion. Furthermore, fossil fuels used in other processes and transportation contribute to the overall environmental footprint. Mitigating these impacts would benefit from enhancing energy efficiency, reducing GHG emissions, and expanding the use of renewable energy in production processes. These measures could substantially lessen the environmental effects associated with pelletized biomass fuel production. The impact of data uncertainties in steam production from biomass pellets was assessed through sensitivity analysis. Four key parameters were identified as having significant variability, including transportation of pellets from production plants to steam plants, corn kernel selling price, natural rubber selling price, and allocation method. The transportation distance and agricultural product prices (corn kernel and natural rubber) introduce minimal uncertainty into the LCA results within the tested range (±10%).

Keywords: Life Cycle Assessment; Pelletized Biomass Fuel; Corn Cobs; Rubberwood Sawdust

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1. Introduction

Over the past 30 years, human activities have led to a continuous increase in CO_2 emissions due to rising energy demands (García *et al.*, 2018; Kizuka *et al.*, 2019). An overview of energy consumption in Thailand in 2023 shows a 0.8% increase compared to the previous year, driven by an improving domestic economy that continued from 2022 (EPPO, 2024). In the pursuit of sustainable energy, agricultural residues offer a sustainable alternative to fossil fuels for bioenergy production, with significant potential to reduce greenhouse gas emissions and promote waste management (Guddaraddi *et al.*, 2023). The valorization of diverse crop residues into pellets presents opportunities for circular bioeconomies, though social sustainability aspects require further study (Svensson *et al.*, 2024). The choice of wood-based biomass as a resource for energy production has become a key option in achieving carbon neutrality (Kizuka *et al.*, 2019). Additionally, the use of renewable energy helps reduce energy costs associated with fossil fuels (Nunes *et al.*, 2019). There is a focus on agricultural residues, such as corn, which farmers often burn after harvest, causing air pollution in the form of smog affecting nearby communities. Therefore, using these residues to produce pelletized biomass fuel is a solution. Moreover, wood from general plantations is not suitable as a primary energy source due to its low density and high moisture content (50%). However, when wood is processed into sawdust and dried to reduce its moisture content (6.5%), it is compacted into pellets, doubling its energy density per unit volume. This increases the efficiency of transportation, handling, and fuel combustion (USDA,2009). The demand for wood pellets has been projected using an Integrated Open Leontief model to assess biomass pellet requirements across various sectors. The analysis indicates that biomass pellets will continue to play a significant role in the energy sector from 2023 to 2036 (Buasan *et al.*, 2025).

Pelletized biomass fuel has been used for decades and has been gaining popularity. Thailand ranks second in biomass production, only behind Indonesia, making pelletized biomass fuel an alternative renewable energy source that can meet the increasing domestic energy demand in the future. This is driven by rising demand in foreign markets, abundant domestic raw materials, favorable prices, pollution reduction, and government support (Katinntakul, 2022). However, consumers prefer high-

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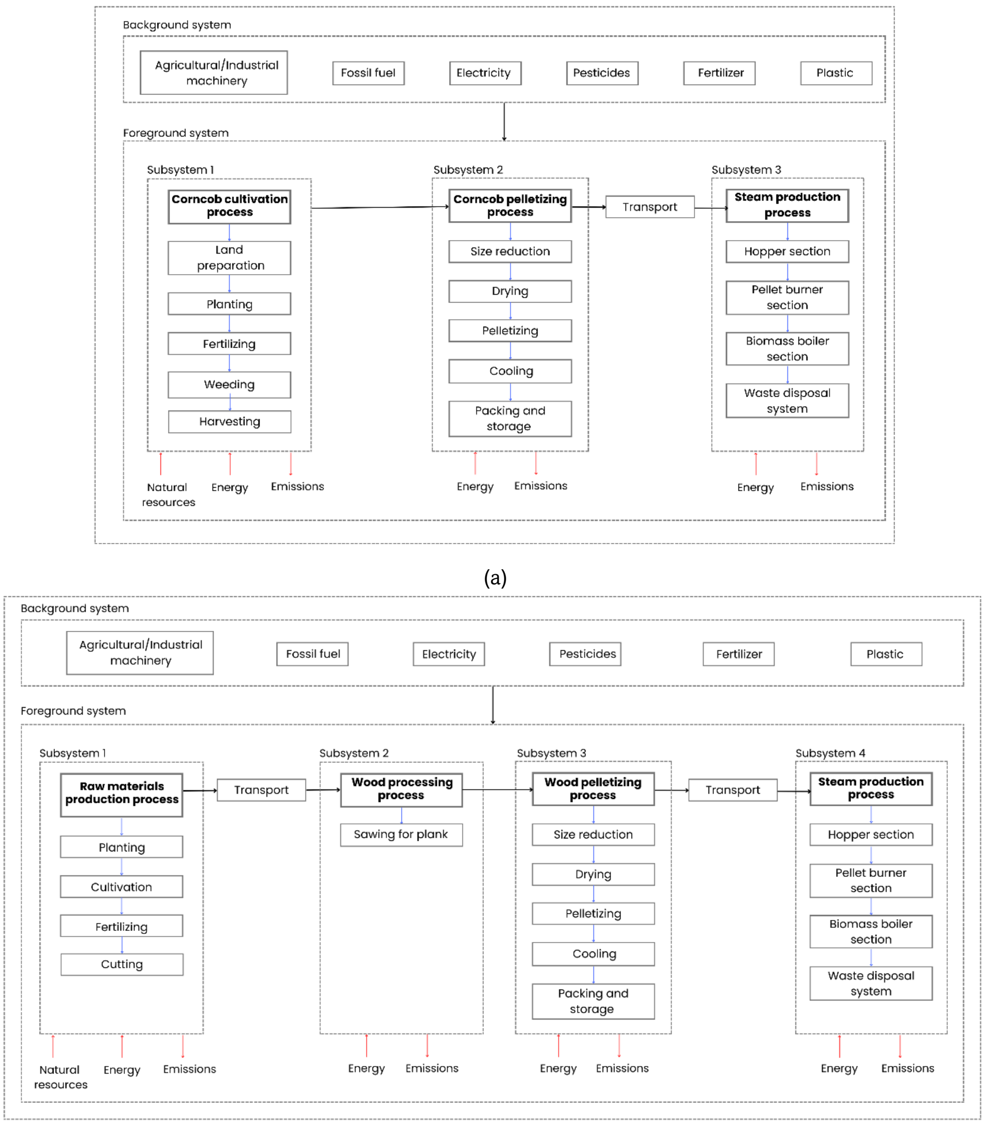
quality pellets that offer high efficiency and produce minimal ash, thereby reducing pollution. Clearly communicating the composition of the fuel is essential to ensure transparency and meet consumer expectations (Zlateva *et al*., 2025).

Life Cycle Assessment (LCA) is a suitable tool for assessing environmental impacts and is widely used for product improvement, strategic planning, and marketing. It measures impacts at all stages, from raw material acquisition to production, transportation, usage, and waste disposal. The study follows ISO 14040:2006 and ISO 14044:2006 standards (ISO 14040, 2006). Regarding environmental issues of biomass pellets, the environmental impact varies depending on the biomass source and production process (Wahyono *et al*, 2022). The environmental impacts of pellet production resulted from fossil depletion, climate change, and particulate matter emissions, largely due to electricity consumption (Nasrin *et al.*, 2017). In addition, a review of research by Muazu *et al.* (2017) emphasized that transportation fuel use is a significant factor in environmental impacts. Besides transportation, the pelletizing and drying processes are identified as critical points contributing to environmental impacts (De la Fuente *et al.*, 2018). The pelletizing process is energy-intensive and involves wood residues, with electricity being a key component of the system's operation (Reed *et al.*, 2012). Activities within pellet plants, such as grinding, pelletizing, and packaging, require large amounts of electricity, significantly contributing to the environmental impact of the production process. Using raw biomass from natural sources has an environmental impact of less than 10%, whereas electricity use across the entire pellet fuel production system contributes to 90% of the total environmental impact (Laschi *et al.*, 2016). An LCA study on wood pellets obtained from sawmills and furniture indicated that the highest contribution was shown by the wood pellets produced from the softwood sawdust in marine aquatic ecotoxicity. In addition, the use of lubricating oil in the production of wood pellets had a substantial impact on the overall environmental outcomes (Hassan *et al.,* 2023). Brás *et al.* (2025) conducted a comprehensive LCA to evaluate the environmental impacts of replacing natural gas (NG) with plant biomass fuels—specifically wood pellets and wood chips. The study revealed that biomass fuels offer significant environmental benefits over NG, including 19% lower GHG emissions and 16% reduced fossil resource depletion; however, biomass options showed higher impacts in land use and certain toxicity categories. The objective of this research is to conduct a comparative life cycle assessment of pelletized biomass fuels from corn cobs and rubberwood sawdust from para rubber trees (*Hevea brasiliensis*). The study will examine the environmental



(b)

Fig. 1 (a) System boundary for the LCA of pelletized biomass fuel from corn cobs**, (b)** System boundary for the LCA of pelletized biomass fuel from rubberwood sawdust

Table 1
Data acquisition and sources of data

Parameter	Corncob pellet		Rubberwood pellet	
	Acquisition	Data source	Acquisition	Data source
Quantity of materials used in process	Primary	Field survey	Primary	Field survey
Electricity and fuel consumption of Wood pelletizing process and Steam production process	Primary	Field survey	Primary	Field survey
Types of machinery and equipment	Primary	Field survey	Primary	Field survey
Modes of transport and distance	Primary	Field survey	Primary	Field survey
Electricity and fuel consumption of cultivation and harvesting	Secondary	Supasri *et al.* (2020)	Secondary	Phungrassami and Usubharatana (2015)
Electricity and fuel consumption of Rubberwood processing	N/A	N/A	Secondary	Phomsoda (2008)
Fuel analysis (As-received basis)	Secondary	Khumhem *et al.* (2017)	Secondary	Arromdee and Kuprianov (2019)

impacts of cultivation, harvesting, wood processing, transportation, pelletized biomass fuel production, and its usage in industrial steam generators. The results will be analyzed and compared, evaluating the life cycle of pelletized biomass fuel from cradle to grave using the openLCA software.

2. Research Methodology

2.1 Goal and Scope Definition

The Life Cycle Assessment (LCA) method was used to analyze and assess the environmental impacts throughout the life cycle of pelletized biomass fuel in both cases. This evaluation covers the production processes and related activities in terms of raw materials and energy used, as well as the outputs from various processes, following the steps outlined in the ISO 14040 life cycle assessment standards series. The functional unit is defined as 1 ton of steam equivalent to 2.78 MJ. The assessment was carried out using the openLCA software (version 1.10.3) with the CML (baseline) 2015 method and the Ecoinvent 3.4 database.

The system boundary includes the processes throughout the life cycle (cradle-to-grave), starting from the acquisition of raw materials for production, processing, pelletized biomass fuel production, fuel usage in industrial steam generators, and transportation. The study was conducted in two pelletized biomass fuel production plants: in Lampang Province (for corncob pellets) and in Rayong Province (for rubberwood pellets). Additionally, the study covered the usage of biomass

Table 2a
Allocation values for pelletized biomass fuel products from corn cobs

Process	Product	Quantity (1) (kg)	Price (2) (THB/kg)	(1) x (2)	Economic Allocation (%)
Corn Cultivation	Corn kernels	927.20	12.35*	11450.92	98.88
	Corncob	223.16	0.58**	129.43	1.12
				Total	100

Note: Data Sources
*The Thai Maize and Produce Traders, June 2024, Thai Maize and Seed Traders Association (2024)
**Absolute Clean Energy (ACE) Company, 2024, Absolute Clean Energy (ACE, 2024a)

Table 2b
Allocation values for pelletized biomass fuel products from rubber wood sawdust

Process	Product	Quantity (1) (kg)	Price (2) (THB/kg)	(1) x (2)	Economic Allocation (%)
Tree planting	Latex	747.88	60.00*	44872.80	93.45
	Rubberwood	1331.66	1.65**	2197.24	4.58
	Rubber residue	18.23	52.00*	947.96	1.97
				Total	100
Tree cutting	Wood logs	1108.51	1.65**	1829.04	93.18
	Branches	223.15	0.60***	133.89	6.82
				Total	100
Wood processing	Timber	500.04	18.00****	9000.72	95.98
	Fresh sawdust	119.56	0.70***	83.69	0.89
	Wood chips	488.91	0.60***	293.35	3.13
				Total	100

Note: Data Sources
*Thai Rubber Association, 2024, Thai Rubber Association (2024a)
**Thai Para Rubber Wood Business Association, 2024, Thai Rubberwood Business Association (2024b)
***Absolute Clean Energy (ACE) Company, 2024, Absolute Clean Energy (ACE, 2024b)
****Heng Panich Timber Trading Co., Ltd., 2024, Hengpanit Co., Ltd. (2024)

Table 3a Life cycle inventory of corncob biomass pellets per functional unit

Process		Flow	Unit	Quantity
Corn Cultivation	Input	Maize seed	kg	0.04
		Nitrogen fertilizer	kg	0.48
		Phosphate fertilizer	kg	0.14
		Potassium fertilizer	kg	0.14
		Atrazine	kg	0.01
		Pesticide	kg	0.01
		Poultry manure	kg	2.94
		Combine harvesting	m^2	23.55
		Tillage ploughing	m^2	23.55
	Output	Corn kernels	kg	926.32
		Corncob	kg	223.16
Pellet Production	Input	Corncob	kg	223.16
		Corncob pellet	kg	9.564
		Polypropylene	kg	0.383
		Electricity	kWh	21.55
		Transport, forklift truck	t*km	0.032
		Transport, loader truck	t*km	0.032
	Output	Corncob pellet	kg	127.52
		Particulates	kg	0.16
Steam production	Input	Corncob pellet	kg	127.52
		Tap water	kg	2666.67
		Electricity	kWh	170.5
		Transport, 18-wheel truck	t*km	10.20
	Output	Steam	kg	1000
		Silica	kg	0.2
		Ash	kg	0.13
		CO_2	kg	174.72
		NO_2	kg	1.57
		SO_2	kg	0.14
		H_2O	kg	55.95

Table 3b Life cycle inventory of rubber wood sawdust pellets per functional unit

Process		Flow	Unit	Quantity
Plantation	Input	Diesel	kg	0.99
		Lubricating oil	kg	0.02
		N – fertilizer	kg	3.56
		P_2O_5 - fertilizer	kg	1.42
		K_2O – fertilizer	kg	3.65
		Urea	kg	7.77
		MOP	kg	4.99
		Glyphosate	kg	0.38
		Pesticide	kg	0.38
	Output	Rubberwood	kg	1331.66
		Latex	kg	747.88
		Rubber residue	kg	18.23
		Emissions from fertilizer		
		N_2O	kg	0.06
		NH_3	kg	0.36
		NMVOC	kg	2.12E-08
		NO_x	kg	0.75
		PM_{10}	kg	5.56
		CO_2 (from urea)	kg	5.70
		NO_3^-	kg	1.07
		Emissions from fuel		
		CO_2	kg	2.23
		CH_4	kg	1.4E-04
		N_2O	kg	8.6E-04
		CO	kg	1.1E-02
		NMVOC	kg	3.4E-03
		NO_x	kg	3.5E-02
		PM_{10}	kg	1.7E-03
		SO_x	kg	3.5E-02
Cutting	Input	Rubberwood	kg	1331.66
		Diesel	kg	0.35
		Lubricating oil	kg	0.02
	Output	Wood logs	kg	1108.51
		Branches	kg	223.15
		CO_2	kg	0.80
		CH_4	kg	3.20E-05
		N_2O	kg	6.50E-06
		CO	kg	4.30E-04
		NMVOC	kg	1.10E-04
		NO_x	kg	1.10E-03
		PM_{10}	kg	2.30E-04
		SO_x	kg	1.50E-03
Sawing for plank	Input	Wood logs	kg	1108.51
		Diesel	kg	0.47
		Electricity	kWh	28.80
	Output	Timber	kg	500.04
		Wood chips	kg	488.91
		Fresh sawdust	kg	119.56
		CO_2	kg	1.47
		CH_4	kg	0.10
		N_2O	kg	0.01
		NO_x	kg	16.08
		CO	kg	20.10
		NMVOC	kg	4.02
Wood pelletizing	Input	Fresh sawdust	kg	119.56
		Wood chips	kg	29.89
		Electricity	kWh	17.45
		Polypropylene	kg	0.30
		Tap water	kg	0.04
		Transport, forklift truck	kg*km	1.59
	Output	Rubberwood pellet	kg	99.63
		Particulates	kg	3.98
Steam production	Input	Rubberwood pellet	kg	99.63
		Electricity	kWh	170.50
		Tap water	kg	2666.67
		Transport, 18-wheel truck	kg*km	7970.67
	Output	Steam	kg	1000
		Ash	kg	0.13
		Silica	kg	0.20
		CO_2	kg	163.29
		H_2O	kg	48.06
		SO_2	kg	0.12
		NO_2	kg	0.82

fuel in a steam generator (about 10 bar pressure and 180°C temperature) at one industrial plant, Songserm Thai Industries Co., Ltd., in Samut Prakan Province. The research scope is illustrated in Figure 1.

2.2 Life Cycle Inventory

In conducting this research, the data used for the LCA was collected from reliable sources and divided into primary and secondary data. The sources of the data are shown in Table 1.

In cases where a process produces more than one type of product, data allocation is necessary. The allocation values for the products are shown in Table 2. This study used economic value as the basis for determining the allocation ratio (economic allocation) to clarify the true environmental impacts of the products or processes being assessed. This approach allows for more accurate differentiation of the impacts arising from the shared use of resources or the joint release of waste.

Details of the input and output data set for each process from the Ecoinvent 3.4 database are shown in Table 3. The data acquisition and relevant assumptions for each process are explained as follows.

2.2.1 Raw Material Production Process

In the case of corncob acquisition, the process starts with cultivating animal feed corn until it produces the corn kernels, which are then shelled and sold. After the corn kernels are separated from the stalk during harvesting, the remaining parts, such as the cob, leaves, and stalk, are left in the field. Harvesting corncobs can be done either manually or with machinery. Various types of machines can be used, including harvesters that separate the corncobs from the stalks and collect them in large containers, thus reducing the time and labor required in the process. Once collected, the corncobs are sent to a biomass pellet fuel production facility.

In the case of rubberwood, the raw material acquisition process is divided into two subprocesses: cultivation and logging. It begins with the preparation of the raw materials from natural sources, including plowing and leveling the land, planting rubber seedlings, maintenance, applying chemicals for pest control and weed removal, harvesting latex, and finally logging the trees. The latex yield decreases when rubber trees reach 25–30 years of age, after which they are felled and replaced with new trees. Other agricultural by-products are used for different purposes, while rubber wood logs with a diameter greater than 6 inches are transported to a rubber wood processing factory. In this research, the LCI data for cultivation were sourced from studies covering data per hectare, collected from 63% of the total rubber tree plantation area in Thailand. The data for logging were sourced from studies covering data yearly.

2.2.2 Wood Processing Process

Rubberwood logs are treated with chemicals immediately due to their high moisture content, which creates ideal conditions for mold and insect growth. Chemical treatment helps reduce mold formation and insect infestation, which could otherwise damage the wood. Upon arrival at the processing factory, the logs are inspected and classified based on type and quality. High-quality logs are sent to a primary sawmill for initial cutting. During this stage, the logs are sawn into long sections according to the required dimensions. Afterward, the initially sawn wood undergoes further cutting in a precision sawmill to achieve a more accurate size and shape. The leftover wood and sawdust from this process are often regarded as waste or useless materials. However, with the initiative to reuse these wastes, sawdust from rubberwood is processed into biomass pellet fuel, which is an increasingly popular renewable energy alternative today.

2.2.3 Wood Pelletizing Process

The process begins with transporting the residual biomass from the previous process to the biomass pellet production facility. The raw material is then subjected to size reduction using machinery to achieve an appropriate size for pelletizing. The biomass powder is dried to adjust the moisture content to around 10-15%. Subsequently, the biomass is pelletized using a pelletizing machine, which applies heat and high pressure to compress the biomass into dense fuel pellets. After pelletizing, the pellets are cooled to reduce their temperature and are stored in a dry area to prepare for packaging into appropriate bags or containers. This process involves a significant amount of machinery with varying operating hours. The energy consumption of each machine is calculated based on its power and operating time (for details on machine energy consumption, see the supplementary data file).

2.2.4 Steam Production Process

For the utilization of the biomass pellets studied in this research, the analysis focuses on using the biomass pellets in an industrial facility. The fuel pellets are fed into a 4-ton-per-hour steam generator via an automatic feed system that accurately controls the fuel input to ensure efficient combustion. The heat generated from combustion is used to produce steam, which is then utilized in various production processes within the factory. It is assumed that the generated ash (both fly and bottom ash) is sent to the landfill as the default disposal method, as no specific ash recovery or hazardous waste treatment processes were reported.

2.2.5 Transportation

In the case of corncobs, there is no transportation of corncob products from the farm to the biomass pellet production plant because the biomass pellet plant cultivates and harvests its corn, ensuring a continuous supply of raw materials for fuel production. This also reduces the cost and time involved in transporting raw materials from external sources. The first transport involves moving corncobs within the biomass pellet production facility, using a loader to cover a distance of 1 km (with a load capacity of 1 ton). A forklift is also used within the plant to transport biomass pellets over a distance of 1 km (with a load capacity of 1 ton). The second transportation phase involves transporting the biomass pellet packaging from the production facility to the industrial factory using an 18-wheel truck over a distance of 80 km (with a load capacity of 30 tons).

For rubberwood, the first transport involves moving rubberwood logs to the wood processing and biomass pellet production factory using a 6-wheel truck over a distance of 9 km (with a load capacity of 6 tons). A pickup truck is also used within the rubberwood plantation to transport logs and branches over a distance of 9.6 km (with a load capacity of 1.5 tons). The second transportation phase involves transporting the biomass pellet packaging from the pellet production facility to the industrial factory using an 18-wheel truck over a distance of 80 km (with a load capacity of 30 tons). A forklift is used to transport sawdust and pellet packaging within the rubberwood processing and biomass pellet production facility over a distance of 1 km (with a load capacity of 0.5 tons). According to the Department of Land Transport of Thailand, most vehicles operating in Thailand comply with the Euro-3 emissions standard (for details on the types of vehicles, distances, and other parameters associated with transportation, see the supplementary data file).

2.3 Impact Assessment

The CML (baseline) 2015 method was used for impact assessment and analysis. Five mid-point impact categories, which are most significant for the environment in Thailand and relevant to the studied parameters, were selected. These include Climate Change (CC), Fossil Depletion (FD), Human

Toxicity (HT), Marine Aquatic Ecotoxicity (MAE), and Freshwater Aquatic Ecotoxicity (FAE). The CML method was chosen as it comprehensively covers all categories relevant to this study (Goree *et al.,* 2002). The LCA quantifies and demonstrates the environmental impacts of corncob biomass pellets throughout the product's life cycle. This analysis was conducted using the openLCA software with the Ecoinvent 3.4 database.

3. Results and Discussion

3.1 Environmental Impacts of Key Processes

The percentage contributions representing the environmental impacts from different processes are shown in Figure 2. The five impact categories were assessed across three processes: raw material acquisition, biomass pellet production, and steam production for the case of corncob pellets. For the case of rubberwood pellets, an additional process, wood processing, was evaluated compared to the corncob pellet case. From Table 4, the LCA results for both biomass pellet types indicate that the environmental impacts of rubberwood pellets are higher than those of corncob pellets in all impact categories. This is due to the greater consumption of resources and energy in each process. Additionally, the environmental impacts in each process are generally higher, except for raw material acquisition. In the case of corncob pellets, this is attributed to the extensive use of chemicals in corn cultivation to boost yields and meet market demand.

However, the analysis highlights that the majority of environmental impacts arise from the biomass pellet production process, which affects multiple impact categories the most. This is because it involves more complex subprocesses compared to other stages and has a relatively high electricity and machine energy consumption. The steam production process for both cases also exhibits considerable energy and electricity usage, and there are significant greenhouse gas emissions resulting from the combustion of biomass pellets, which notably impacts the climate change category.

In the wood processing stage for rubberwood, which involves the use of heavy machinery and diesel fuel, processing large volumes of wood results in significant emissions of carbon dioxide (CO_2) and other greenhouse gases. However, during the raw material acquisition stage, the environmental impact associated with obtaining corncobs and rubberwood is relatively low—less than 6% compared to other life cycle stages. This is primarily due to economic allocation, whereby rubberwood and corncobs are assigned only 4% and 1% of the total product value, respectively, since latex and corn kernels possess significantly higher economic worth. This allocation method substantially reduces the environmental burdens attributed to cultivation and harvesting. Nevertheless, the influence of an alternative physical allocation approach was examined through a sensitivity analysis.

3.2 Environmental Impact of Each Process

To identify the stages with the highest environmental impacts, each main process is disaggregated into specific sub-activities. This breakdown facilitates the identification of critical points where targeted improvements can most effectively reduce overall impacts. Furthermore, this approach provides a foundation for the development of new technologies and innovations aimed at mitigating environmental burdens.

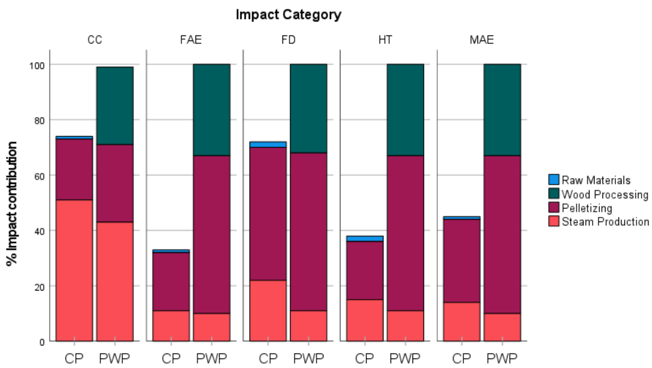


Fig. 2 Percentage contribution of the main processes to various environmental impacts of corncob pellets (CP) and rubberwood pellets (PWP)

Table 4
Environmental impacts of biomass pellets per functional unit

Impact category	Reference unit	Raw material production process	Wood processing process	Pelletizing process	Steam production process	Total
CC (CP)	$kgCO_2$ eq	2.53	N/A	93.51	220.30	316.34
CC (PWP)	$kgCO_2$ eq	0.30	123.34	123.22	187.98	434.84
FD (CP)	MJ	44.63	N/A	1187.67	548.98	1781.28
FD (PWP)	MJ	4.33	794.43	1392.54	270.27	2461.57
FAE (CP)	kg1,4-DB eq	1.25	N/A	35.30	18.14	54.69
FAE (PWP)	kg1,4-DB eq	0.06	54.41	94.06	16.09	164.62
HT (CP)	kg1,4-DB eq	2.70	N/A	31.47	18.08	52.25
HT (PWP)	kg1,4-DB eq	0.16	38.66	66.47	13.45	118.74
MAE (CP)	kg1,4-DB eq	5.62E+03	N/A	1.28E+05	5.99E+04	193520
MAE (PWP)	kg1,4-DB eq	1.79E+02	1.39E+05	2.41E+05	4.33E+04	423479

Note: Climate change (CC), Fossil fuel depletion (FD), Human toxicity (HT), Freshwater aquatic ecotoxicity (FAE), Marine aquatic ecotoxicity (MAE), Corncob pellet (CP), Rubberwood pellet (PWP)

3.2.1 Environmental Impact of Raw Material Acquisition Process

The raw material acquisition processes for both cases have different substances or variables that contribute to environmental impacts. In the case of corncob raw material acquisition, there is no transportation using pickup trucks and six-wheel trucks, as harvesting can occur immediately on-site. Therefore, the primary cause of impact comes from the use of nitrogen fertilizers applied to the soil. Part of the nitrogen is converted into nitrous oxide (N_2O) gas through the nitrification and denitrification processes in the soil. Nitrous oxide is a greenhouse gas with a global warming potential over 300 times greater than CO_2, which affects the climate. When nitrogen fertilizers are used in excess of what is required for corn, nitrates (NO_3) that are not absorbed by plants are leached into groundwater and surface water sources. The accumulation of nitrates in the water leads to rapid algae growth (algal blooms), resulting in eutrophication that decreases oxygen levels in the water and disrupts aquatic ecosystems. Farmers often apply nitrogen fertilizers in amounts that exceed what is necessary. In Thailand, upland crops like cassava, maize, and sugarcane also receive substantial nitrogen inputs, ranging from 20 to 70 kg N/ha (Luanmanee and Paisancharoen, 2011). As a result, excessive fertilizer use can lead to severe impacts on health and the environment. Apart from nitrogen fertilizer, land use change (LUC) associated with corn cultivation has been a significant concern for greenhouse gas emissions. Dunn *et al.* (2013) found that corn ethanol had higher land-use change greenhouse gas emissions than other biofuel feedstocks, such as miscanthus and switchgrass. However, their research showed that these emissions were lower than previously estimated.

In the case of rubberwood raw material acquisition, the primary cause of impact arises from transporting logs and branches using pickup trucks and six-wheel trucks. This is due to the high fuel consumption and pollution emissions, especially when transporting goods over long distances and carrying heavy loads. In addition to CO_2, pickup trucks and six-wheel trucks also emit nitrogen oxides (NO_x) and volatile organic compounds (VOCs), which can lead to acid rain and negatively affect freshwater and marine environments. Furthermore, the use of urea fertilizers plays a significant role in contributing to environmental impacts. Urea contains nitrogen as its main component, and when applied to the soil, it is converted into nitrous oxide (N_2O) by nitrifying and denitrifying bacteria in the soil. This greenhouse gas has a global warming potential of more than 298 times greater than CO_2 over a 100-year period and can also be washed into water bodies by rain, leading to reduced oxygen levels in the water.

3.2.2 Environmental Impact of Rubberwood Processing Process

The assessment of the environmental impacts of the rubberwood processing process found that the factors contributing most to environmental impacts are electricity consumption and fossil fuel use, accounting for over 55% of the climate change impact and over 98% of other impacts. The sawing process for rubberwood requires significant amounts of electricity to power heavy machinery, which is primarily sourced from fossil fuels that emit high levels of greenhouse gases.

Additionally, emissions from combustion during rubberwood processing can lead to air pollution, such as small particulate matter and toxins, which adversely affect human and animal health, as well as contribute to environmental contamination, particularly in the category of climate change impacts.

3.2.3 Environmental Impact of the Biomass Pellet Fuel Production Process

For the analysis of the environmental impacts of the biomass pellet fuel production process in both cases, it was found that the main cause of impacts is the electricity consumption in the biomass pellet production process, accounting for 99% in all impact categories. This is similar to trends observed in other studies (Muazu *et al.*, 2017; Laschi *et al.*, 2016). The primary reason is the complexity of the production process, which requires a significant amount of electrical energy, particularly during the drying, grinding, and pelletizing stages. If energy usage is not managed or planned effectively, energy loss or excessive energy consumption will increase environmental impacts. Additionally, energy use in various processes can also lead to noise and heat issues, which have environmental impacts as well.

Regarding polypropylene, which is used here as packaging material for biomass pellets, although it represents a smaller portion compared to electricity usage, this material still significantly contributes to greenhouse gas emissions and the consumption of fossil fuel resources during production. Moreover, it may have long-term environmental impacts due to the durability and difficulty of biodegradation of this type of plastic.

3.2.4 Environmental Impact of the Steam Production Process

Figure 3 shows that the steam production process using biomass pellets in both cases has similar environmental impacts across various categories. When considering the environmental impacts of the steam production process, it was found that electricity usage plays a significant role in several impact categories analyzed, including FD, FAE, HT, and MAE, with average proportions ranging from 50% to 70%. In contrast, the impact on climate change accounts for only 7% to 16%. The main causes of these impacts arise from electricity consumption in the production process, which, in many countries, still relies on fossil fuels.

Although the electricity usage is lower than that in the biomass pellet production process, greenhouse gas emissions and environmental impacts remain critical considerations. In terms of carbon dioxide and other toxic emissions from the combustion of biomass pellets, although the percentage for Rubberwood pellets is higher, the corncob pellet has a more significant impact on climate change. This is due to the combustion of corncob pellets, which contain organic materials that can produce nitrogen oxides (NO_x) and sulfur dioxide (SO_2); these compounds are air pollutants that adversely affect both the environment and human health. Conversely, biomass pellets made from rubberwood have lower impact values because they emit fewer volatile substances; generally, rubberwood contains fewer pollutant compounds than corncobs.

Moreover, factors related to combustion indicate that corncob biomass pellets have diverse components and higher moisture content, which may result in incomplete combustion and the release of black smoke or carbon monoxide (CO), both of which are harmful to the environment. In contrast, rubberwood biomass pellets exhibit more complete combustion due to their density and properties that facilitate continuous burning.

Although biomass pellets are regarded as a sustainable alternative energy source, emissions of gases and toxins from

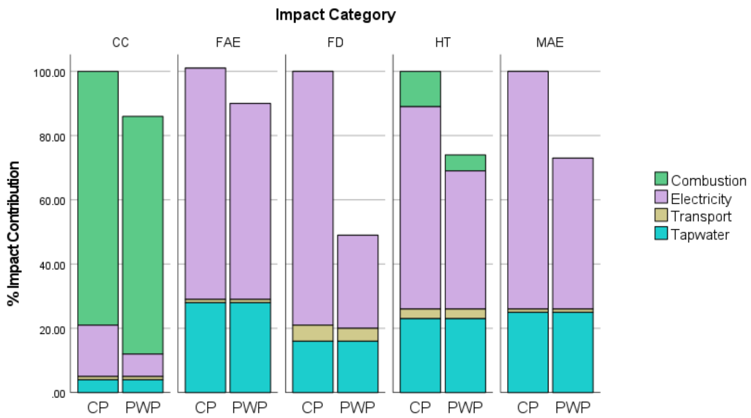


Fig. 3 Percentage contribution of the steam production process to various environmental impacts

combustion still present significant impacts that need consideration. The use of municipal water in the steam production process also plays a vital role, as municipal water is utilized as feedwater for the steam boiler, which requires energy and resources derived from fossil fuels for water sourcing, treatment, and distribution. This may contribute to greenhouse gas emissions and other pollutants. Furthermore, the transportation of goods by 18-wheel trucks impacts fossil fuel depletion and climate change, as transporting goods relies on fossil fuels, leading to greenhouse gas emissions and toxins that also affect the environment.

3.3 Comparison of Environmental Impacts with Related Research

This section compares the environmental impacts of this study with other similar biomass pellet products, namely corncob pellets and blue pine pellets (Arromdee and Kuprianov, 2019; Rashedi *et al.*, 2022), which are sourced from crops grown in Pakistan. The aforementioned study was compared using a functional unit of 1 kilogram of biomass fuel pellets. Therefore, the results of this study have been slightly adjusted to allow comparison with the functional unit of the previous study. The impact categories assessed include CC, HT, FAE, and MAE.

Figure 4 shows the comparison of environmental impacts for 1 kilogram of biomass fuel pellets. It is found that three out of four impact categories, namely CC, HT, FAE, and MAE, of Rubberwood pellets in this study have significantly higher impacts compared to other types of biomass products. This is because Para rubber wood undergoes complex processes and additional processing, resulting in higher energy consumption. Additionally, previous studies utilized additives or oils to reduce friction within the pelletizing machines during the production of biomass pellets, which directly affects the CC and HT impact categories, leading to higher impacts compared to this study, except for the CC impact category in the case of Rubberwood pellets, where energy consumption remains higher in other areas.

For a broader overview, the current CC results—expressed as global warming potential (GWP)—were compared with a wide range of findings from previous studies. The comparison was based on a common functional unit of 1 MJ of calorific value from pelletized biomass fuels (excluding steam production), enabling a consistent and meaningful evaluation across different feedstocks and system boundaries. Life cycle assessments (LCAs) of wood pellets in particular have shown considerable variation in greenhouse gas (GHG) emissions. A review by Martín-Gamboa *et al.* (2020) reported GWP values ranging from –25 to 488 gCO_2eq/MJ, depending on methodological choices and system boundaries. As summarized in Table 5, our comparison reveals a similarly broad spectrum of GWP values—from 14.9 gCO_2eq/MJ for wood chip pellets in Europe (Sgarbossa *et al.*, 2020) to 1,267 gCO_2eq/MJ for straw pellets in China (Jiang *et al.*, 2020). The lowest impacts were linked to efficient wood processing, while the highest resulted from energy-intensive production processes relying on fossil fuel-based electricity. Intermediate values were observed for

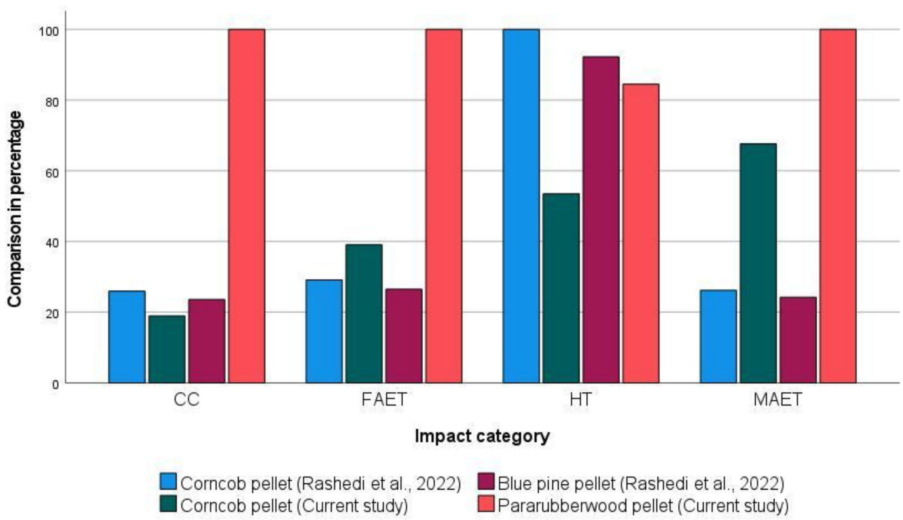


Fig. 4 Comparison of environmental impacts in various aspects of 1 kg of biomass fuel pellet

Table 5
Comparative GWP results from previous studies across different locations and biomass types

Study	Location	System boundary	Pellet type	GWP (gCO_2eq/MJ)	Key contributor
Current study	Thailand	cradle-to-grave	Pararubber wood Corncob	55.1 141.6	raw material and pelletizing processes
Sgarbossa *et al.* (2020)	Europe	cradle-to-grave	Wood chip	14.9-27.6	wood processing
Żelazna *et al.* (2018)	Poland	cradle-to-gate	Wheat straw	20.7-33.2	transport and fertilizers
Petlickaite *et al.* (2024)	Lithuania	cradle-to-grave	Maize Fibrous hemp Faba bean	29.1 21.6 22.0	biomass and pellet production
Zheng *et al.* (2022)	Denmark	cradle-to-gate	Wood pellets	79.19	combustion (in CHP)
Adam *et al.* (2015)	Europe	cradle-to-gate	Scots pine (torrefied pellets)	17.5-40.5	combustion
Jiang *et al.* (2020)	China	cradle-to-gate	Straw	932-1,267	pellet production (energy consumption)

wheat straw, hemp, maize, and faba bean pellets, where emissions were primarily driven by agricultural inputs, transportation, and biomass processing. Notably, even among similar feedstocks, GWP outcomes varied considerably due to differences in system boundaries (e.g., cradle-to-gate vs cradle-to-grave) and regional energy profiles. Overall, the comparison underscores the importance of both feedstock characteristics and local production conditions in assessing the environmental performance of bioenergy systems.

3.4 Sensitivity analysis

This study assessed the impact of data uncertainties in steam production from biomass pellets through sensitivity analysis. The goal was to identify parameters that significantly influence the final results, enabling improvements in the reliability of the LCA and highlighting areas where further data collection may be necessary. Four key parameters were identified as having significant variability, including transportation of pellets from production plants to steam plants, corn kernel selling price, natural rubber selling price, and allocation method. In the baseline scenario, the distance between pellet production plants and steam plants was assumed to be 80 km. However, this value can vary depending on the specific locations of production and steam plants. Additionally, the selling prices of the main agricultural products—corn kernels and natural latex—are subject to seasonal fluctuations, which can affect the economic allocation factors used in the analysis. To examine the sensitivity of impact results to changes in these parameters, the study varied them by ±10%.

Beyond parameter variability, an alternative allocation method was also evaluated. The default approach applied economic allocation because mass-based allocation tends to overestimate impacts from lower-value by-products (e.g., corn cobs compared to corn kernels, or rubberwood compared to natural latex) (Williams and Eikenaar, 2022). However, to assess the effect of allocation choice on the LCA results, a physical (mass-based) allocation was tested in the sensitivity analysis. Table 6 presents the sensitivity of impact results in response to ±10% parameter variations and the alternative allocation method.

The results showed that transportation distance and agricultural product prices (corn kernel and natural rubber) introduce minimal uncertainty into the LCA results within the tested range (±10%). In contrast, allocation method choice is the most influential factor, particularly for Para Wood Pellets. Physical allocation leads to much higher impact changes compared to the baseline economic allocation, particularly in categories sensitive to material flows such as HT. This highlights the importance of carefully selecting allocation methods in LCA studies involving multiple co-products, as it can drastically alter the results.

4. Conclusions

The LCA results demonstrate that corn stover biomass pellets have notably lower environmental impacts than rubber wood biomass pellets across all life cycle stages, namely raw material preparation, pelletizing, and steam production in industrial use. This is primarily due to the fact that corn stover, as an agricultural residue, requires simpler processing and consumes less electricity compared to rubber wood, which involves more energy-intensive operations such as drying and handling. Moreover, corn is harvested more frequently, making corn stover more readily available and renewable without additional land use or deforestation. Therefore, corn stover presents a more sustainable and environmentally favorable option for biomass pellet production, with lower energy inputs and reduced environmental burdens throughout its life cycle.

However, this study focused on the environmental impacts of each process. The analysis of both cases revealed that the production process of biomass pellets has the most

Table 6
Sensitivity of impact results responding to parameter variations (±10%) and change in allocation method

Parameter	Pellet type	% Sensitivity				
		CC	FAE	FD	HT	MAE
Transport (pellet production plant to boiler)	CP	0.05%	0.03%	0.15%	0.13%	0.03%
	PWP	0.04%	0.02%	0.12%	0.10%	0.02%
Corn kernel price	CP	0.00%	0.00%	0.00%	0.01%	0.00%
Natural rubber (latex) price	PWP	0.00%	0.00%	0.00%	0.00%	0.00%
Physical allocation	CP	0.19%	0.43%	0.48%	0.89%	0.57%
	PWP	3.25%	4.14%	6.44%	13.96%	4.68%

significant impacts, primarily due to the high electricity consumption associated with machinery such as saws, pellet presses, and dryers. The steam production process has the most significant impact in terms of climate change due to greenhouse gas emissions from burning biomass pellets during the process. The raw material acquisition process has the least impact across all impact categories, accounting for less than 6% because the allocation based on economic value helps reduce the environmental impact associated with the cultivation and harvesting of the crops. This is because rubber latex and corn kernels have a higher economic value than rubber wood and corn stover, leading to most impacts being allocated to rubber latex and corn kernels. The use of fossil fuels in other processes and transportation also plays a significant role. However, reducing impacts from various processes should focus on improving energy efficiency, reducing greenhouse gas emissions, and promoting the use of renewable energy. Additionally, enhancing transportation management efficiency, such as through product consolidation or using highly efficient trucks, can significantly reduce environmental impacts.

5. Recommendations

Since the open-source software program openLCA is developed abroad and is not widely used in Thailand, the database is insufficient for practical applications. It may be necessary to add or develop a database specific to Thailand, along with training or seminars on how to use the software and conduct LCA analyses to enhance users' skills and knowledge. The Ecoinvent Database Version 3.4, used in this LCA analysis, covers environmental data for a variety of products and manufacturing processes globally. Therefore, the database needs to be continuously updated to ensure accurate and reliable results. While this study does not specifically analyze the composition of heavy metals in the ash produced during biomass pellet production, future research should consider the detailed heavy metal analysis in ash to enhance the comprehensiveness of environmental impact evaluations.

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