



Carbon Footprint Assessment and GHG Reduction Guidelines for the Rubberwood Processing Industry in Yala Province

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Abstract: This study presents a Cradle-to-Gate carbon footprint assessment (CFP) of a representative rubberwood (*Hevea brasiliensis*) processing factory in Yala Province, Thailand, conducted in accordance with the Life Cycle Inventory (LCI) framework and ISO 14067:2018. The functional unit was defined as one cubic meter (1 m³) of processed rubberwood leaving the factory gate. The total greenhouse gas (GHG) emission intensity was calculated as 40.83 kgCO₂-eq/m³, with raw materials and processing residues identified as the dominant emission sources, accounting for approximately 90% of total emissions. Electricity (2.33 kgCO₂-eq/m³) and diesel fuel (0.11 kgCO₂-eq/m³) constituted secondary contributors, while consumables and auxiliary materials contributed negligibly. The findings should be interpreted as a single-factory case study rather than an industry-wide representative baseline. Potential mitigation pathways, drawn from analogous studies, include optimized inventory management (15–30% reduction potential), biomass fuel substitution (50–85%), operational efficiency improvements through preventive maintenance and AI-assisted optimization (5–15%), and waste valorization through biochar conversion. These hotspots align with Thai national policy frameworks, including the Nationally Determined Contribution (NDC), Carbon Neutrality (2050), Net Zero (2065), the TGO Carbon Label Program, the EU Carbon Border Adjustment Mechanism (CBAM), the Bio-Circular-Green (BCG) economic model, and the energy policies under the Power Development Plan (PDP) and the Department of Alternative Energy Development and Efficiency (DEDE). The study provides empirical baseline data for the rubberwood processing sector and serves as a methodological reference for future, larger-scale assessments.

Keywords: Carbon footprint; greenhouse gas emissions; rubberwood processing; cradle-to-gate

1. Introduction

Rubberwood is a principal timber resource for the wood-based industries in Southeast Asia [1]. The rubber tree (*Hevea brasiliensis*) is primarily cultivated for latex production, and its wood is widely used as a raw material in furniture manufacturing and other downstream applications [2]. The Thai rubber sector is a major component of the national economy. In 2022, rubber plantations covered approximately 28,736 km², and the sector recorded an average annual growth rate of 15.15% during 2019–2022, positioning Thailand as the world's second-largest natural rubber producer after Indonesia [3]. Approximately 40% of the Thai workforce is employed in agriculture [4]. The

total area under rubber cultivation increased to 32,276.8 km² by 2018, with the southern region accounting for the largest share (61%), followed by the northeast (22%), the central region (11%), and the north (6%). Rubber plantations supply raw material to several downstream industries, including rubberwood processing, furniture manufacturing, and biomass-based power generation.

In Thailand's southern border provinces — Yala, Narathiwat, and Pattani — rubber is among the most economically significant crops, with Yala possessing the largest plantation area among the three. Consequently, the rubberwood processing industry has become an important source of livelihood in this region. In 2022, 51 rubberwood processing factories were licensed in Yala Province, of which 29 were operational, with a combined annual production capacity of approximately 357,395 m³. Processed rubberwood from this region is exported primarily to Malaysia and China, in addition to supplying domestic downstream industries [5]. The global mean surface temperature in 2023 reached 1.45 °C above pre-industrial levels, approaching the 1.5 °C threshold established under the Paris Agreement. The Intergovernmental Panel on Climate Change (IPCC) has emphasized the need to achieve net-zero CO₂ emissions globally by 2050 [6]. Thailand has committed to attaining Carbon Neutrality by 2050 and Net Zero Emissions by 2065 [7], and has set a Nationally Determined Contribution (NDC) target to reduce GHG emissions by 30%–40% below the Business-as-Usual (BAU) projection by 2030 [8].

Despite this policy momentum, factory-level empirical data on GHG emissions from rubberwood processing in Yala Province remain limited. Quantifying the product carbon footprint (CFP) and identifying emission hotspots within the LCI framework are therefore essential for evidence-based mitigation planning. This study provides a Cradle-to-Gate carbon footprint assessment of one operational rubberwood processing factory in Yala Province as an empirical case study. The contribution of this work is the provision of factory-level baseline data; it is not intended as a methodological advance, and its findings should be interpreted within the context of the single-factory scope.

2. Materials and Methods

This study employed an applied research design to quantify GHG emissions from a rubberwood processing facility. The environmental impact was evaluated using Global Warming Potential (GWP) and reported as the Product Carbon Footprint (CFP), expressed in kilograms of carbon dioxide equivalent (kgCO₂-eq).

2.1 Study scope and system boundary

GHG quantification was conducted within the LCI framework and adopted a Cradle-to-Gate system boundary, in accordance with ISO 14067:2018 (Greenhouse gases, Carbon footprint of products, Requirements and guidelines for quantification). A single rubberwood processing factory in Yala Province, Thailand (255/16 Moo 97, Sateng Nok Subdistrict, Mueang Yala District), was selected through purposive sampling as the case-study site. Selection was based on the factory's willingness to disclose detailed monthly inventory data and its operational status during the study period. The facility occupies approximately 8,000 m² and produces 832,000 kg (1,280 m³) of pallet rubberwood annually [9]. It employs 62 administrative staff and 20 production workers, and operates 15 sawing/processing machines, 15 cyclones, and 7 forklifts. The selected factory's annual processed-wood output (~9,645 m³) represents only a small fraction of the total provincial capacity (357,395 m³). Consequently, this study should be interpreted as a single-factory case study rather than a statistically representative baseline for the Yala rubberwood industry as a whole. The system boundary encompasses the in-factory production stage, from the receipt of raw or semi-finished rubberwood to the dispatch of finished processed wood at the factory gate. Inclusions: rubberwood input, in-factory unit operations (sawing, cutting, sorting), energy consumption (electricity and diesel), auxiliary consumables (lubricants, cleaning agents, personal protective equipment, lighting fixtures), and on-site solid-waste handling. Exclusions: upstream processes (plantation establishment, silvicultural management, harvesting, and inbound transport), downstream processes (use phase and end-of-life), and land-use change (LUC) effects. The detailed material flows, in-factory unit operations, and the established Cradle-to-Gate system boundary are illustrated in the schematic diagram shown in Figure 1.

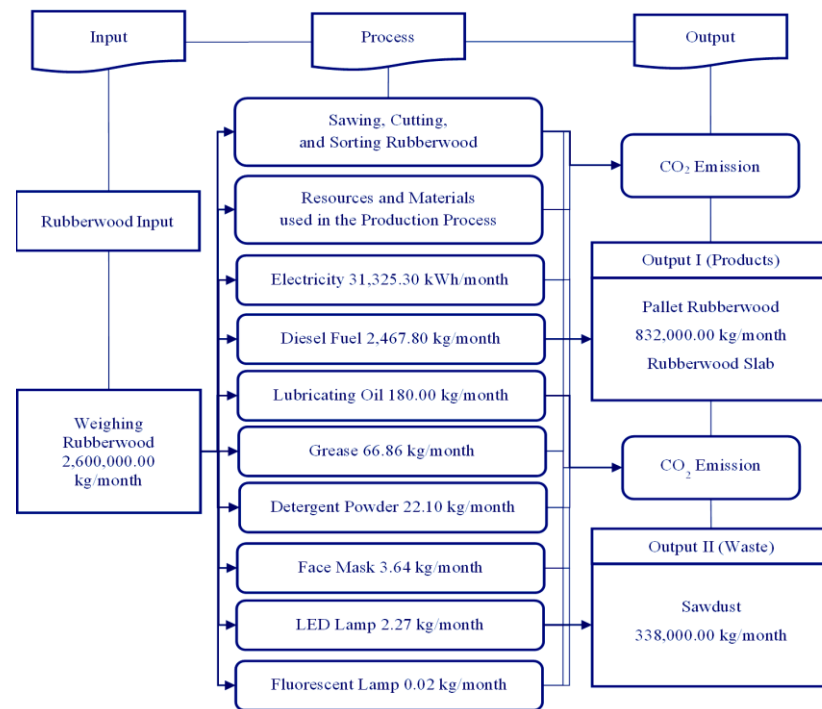


Figure 1. Process-flow diagram showing inputs, in-factory unit operations (receiving → sawing → cutting → sorting → drying/finishing → dispatch), outputs, and the Cradle-to-Gate system boundary of the rubberwood processing factory

2.2 Treatment of biogenic carbon

Rubberwood is a biogenic material whose carbon content was sequestered from atmospheric CO₂ during tree growth. In accordance with ISO 14067:2018 (Annex D), biogenic CO₂ emissions and removals associated with the use of biomass should be reported separately from fossil GHG emissions. The emission factors applied to rubberwood inputs and outputs in this study (Table 1) were derived from the factory's internal life cycle inventory data [9] and represent the on-site processing-related GHG burdens (predominantly fossil-derived from electricity, diesel, and lubricants used during processing) attributable to each unit mass of material handled. They do not represent the biogenic CO₂ stock contained within the wood itself, nor do they reflect plantation-level sequestration or land-use change. Consequently, the long-term biogenic carbon storage embodied in finished rubberwood products is not quantified in this assessment. This exclusion is acknowledged as a limitation; comprehensive treatment would require an extended Cradle-to-Grave LCA incorporating plantation carbon-stock dynamics, which is beyond the scope of this single-factory baseline.

2.3 Functional unit

The functional unit (FU) was defined as one cubic meter (1 m³) of processed rubberwood leaving the factory gate. This FU is consistent with international wood-industry CFP studies, including the carbon footprint assessment of rubberwood sawmilling in Peninsular Malaysia by Ratnasingam et al. [1] and the supply-chain CFP for imported timber-based wooden furniture by Wang et al. [10], thereby enabling regional benchmarking.

2.4 Inventory data collection

Activity data were obtained from the factory's 2022 annual production report [9] each month (N = 12) and aggregated into monthly averages, yielding a 13-line inventory (N = 13) covering all inputs and outputs within the system boundary. Because reference [9] is an unpublished internal factory document, all activity data and the corresponding emission factors derived from it are reproduced in full in Table 1 to support transparency and reproducibility. Cross-verification against the publicly available Thailand Greenhouse Gas

Management Organization (TGO) emission-factor database [13] and the ClimaTiq emission-factor repository [14] was conducted for energy and selected consumable inputs; the values used in the calculation are within the same order of magnitude as those publicly reported.

The inventory comprises:

- Raw materials (inputs and outputs): rubberwood, pallet rubberwood, rubberwood slab, sawdust
- Energy: electricity (kWh) and diesel fuel (kg)
- Consumables: grease, lubricating oil, detergent powder, fabric gloves, face masks, fluorescent lamps, LED lamps (kg)

lamps, LED lamps (kg)

2.5 Carbon footprint calculation

The total CFP was calculated using the standard equation:

$$\text{CFP (kgCO}_2\text{-eq)} = \text{Activity Data} \times \text{Emission Factor (EF)}$$

where Activity Data denotes the quantity of input or output (kg, kWh, etc.) and EF (kgCO₂-eq/Unit) represents the GHG emissions per unit of activity. EFs for energy and most consumables were drawn from peer-reviewed and database sources [10–16]; EFs for rubberwood materials originated from the factory's internal LCI documentation [9]. The emission factors of 0.0471 kgCO₂-eq/kg (rubberwood and pallet rubberwood inputs) and 0.0829 kgCO₂-eq/kg (rubberwood slab and sawdust outputs) are interpreted as the on-site, processing-stage GHG burden per unit mass of material handled within the factory. The slightly higher EF for slab and sawdust reflects the additional processing energy and material-handling steps (sorting, conveying, on-site management) associated with these intermediate output streams before they leave the factory gate. The values represent fossil-derived emissions from material handling and do not capture biogenic CO₂ flows. As these EFs originate from a single internal source, the resulting emission estimates should be regarded as indicative rather than definitive; this constraint is discussed further in Section 3.4.

2.6 Data analysis

Total GHG emissions were obtained by summing the monthly kgCO₂-eq values for all inventory items. The factory-level CFP intensity was derived by dividing the total monthly GHG emissions by the total monthly volume of processed wood (8,037.19 m³). Emission hotspots were identified by ranking the percentage contribution of each inventory item. The calculated percentage contributions of all 13 inventory items are presented in Figure 2, utilizing a custom segmented linear scale on the X-axis to ensure legibility across widely disparate data ranges. The Consumables (Combined) category accounts for 0.074% of the total CO₂ emissions, which is broken down into Lubricating Oil, Grease, Detergent Powder, Fabric Gloves, LED Lamp, Face Mask, and Fluorescent.

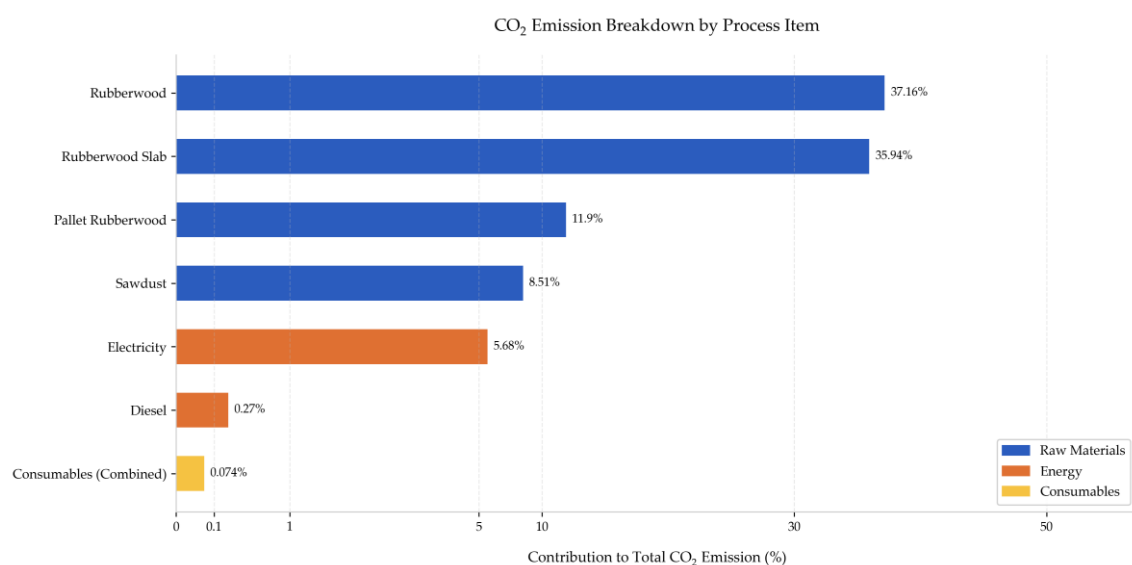


Figure 2. Percent CO₂ Emissions of the Rubberwood Processing Factory

2.7 Uncertainty considerations

Quantitative uncertainty propagation (e.g., Monte Carlo simulation) was not performed because parameter distributions for the internally derived rubberwood EFs were unavailable. A discussion of qualitative uncertainty is presented in Section 3.4. Key uncertainty sources include: (i) reliance on a single-year (2022) inventory that may not capture inter-annual or seasonal variability; (ii) use of internally derived EFs for rubberwood that have not been peer-reviewed; (iii) the single-factory scope, which precludes generalization to the provincial industry; and (iv) the exclusion of upstream, downstream, and land-use-change emissions. The environmental inventory data, including the category, item, and greenhouse gas (GHG) emissions of the rubberwood processing factory are presented in Table 1.

Table 1. Environmental Inventory Data (Cradle-to-Gate) of the Rubberwood Processing Factory

Category	Item	Unit	Inventory Data /month	EF (kgCO ₂ -eq/Unit)	CO ₂ Emission /Month (kgCO ₂ -eq)	GHG (kgCO ₂ -eq/m ³)	% CO ₂
Raw Materials	Rubberwood	kg	2,600,000	0.0471 [9]	122,460.00	15.24	37.16
	Pallet Rubberwood	kg	832,000	0.0471 [9]	39,187.20	4.88	11.95
	Rubberwood Slab	kg	1,430,000	0.0829 [9]	118,547.00	14.74	36.13
Energy	Sawdust	kg	338,000	0.0829 [9]	28,020.20	3.49	8.54
	Electricity	kWh	31,325.3	0.5986 [13]	18,751.32	2.33	5.71
	Diesel	kg	2,467.8	0.3522 [13]	869.16	0.11	0.26
Consumables	Grease	kg	66.86	1.0547 [10]	70.52	0.009	0.02
	Lubricating Oil	kg	180	0.8319 [14]	149.74	0.019	0.05
	Detergent Powder	kg	22.1	0.405 [12]	8.95	0.0011	0.003
	Fabric Gloves	kg	1.63	2.11 [14]	3.44	0.00043	0.001
	Face Mask	kg	3.64	0.02 [15]	0.07	0.000009	0.00002
	Fluorescent Lamp	kg	0.02	0.477 [14]	0.01	0.000001	0.000002
	LED Lamp	kg	2.27	0.5986 [14]	1.36	0.00017	0.0004
Total					328,068.50	40.83	100.00

Notes: Inventory data (N = 13 items) include all inputs and outputs within the Cradle-to-Gate boundary. Functional Unit (FU): 1 m³ of processed rubberwood leaving the factory gate; total processed-wood output sums to 8,037.19 m³/month. EFs cited as [9] are derived from the factory's internal LCI documentation and represent on-site, processing-stage GHG burdens (predominantly fossil-derived). Biogenic CO₂ stock within the wood and plantation-level sequestration is not included in these EFs. The total intensity per FU (40.83 kgCO₂-eq/m³) is the sum of all line-item intensities and supersedes any single-item intensity (e.g., the slab line at 14.74 kgCO₂-eq/m³) for factory-level reporting.

3. Results and Discussion

3.1 Inventory results and emission hotspots

Table 1 presents the complete environmental inventory and corresponding monthly GHG emissions for the studied factory. Total monthly GHG emissions amount to 328,068.50 kgCO₂-eq. With a total monthly processed-wood output of 8,037.19 m³, the factory-level CFP intensity is 40.83 kgCO₂-eq/m³ (see Table 4). This figure represents the aggregate GHG emission per functional unit and supersedes any per-line-item intensity (such as the 14.74 kgCO₂-eq/m³ value associated specifically with the rubberwood-slab line in Table 1) when

characterizing factory-level performance. Raw materials (rubberwood input, pallet rubberwood, rubberwood slab, and sawdust output) collectively contribute approximately 308,214 kgCO₂-eq/month, or about 93.9% of total monthly emissions. Within this category, rubberwood input alone accounts for 37.16% of the total, while rubberwood slab accounts for 36.13%. Electricity is the most significant non-material contributor (5.71%), followed by diesel (0.26%); all other consumables collectively contribute less than 0.1%. The rubberwood-slab and sawdust line items represent intermediate output streams that undergo additional in-factory handling (sorting, conveying, on-site temporary storage) before leaving the gate. The associated EFs, therefore, capture the processing-stage GHG burden per unit mass handled rather than emissions generated by the materials themselves. If these output streams were excluded from the boundary, only the rubberwood and pallet-rubberwood input lines would remain attributable to material handling, and the energy share of total emissions would rise correspondingly.

3.2 Comparison with related studies

The dominance of raw materials in the CFP of this rubberwood processing factory is qualitatively consistent with prior wood-industry LCA studies. Ratnasingam et al. [1] reported that raw materials and energy are the principal drivers of the carbon footprint in Peninsular Malaysian rubberwood sawmilling. Wang et al. [10] found that upstream processes account for 74.6%–80.7% of total CFP for imported timber-based wooden furniture supply chains. By contrast, Srichat et al. [11] reported the dominance of energy use in wood-pellet production — a finding that differs from the present study (in which raw-material handling rather than energy dominates), reflecting the substantially higher thermal-energy intensity of pelletization compared with sawmilling. This contrast underscores the need to tailor mitigation strategies to the specific operational profile of each wood-processing sub-sector. The CFP intensity reported here (40.83 kgCO₂-eq/m³) is broadly within the same order of magnitude as that reported in the Malaysian sawmilling study, although direct numerical comparison is constrained by differences in system boundaries, EF sources, and biogenic-carbon treatment. Table 2 summarizes the thematic alignment of the present findings with related studies, with citations corrected to reflect each study's actual focus.

3.3 Mitigation strategies and policy linkages

Table 3 outlines potential GHG reduction measures relevant to the rubberwood processing industry. The numerical reduction ranges (15–30% for inventory optimization; 50–85% for biomass substitution; ~4% for renewable electricity; 5–15% for operational efficiency) are drawn from analogous studies in related sub-sectors and are presented as *indicative potentials*. They have not been derived directly from the present factory's data, and their applicability to a sawmilling-type operation such as the studied facility may differ from the source contexts (for example, the 50–85% biomass-substitution range originates from a thermal-energy-intensive wood-pellet study [11], whereas sawmilling is comparatively electricity-dominant). Site-specific feasibility assessment would therefore be required before adopting any of these ranges as concrete reduction targets for the studied factory. Table 4 connects the identified carbon hotspots to relevant Thai national policy instruments. Optimized inventory management of raw materials and offcuts supports the national NDC, Carbon Neutrality (2050), and Net Zero (2065) targets [17]. Reporting CFP at the product level enables manufacturers to participate in the TGO Carbon Label Program [18] and supports compliance with the EU Carbon Border Adjustment Mechanism (CBAM), thereby enhancing export competitiveness in environmentally stringent markets. Conversion of sawdust and offcuts into biochar is consistent with the Bio-Circular-Green (BCG) economic model and Circular Economy policy [19], offering both waste reduction and potential long-term carbon sequestration. Substitution of fossil thermal energy with biomass and the adoption of rooftop solar PV are aligned with the Power Development Plan (PDP) and the DEDE energy-conservation policy [20]. The consistency comparison with prior studies and the GHG reduction measures are presented in Table 2 and Table 3, respectively.

Table 2. Consistency of Research Findings with Related Studies

Thematic Area	Supporting Study	Key Findings	Consistency with Current Study
I. Raw-material dominance in GHG emissions	Ratnasingam et al. [1]	Raw materials and energy are the main drivers of the carbon footprint in rubberwood sawmilling. Indicative GHG reduction potential: 15–30% through inventory optimization.	Confirms that rubberwood inventory management is the most critical intervention point for carbon reduction in the present case (~90% of CO ₂ emissions).
II. Upstream-stage dominance in supply-chain CFP	Wang et al. [10]	Upstream processes accounted for 74.6%–80.7% of total CFP in imported timber-based wooden-furniture supply chains. Indicative GHG reduction potential: ~4% through renewable-electricity transition.	Confirms that material/upstream inventory is the primary carbon hotspot. Energy is a secondary but actionable factor.
III. Energy-dominated profile in pelletization (CONTRAST)	Srichat et al. [11]	Most GHG emissions in wood-pellet production originate from energy consumption. Indicative GHG reduction potential: 50–85% through biomass-fuel substitution.	Differs from the present sawmilling case (raw materials dominate, not energy). The contrast is attributed to the higher thermal energy intensity during pelletization. Reduction from this source primarily applies to thermal-energy-intensive processes.
IV. Operational-energy and machinery-fuel contribution	Thaipradith et al. [12]	Fossil-fuel consumption in production is a significant contributor to GHG emissions—indicative GHG reduction potential: 5–15% through operational efficiency improvements.	Supports the strategy of targeted mitigation of diesel and lubricating oil use in machinery.

Table 3. Indicative GHG Reduction Measures Drawn from Analogous Studies

Mitigation Strategy	Focus Area	Indicative Reduction	Source Context and Applicability
Optimized inventory management	Raw-material handling; reducing spoilage	15–30%	From rubberwood sawmilling [1]; directly relevant to the present case, given the dominance of raw-material emissions.
Biomass-fuel substitution	Thermal energy (drying/heat)	50–85%	From wood-pellet production [11], it is directly applicable only to thermal-energy-intensive operations. The present sawmilling case has limited drying/thermal demand, so the realizable reduction is expected to be lower.
Renewable electricity	Electricity consumption	~4%	From hard-to-abate industrial sectors [10], modest but actionable for the present factory's electricity load.
Operational efficiency (machinery maintenance + AI-assisted scheduling)	Diesel/fuel optimization	5–15%	From the CFP of wooden-chair production [12], applicable to forklift and machinery operations.
Waste valorization (sawdust → biochar)	Carbon sequestration	Indicative ~3–6% global CO ₂ avoidance per global biochar literature	From global biochar studies [16], site-specific feasibility depends on local biochar uptake and end-use markets.

3.4 Limitations and uncertainty

Several limitations should be considered when interpreting these results. **(1)** The study is based on a single factory selected by purposive sampling; the selected facility's annual output (~9,645 m³) is approximately 2.7% of the total Yala provincial capacity (357,395 m³ across 29 active factories), and the findings cannot be assumed to be representative of the industry as a whole. **(2)** Activity data are drawn from a single calendar year (2022), and seasonal or inter-annual variability is not captured. **(3)** The EFs for rubberwood-related items are derived from an unpublished internal factory document [9] and have not been peer-reviewed. However, the values are reproduced transparently in Table 1 and were cross-checked against external databases [13,14] for energy and consumable items; independent verification of the rubberwood-specific factors was not feasible. **(4)** Biogenic CO₂ stock within rubberwood, plantation-level sequestration, and land-use change are excluded, in line with the Cradle-to-Gate boundary; a complete biogenic-carbon balance would require a Cradle-to-Grave or Cradle-to-Cradle assessment. **(5)** Formal uncertainty propagation (e.g., Monte Carlo simulation) was not performed because parameter distributions for the internally derived EFs were unavailable. Future research should expand to multi-factory sampling within Yala Province, incorporate peer-reviewed or independently audited EFs for rubberwood, include biogenic carbon and land-use-change effects, and conduct quantitative uncertainty and sensitivity analyses. The policy analysis and associated GHG mitigation impacts for the industry are presented in Table 4.

Table 4. Policy Analysis and GHG Mitigation Impact in the Rubberwood Industry

Key Finding (Carbon Hotspot)	Proposed Mitigation Strategy	Relevant National Policy / Goal	Policy Linkage and Significance
Raw materials and wood offcuts (~90% of GHG)	Optimized inventory management (15%–30% indicative reduction)	NDC (30%–40% reduction by 2030), Carbon Neutrality (2050), and Net Zero (2065) [17]	Factory-level data provide the empirical basis for setting GHG-reduction strategies in the industrial sector that align with national NDCs and long-term goals.
Total CFP intensity = 40.83 kgCO ₂ -eq/m ³ (corrected total)	GHG reduction based on CFP data	TGO Carbon Labeling Program [18] and EU CBAM	Supports manufacturers in using CFP data for the Carbon Label and trade competitiveness in environmentally stringent export markets.
Wood offcuts/sawdust (production residues)	Waste valorization (sawdust → biochar)	BCG Economic Model and Circular Economy Policy [19]	Promotes resource efficiency by converting residues into high-value products with potential long-term carbon sequestration.
Energy (electricity and diesel) — secondary driver	Biomass-fuel substitution and renewable energy (e.g., rooftop solar)	Power Development Plan (PDP) and DEDE Energy Conservation Policy [20]	Supports national energy policy to reduce reliance on fossil fuels and promote clean-energy and energy-saving measures within factories.

4. Conclusions

This study provides a Cradle-to-Gate baseline carbon footprint assessment for one operational rubberwood processing factory in Yala Province, Thailand. The factory-level CFP intensity is 40.83 kgCO₂-eq/m³, with raw materials and processing residues responsible for approximately 90% of total emissions, and electricity and diesel fuel acting as secondary contributors. The findings are presented as single-factory empirical evidence rather than a provincial baseline. Indicative mitigation pathways drawn from the literature — optimized inventory management, biomass-fuel substitution, operational efficiency, and biochar-based waste valorization — offer entry points for evidence-based emission-reduction planning, conditional on site-specific feasibility evaluation. These hotspots align with Thailand's NDC, Carbon Neutrality, and Net Zero targets; the TGO Carbon Label Program and the EU CBAM; the Bio-Circular-Green economic model; and the PDP/DEDE energy framework. The study is constrained by its single-factory scope, single-year inventory, exclusion of biogenic carbon and land-use change, and reliance on internally derived EFs for rubberwood; multi-factory studies with independently verified EFs and quantitative uncertainty analysis are recommended as next steps.

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