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CO_2 Footprint of the Seeds of Rubber (*Hevea brasiliensis*) as a Biodiesel Feedstock Source

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Abstract: Crude rubber seed oil (CRSO) is a promising but currently underutilized biodiesel feedstock alternative, extracted by pressing the seeds of the rubber tree (*Hevea brasiliensis*). Rubber trees are cultivated across more than 11.4 million hectares worldwide, mainly in Southeast Asia. Despite their suitability as a biodiesel feedstock source, rubber seeds are currently treated as waste in the monocultural plantation system. To date, no assessments have been performed to examine the potential impact of rubber seed-based biodiesel production on GHG emissions. This study analyses the global warming potential of rubber seed methyl ester (RSME) production in Southeast Asia. The functional unit used is 1 MJ of biodiesel. A sensitivity analysis assesses the influence of key parameters (e.g., rubber seed yield) on the GHG mitigation potential. A scenario analysis evaluates the effect of using RSME by-products for energy generation. In comparison to fossil diesel, RSME has a carbon mitigation potential of 67 g CO_2.eq. MJ^{-1}, based on allocation by mass. On the condition of compliance with international sustainability standards that call for deforestation-free value chains, the generation of RSME biodiesel on rubber tree plantations in Southeast Asia would have a total mitigation potential of around 2.8 million tonnes of CO_2 eq. per year.

Keywords: LCA; GHG emissions; rubber tree seeds; biodiesel; mitigation potential; CO_2 footprint

1. Introduction

Since the industrial age, fossil resources have been utilized to provide human societies with materials and energy. The associated increase in atmospheric concentrations of carbon dioxide and other greenhouse gases (GHG), however, has forced policy-makers to acknowledge climate change as an eminent threat to human wellbeing and has accelerated the transition to post-fossil societies [1,2]. As a result, many industrialized nations have introduced policies for the past few decades to stimulate renewable energy production and reduce both GHG emission levels and the dependency on imported fossil fuels [3]. Biodiesel is regarded as one alternative to crude oil-based diesel, as it is derived from bio-based materials such as plant oils and microalgae [4–9].

Biodiesel from palm oil and its various blends accounts for the largest share of global biodiesel production, with Indonesia and Malaysia being the main producers to date [10,11]. These two countries promote biodiesel production chains to generate new income sources and broaden livelihood opportunities in rural regions [12,13]. However, the rapid expansion of palm oil plantations in Southeast Asia (SEA) during the past decades has been accompanied by severe environmental problems including deforestation, peat-soil drainage, and loss of biodiversity [10,14–16]. As a result, further options are required to broaden the global feedstock basis and thus avoid environmental damage caused by the expansion of palm oil plantations into tropical forest ecosystems and landscapes of high conservation importance [17].

One promising and currently underutilized biodiesel feedstock alternative is crude rubber seed oil (CRSO). This is extracted from the seeds of the rubber tree (*Hevea brasiliensis* Müll. Arg.). Rubber tree seeds are predominantly treated as waste in the current plantation system, despite their high oil content of 40 to 50%. The oil can be used for combustion-engine purposes without further modification [18–22]. An additional factor making CRSO-based biodiesel an attractive biodiesel option is the fact that rubber plantations already exist, in particular in Thailand, Indonesia and Malaysia. Other Asian countries that have substantially increased their rubber plantation area in recent years include China (mainly Yunnan Province and Hainan Island), Vietnam, Myanmar and Laos [23]. SEA accounts for approximately 78% of the current global rubber plantation area of more than 11.4 million hectares [24].

Despite CSRO's role as an emerging biodiesel feedstock source, no assessments have been performed to date on the GHG mitigation potential of rubber seed-based biodiesel production chains in comparison to a fossil reference. For biofuels, the assessment of GHG emissions is crucial for economic reasons, in addition to their tremendous environmental importance with respect to climate change. For example, if the biofuel is intended for sale in the European Union, the sustainability criteria of the European Renewable Energy Directive have to be fulfilled. Here, GHG mitigation targets constitute one of the most important criteria, which apply to all biofuels consumed in the EU [25].

Against this backdrop, the aim of this study is to analyse the GHG mitigation potential of rubber seed methyl esters (RSME) using the Life-Cycle Assessment (LCA) methodology. A full plantation cycle of *Hevea brasiliensis* is assessed with rubber plantation areas in Southeast Asia as a system boundary. It includes a detailed description of rubber plantation management practices, CRSO extraction and the processing of the derivate RSME. A sensitivity and a scenario analysis assess the impacts of fertilizer levels, rubber seed yields, transport distances and by-product use on potential GHG emissions. The study concludes with an outlook on the development potential and environmental benefits of biofuels derived from RSME.

2. Materials and Methods

2.1. Goal and Scope Definition

The goal of this study was to analyse the GHG emissions associated with the production and extraction of rubber seed-based biodiesel from a cradle-to-grave perspective using a generic rubber tree plantation system located in the main production area of the tropical belt of Southeast Asia. For this purpose, a Life-Cycle Assessment (LCA) was conducted. LCA is a framework for evaluating the environmental burdens associated with a product, process or activity throughout its life cycle, and is standardized by two ISO norms, 14040 and 14044 [26,27].

The study is based on data from published reports and literature focusing on the major rubber tree plantation areas in southern China, Malaysia, Indonesia and Thailand. Background data were taken from the GaBi database. The functional unit was defined as 1 MJ of biodiesel. LCA computations were carried out in GaBi 7.2, applying the CML 2001 *baseline* method. A sensitivity analysis was conducted to analyse the influence of the reported variability in rubber seed yields, fertilizer levels and transport distances on GHG emission potentials of rubber seed-based biodiesel production. A scenario analysis takes into account the recycling of by-products (rubber wood, rubber seed shells, press cake) during the biodiesel production process. A *best/worst-case* scenario is used to combine the reported upper and lower levels of employed input datasets to assess their importance on computed GHG balances (for further explanation: see Section 2.3). The results of this study were compared to fossil diesel as a reference system.

2.2. Inventory Analysis

This section describes the data used to develop the *baseline* scenario. The rubber seed-based biodiesel production chain was divided into three main processes: rubber tree cultivation, rubber seed oil extraction and rubber seed oil transesterification (Figure 1).

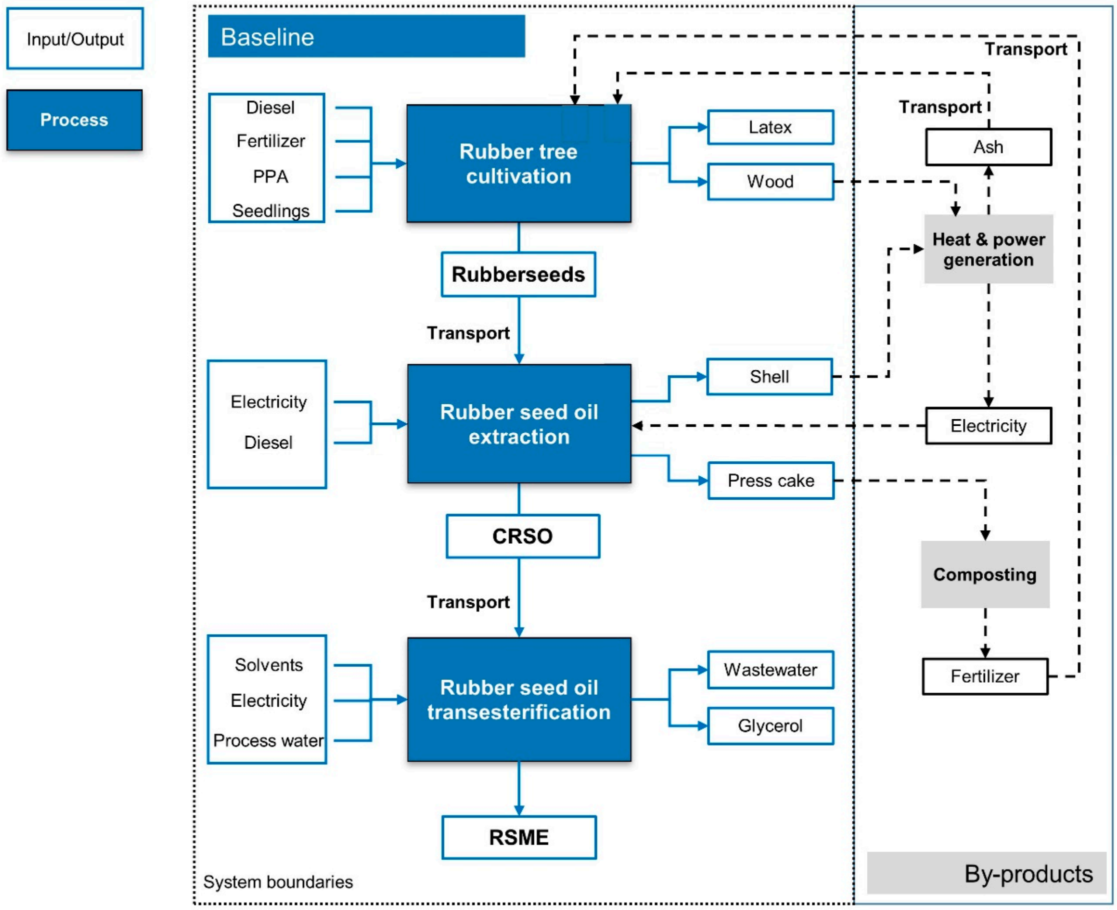

Figure 1. Process tree for the *baseline* rubber seed biodiesel production chain and system boundaries extended by *by-product* scenario (on the right in grey); PPA: Plant protection agents; CRSO: crude rubber seed oil; RSME: rubber seed methyl ester.

2.2.1. Rubber Tree Cultivation

The rubber tree cultivation module was set up based on an average tree density of 468 trees ha^{-1} and a re-plantation cycle of 25 years [28]. When apportioned to one year, this gives 19 seedlings ha^{-1} and a total of 205.7 kg ha^{-1} a^{-1} seedlings, with an estimated single seedling weight of 11 kg including the polybag and soil [29–31]. A diesel consumption of 0.78 litres ha^{-1} year^{-1} was assumed for the soil preparation before the planting of the rubber trees, based on Jawjit et al. (2010) [32]. The only plant protection agent (PPA) applied was 37.5 kg ha^{-1} a^{-1} sulphur powder [33]. The amounts of N, P_2O_5, K_2O and MgO fertilizer applied during a 25-year rubber tree cultivation cycle were computed using ammonium nitrate for N, triple superphosphate for P_2O_5, potassium chloride for K_2O and magnesium oxide for MgO (Table 1). As fertilizer application rates differ depending on tree stand age, values were averaged for a 25-year growth cycle [28]. An average transport distance of 50 km was used to calculate emissions associated with the transport of input substrates, such as fertilizers and seedlings, from producer to plantation.

Table 1. Inputs and outputs of a rubber tree plantation cycle.

Input	Unit	Amount	Sources
Seedlings	kg ha^{-1} a^{-1}	205.70	[29–31]
Fertilizer			
N	kg ha^{-1} a^{-1}	83.00	[28]
P_2O_5	kg ha^{-1} a^{-1}	81.00	[28]
K_2O	kg ha^{-1} a^{-1}	108.00	[28]
MgO	kg ha^{-1} a^{-1}	19.60	[28]
Pesticides	kg ha^{-1} a^{-1}	37.50	[28]
Output			
Rubber seeds	kg ha^{-1} a^{-1}	587.44	[21,32,34–41]
Latex	kg ha^{-1} a^{-1}	2291	[34,39,42–46]
Wood	kg ha^{-1} a^{-1}	3422	[31,41,47]

The main plantation outputs considered are the rubber seeds with an average yield of 587.44 kg ha^{-1} a^{-1} [21,32,34–41]. As seeds are normally hand-picked [48], no emissions associated with the harvest of the seeds are included in this study. In addition, studies investigating palm-based biodiesel production showed that the influence of the harvest process on total GHG emissions is relatively small [49]. To simplify collection, weeds covering the seeds need to be eliminated [50]. In this study, tapped latex (usually the main rubber plantation product) is treated as a by-product with an average yield of 2291 kg ha^{-1} a^{-1} (Table 1) [34,39,42–46]. Rubber wood is an additional by-product. It is harvested after the plantation cycle is complete, and old trees are replaced by new seedlings. When rubber wood production is apportioned on a yearly basis, a total wood yield of 85,550 kg per ha and cultivation cycle gives 3422 kg ha^{-1} a^{-1} rubber wood [41,47,51]. The diesel consumption and emissions associated with the timber harvest were included in the study. The rubber tree seeds are transported 28.75 km by truck to the rubber seed oil extraction facility.

2.2.2. Rubber Seed Oil Extraction

The extraction process requires the application of screw presses and hammer mills as well as 40.35 MJ ha^{-1} a^{-1} electrical energy [11,52–54] and 1.06 l ha^{-1} a^{-1} fossil diesel [11,53] (Table 2). These values are based on biodiesel production from palm oil, as no values for the energy consumption of rubber seed oil extraction were available. An average of 267.02 kg ha^{-1} a^{-1} rubber seed oil is extracted [21,22,34–41,50,51,54–58] and an average of 214.07 kg ha^{-1} a^{-1} rubber seed shells are separated during extraction [21,22,34,41,50,57] accounting for 31% to 40% [21,22] of total seed weight. An additional by-product of this processing step is press cake, amounting to 106.35 kg ha^{-1} a^{-1} [41]. After oil extraction, the CRSO is transported 311 km by truck to the rubber seed oil transesterification facility (Table 3).

Table 2. CRSO extraction inputs and outputs.

Input	Unit	Amount	Sources
Rubber seeds	kg ha^{-1} a^{-1}	587.44	[21,32,34–41,51]
Electricity	MJ ha^{-1} a^{-1}	40.35	[11,52–54]
Diesel	l ha^{-1} a^{-1}	1.06	[11,53]
Output			
CRSO	kg ha^{-1} a^{-1}	267.02	[21,22,34–41,50,51,54–58]
Shells	kg ha^{-1} a^{-1}	214.07	[21,22,34,41,50,57]
Press cake	kg ha^{-1} a^{-1}	106.35	[41]

Table 3. Transport distances for process modules in *baseline* setting.

Route	Distance (km)
Rubber seeds → Rubber seed oil extraction	28.75 [11,59]
CRSO → Rubber seed oil transesterification	311 [11,60]
RSME → Usage	98.21 [60]
Total	437.96

CRSO: crude rubber seed oil; RSME: rubber seed methyl ester.

2.2.3. Rubber Seed Oil Transesterification

The CRSO is refined in a transesterification process step for utilization in conventional diesel engines. This requires, on average, 75.10 MJ ha^{-1} a^{-1} electrical energy [11,53] and 0.46 m^3 ha^{-1} a^{-1} process water [22] (Table 4). These values are again based on biodiesel production from palm oil, as no values for rubber seed oil transesterification were available. In addition it was shown that the palm oil-based biodiesel production technology can be used for RSME production without any major modifications [58]. Transesterification (combined acid and alkaline) uses 97.66 kg ha^{-1} a^{-1} methanol [34]. The acid transesterification step requires an additional 7.56 kg ha^{-1} a^{-1} H_2SO_4 to reduce the free fatty acid (FFA) content of CRSO by catalysis [34]. The alkaline transesterification step uses 2.05 kg ha^{-1} a^{-1} NaOH to produce RSME [34]. The transesterification process results in 247.61 kg ha^{-1} a^{-1} RSME [21,22,34–41,50,51,55–58], 10.32 kg ha^{-1} a^{-1} glycerol as a by-product of alkaline transesterification [40], and 0.05 m^3 ha^{-1} a^{-1} wastewater [53] (Table 4).

Table 4. Inputs and outputs of rubber seed oil transesterification process.

Input	Unit	Amount	Sources
CRSO	kg ha^{-1} a^{-1}	267.02	[21,22,31,34–41,50,55–58]
Electricity	MJ ha^{-1} a^{-1}	75.10	[11,53]
Water	m^3 ha^{-1} a^{-1}	0.46	[22]
Methanol	kg ha^{-1} a^{-1}	97.66	[34]
NaOH	kg ha^{-1} a^{-1}	2.05	[34]
H_2SO_4	kg ha^{-1} a^{-1}	7.56	[34]
Output			
RSME	kg ha^{-1} a^{-1}	247.61	[21,22,34–41,50,51,55–58]
Glycerol	kg ha^{-1} a^{-1}	10.32	[40]
Wastewater	m^3 ha^{-1} a^{-1}	0.05	[53]

2.2.4. Transport

The outputs from the processes described above need to be transported between the different process facilities. However, as rubber seed-based biodiesel production is still at an experimental stage, no information on relevant distances could be found in the literature. For this reason, related information from palm oil-based biodiesel production facilities was used as a proxy [11,59,60], as shown in Table 3.

2.2.5. Usage

The usage process step comprises the conversion of RSME into energy. RSME has an average calorific value of 37.19 MJ kg^{-1} [55,56], thus the yield of 247.61 kg ha^{-1} a^{-1} gives a potential total energy of 9208 MJ ha^{-1} a^{-1}. Downscaled to the functional unit, 26.9 g of RSME is required to produce 1 MJ of energy.

2.3. Sensitivity and Scenario Analysis

To test the robustness of the LCA results, a sensitivity analysis was conducted that assessed the impact of variations in rubber seed yield, fertilizer level and transport distance on the GHG emission potential. This was followed by a scenario analysis, which evaluated the utilization of by-products on the GHG emissions.

2.3.1. Sensitivity Analysis

In order to assess the effects of variations in key parameters on the results and thus help to evaluate the reliability of the study, a sensitivity analysis was conducted. In this analysis, the rubber seed yields, applied fertilizer amounts and transport distances were increased/decreased in steps of 10% above and below the *baseline* reference (marked yellow in Table 5) to a maximum of plus/minus 30% and the resulting changes evaluated. In the table, Lit_{max} and Lit_{min} refer to the respective highest and lowest values reported in the literature. The seed yield given in the *baseline* scenario is the mean value of rubber seed yields reported in 10 scientific publications (see Table 1).

Table 5. Values of key inventory variables used for the sensitivity analysis of rubber seed yields, fertilizer levels, and transport distances (*best-case* scenario marked in green, *worst-case* scenario marked in red).

Sensitivity Level	Unith a^{-1} a^{-1}	Lit_{min}	−30%	−20%	−10%	*Baseline*	+10%	+20%	+30%	Lit_{max}
1-11 Seed yield	kg	150 [37]	411	470	529	587	646	705	764	1500 [41]
Fertilizer	kg N	n.a.	58	66	74	83	91	99	108	n.a.
	kg P_2O_5		56	64	73	81	89	97	105	
	kg K_2O		76	86	97	108	119	130	140	
Distance	km	152 [41,60]	302	350	394	438	482	526	569	17,705 [a]

[a] based on shipping distance from Indonesia to Rotterdam.

There are wide variations in reported rubber seed yields as a result of different clones and environmental conditions. For example, yields reported by Devi et al. (2012) [37] are ten times higher than those reported by Prabhakaran (2010) [41]. For this reason, the influence of the yield on the results was assessed in a sensitivity analysis. Here, deviations in rubber seed yields around the *baseline* setting were used, with all values of the rubber tree cultivation step kept constant. The *posterior* processes were adjusted to the amount of harvested rubber seeds accordingly. The amounts of harvested wood and latex were not altered.

Changes in fertilization level often have a tremendous effect on the environmental performance of biobased values chains. For this reason, a sensitivity analysis was conducted to assess the impact of changes in fertilizer level on the overall GHG emissions.

To investigate the influence of transportation on the three main production processes, the transport distance employed in the *baseline* scenario was varied while keeping all other variables constant. However, due to a lack of information on transportation patterns for rubber seeds, distances reported for palm oil-based biodiesel production chains were used instead (Table 5). The background data associated with the transport processes were taken from the GaBi database.

2.3.2. Scenario Analysis

Best-/Worst-case: Based on the data obtained, a *best-* and a *worst-case* scenario were developed. In the *best-case* scenario (marked green in Table 5), GHG emissions were assessed for RSME production under the most favourable potential conditions: highest rubber seed yield, lowest fertilizer inputs and shortest transport distance. By contrast, the *worst-case* scenario (marked red in Table 5) assessed GHG emissions for RSME production under the most unfavourable conditions: lowest rubber seed yield, highest fertilizer application rate and longest transport distance.

By-products: In the *baseline*, *best-* and *worst-case* scenarios described above, emissions from stages with more than one product are allocated based on mass. However, rubber wood, seed shells and press cake can also be used to generate internal process energy and organic fertilizer. For this reason, the *baseline* LCA system boundary was expanded to include a heat and power unit and a composting process step (Figure 1). Three additional scenarios were developed based on this setup: *best-case by-product*, *worst-case by-product* and *baseline by-product*. These account for the utilisation of by-products during CRSO/RSME processing.

The three scenarios are based on values of energy and heat generated by a combined heat and power unit (CHP) using wood from rubber tree plantations and the residual shells from CRSO extraction. The ash produced can be used as fertilizer for the rubber tree plantation. The press cake from CRSO extraction has a high nutritional content [61]. It is composted and returned to the plantation as organic fertilizer. The nutrients contained in the ash and composted press cake thus reduce the amount of mineral fertilizer needed. A transport distance of 50 km was assumed for these products. The CHP unit used in the process has a total efficiency of 84.9% (36.3% electrical, 48.6% thermal efficiency) [62]. The energy produced exceeds the demands of the CRSO extraction process (40.35 MJ ha^{-1} a^{-1} electrical energy) and can substitute fossil energy required for other processing steps. To calculate the amount of energy, the specific calorific values of the shells and rubber wood are taken, as shown in the Supplementary Table S1. The organic fertilizer produced is a mixture of the nutrient contents of the ash and press cake produced during screw pressing. These nutrient contents are shown in Table S2. As no values were available for the P_2O_5 and K_2O content of rubber seed press cake, values for palm oil press cake [63] were taken. The energy necessary for transport and application of the fertilizer are included in the calculation.

3. Results

3.1. Worst-Case, Baseline and Best-Case Scenario

Figure 2 shows the results of the *worst-case*, *baseline* and *best-case* scenarios in g CO_2 eq. MJ^{-1} RSME. The largest share of total GHG emissions is caused by the cultivation of the rubber tree stands: about 71% in the *baseline* scenario, 69% in the *worst-case* scenario and 63% in the *best-case* scenario. Here, the production of mineral fertilizers and fertilizer-induced emissions are two of the main sources of GHGs emitted over the 25-year cultivation cycle under consideration. The contribution of the transesterification process step to total GHG emissions ranges from 14% (*worst-case*) to 29% (*best-case*), depending on the scenario setting chosen. The transport distance contributes about 3.3 g CO_2 eq. MJ^{-1} RSME in the *worst-case* scenario. In the *baseline* and *best-case* scenarios, the influence of transport on total GHG emissions is insignificant. The oil extraction process step has a negligible contribution to total GHG emissions in all three scenarios. The variations between the three scenarios stem from the different assumptions regarding rubber seed yield, fertilizer inputs and transport distance.

The analysis of the GHG mitigation potential of RSME biodiesel indicates a considerable potential in all three scenario settings despite the differences in total GHG emissions (Figure 3). The *best-case* scenario gives a GHG mitigation potential of around 72 g CO_2 eq. per MJ RSME, which corresponds to a GHG saving potential of about 86%. Even in the *worst-case* scenario, a GHG saving potential of over 70% is achievable compared to the fossil diesel reference.

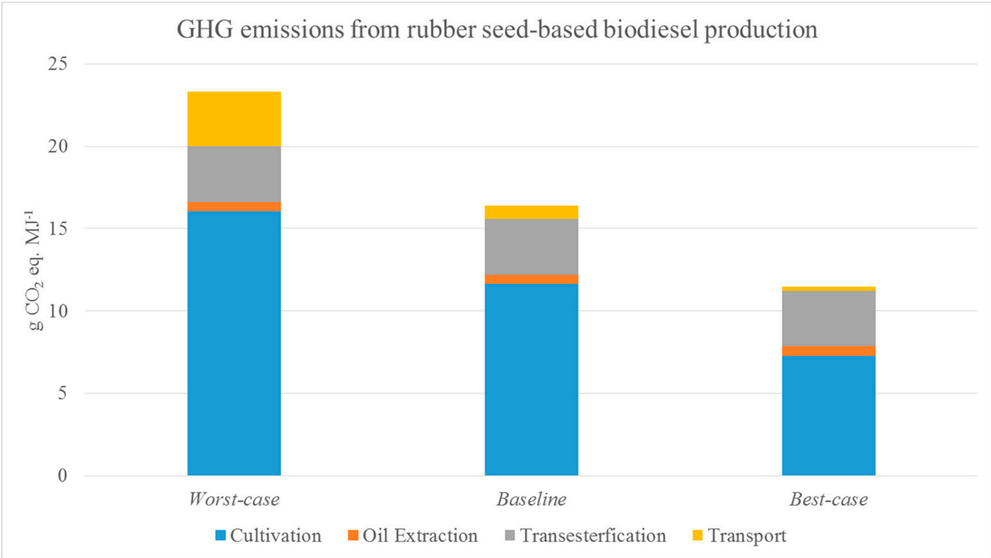

Figure 2. GHG emissions from rubber seed-based biodiesel production in g CO_2 eq. MJ^{-1} RSME for the *worst-case*, *baseline* and *best-case* scenarios.

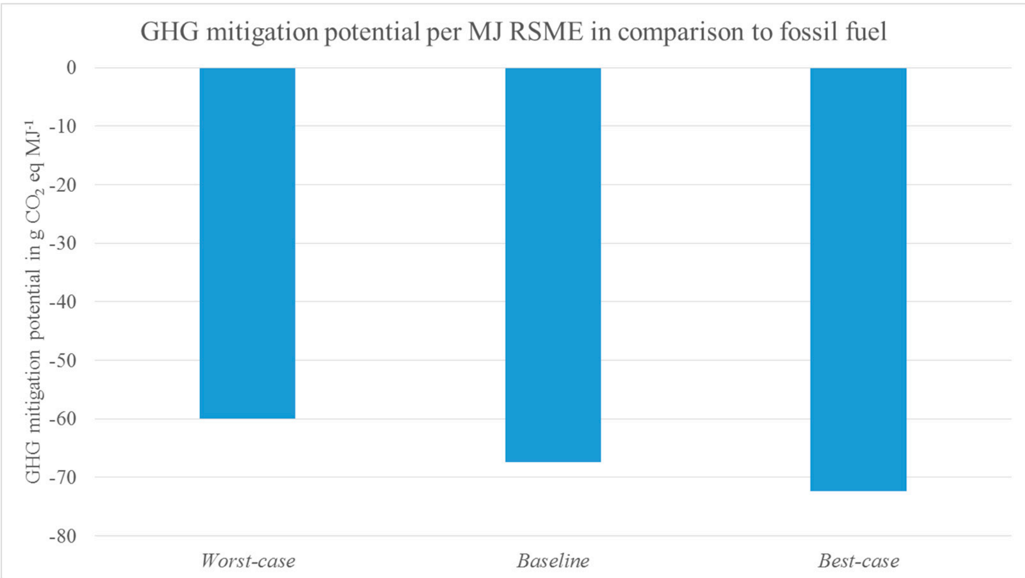

Figure 3. GHG mitigation potential of rubber seed-based biodiesel production in g CO_2 eq. MJ^{-1} RSME for the *worst-case*, *baseline* and *best-case* scenarios.

3.2. Sensitivity Analysis

The results of the sensitivity analyses are shown in Table 6, given in g CO_2 eq. MJ^{-1}, as a percentage of the *baseline* scenario and as GHG mitigation potential in g CO_2 eq. MJ^{-1}. The largest differences stem from variations in amount of fertilizer applied. A 30% increase or decrease in fertilizer leads to an up to 20% increase or decrease in GHG emissions associated with the production of RSME. Variations in rubber seed yield or transport distance lead to only minor changes in total GHG emissions.

Table 6. Results of sensitivity analysis assessing the influence of variations in rubber seed yield, amount of fertilizer applied and transport distance on GHG emissions and GHG mitigation potential.

Sensitivity Analysis	Unit	Lit_{max}	+30%	+20%	+10%	*Baseline*	−10%	−20%	−30%	Lit_{min}
Rubber seed yield	g CO_2 eq. MJ^{-1}	14.92	16.08	16.18	16.29	16.40	16.50	16.62	16.73	17.26
Fertilizer applied	g CO_2 eq. MJ^{-1}	n.a.	19.70	18.59	17.48	16.40	15.29	14.19	13.09	n.a.
Transport distance	g CO_2 eq. MJ^{-1}	18.88	16.64	16.56	16.48	16.40	16.31	16.23	16.14	15.83
Rubber seed yield	in %	91.02	98.07	98.70	99.34	100.00	100.66	101.35	102.04	105.30
Fertilizer applied	in %	n.a.	120.15	113.40	106.64	100.00	93.28	86.57	79.85	n.a.
Transport distance	in %	115.16	101.52	101.01	100.51	100.00	99.49	98.99	98.43	96.57
Rubber seed yield	GHG mitigation potential in g CO_2 eq. MJ^{-1}	−68.38	−67.22	−67.12	−67.01	−66.90	−66.80	−66.68	−66.57	−66.04
Fertilizer applied	GHG mitigation potential in g CO_2 eq. MJ^{-1}	n.a.	−63.60	−64.71	−65.82	−66.90	−68.01	−69.11	−70.21	n.a.
Transport distance	GHG mitigation potential in g CO_2 eq. MJ^{-1}	−64.42	−66.66	−66.74	−66.82	−66.90	−66.99	−67.07	−67.16	−67.47

3.3. By-Product Scenario

Figure 4 shows the results of the three *by-product* scenarios *worst-case by-product*, *baseline by-product* and *best-case by-product* scenario in g CO_2 eq. MJ^{-1} RSME. GHG emissions per MJ RSME are around 40–50% higher in the *by-product* scenarios than in the standard scenarios *worst-case*, *baseline* and *best-case* presented above (see Figure 4). However, in the *by-product* scenarios, more heat and electricity are generated through the combustion of rubber wood and shells in the CHP than is actually required for the RSME production process. This heat and electricity could be utilized to substitute energy generated by fossil sources and thus would lead to an additional GHG mitigation potential of 665 CO_2 eq. MJ^{-1} RSME (Table 7). The additional GHG mitigation potential from the use of these by-products is significantly higher than the CO_2 emissions associated with the production of the rubber seed-based biodiesel. The influence of the reduction in the amount of mineral fertilizer applied through nutrients contained in the ash and composted press cake is negligible.

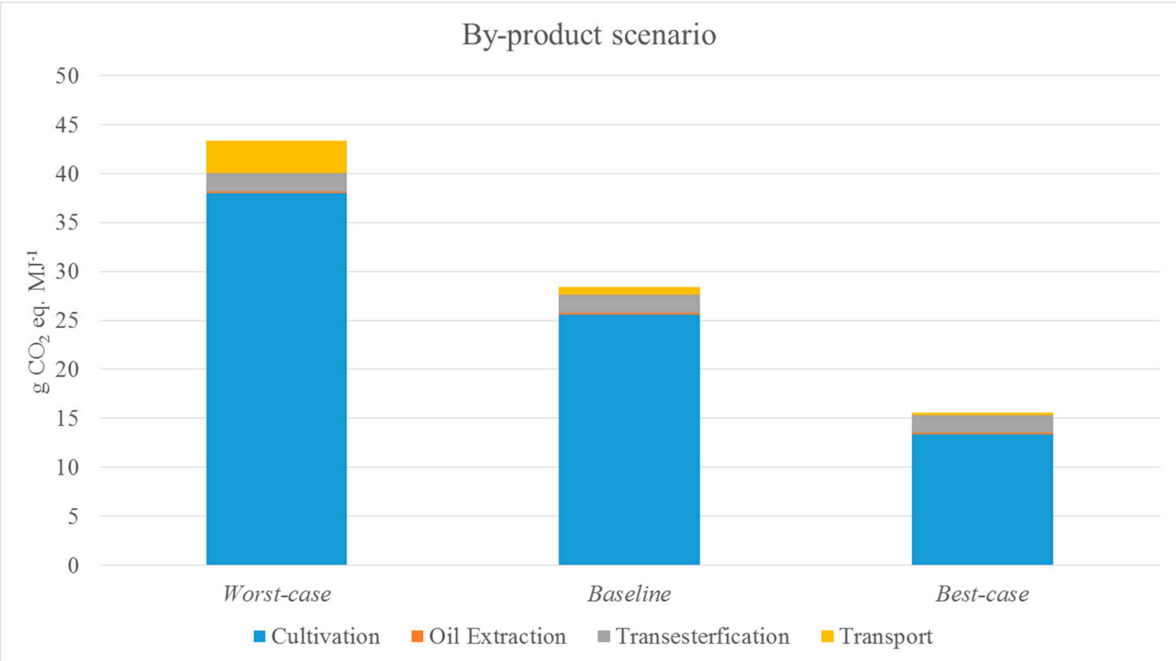

Figure 4. GHG emissions from rubber seed-based biodiesel production in g CO_2 eq. MJ^{-1} RSME applying the *by-product* scenario (i.e., use of rubber wood, seed shells and press cake to generate internal process energy and organic fertilizer).

Table 7. Additional GHG mitigation potential through substitution of fossil-energy sources by heat and electricity generated through combustion of rubber seed by-products under three scenarios.

CHP	Unit	*Worst-Case*	*Baseline*	*Best-Case*
Heat	Additional GHG mitigation potential in g CO_2 eq. MJ^{-1} RSME	1543.38	409.78	173.29
Power		957.84	255.15	108.56
Total		2501.22	664.93	281.85

4. Discussion

This section first discusses the implications of the various scenario settings and associated methodological choices. It also analyses the influences of transport distance, fertilizer level, and rubber seed yield assessed in the sensitivity analysis, together with their significance for the development of a rubber seed-based biodiesel value chain. The second part then discusses the potentials and limitations of rubber seed as a sustainable biomass resource for biodiesel production in Southeast Asia.

The demand for further research is also addressed, in particular with regard to optimization potentials and possible barriers to the implementation of this novel bio-based value chain.

4.1. Implications of Scenario Settings and Methodological Choices

All three main scenarios (*best-case, baseline, worst-case*) show considerably lower GHG emissions compared to the fossil reference. This means that even under the worst-case assumptions of low yields, high fertilizer demand and long transport distances, the GHG mitigation potential is with 60 g CO_2 eq. per MJ RSME still considerable. Analysis of the main hot-spots of rubber seed-based biodiesel production reveals the cultivation stage as the most important emission source. Here, the production of nitrogen fertilizer and nitrogen fertilizer-induced emissions (e.g., N_2O) play a major role. This has also been shown in other studies analysing biodiesel production, for example, from palm oil [64]. The strong impact of fertilization is also visible in the results of the sensitivity analysis. Variations in fertilization level have a more pronounced influence on the results than variations in yield. The influence of transport distance on the GHG emissions is relatively small. For example, the total carbon footprint of the *worst-case* scenario, which includes transport per ship from Southeast Asia to a port in Europe, is only 15% higher than that of the *baseline* scenario, but still significantly lower than the fossil alternative. On a percentage basis, the contribution of transport to total emissions is within 5% of the *baseline* scenario, comparable with other studies [65]. Similarly, the influence of variations in rubber seed yield on GHG emissions is small, amounting to around 10%, even though the yields differ by a factor of ten. This can be partly explained by the assumption that the amount of harvested latex and rubber wood remains constant, irrespective of changes in seed yield. If the seed yield decreases and the amount of harvested latex and rubber wood stays the same, a higher share of the emissions is allocated to these by-products. Therefore, the influence of variations in rubber seed yield on the GHG emissions of RSME is less pronounced.

An additional aspect that needs to be considered is the choice of allocation method. In this study, allocation was based on mass. The type of allocation can have a strong impact on the final results. For example, Morais et al. (2010) showed that economic- and energy-based allocations result in significantly higher negative environmental impacts for soy-based biodiesel than mass-based allocation [66]. However, as the price for natural rubber is highly volatile [67], an allocation based on economic factors appeared inadvisable. As latex, the main product of the rubber tree plantations, is used as a material and not as an energy carrier, an allocation based on mass was deemed most appropriate for our study.

In rubber tree plantations, residues and side streams are often used for energy production, as is also the case for palm oil production [68]. Therefore, in the *by-product* scenarios, the wood and seed shells are utilized for energy generation through combustion and the press cake is used as fertilizer. The results of the *by-product* scenarios differ substantially from the scenarios discussed above. Part of the heat energy is used for the biodiesel production process, but in fact most of the generated heat energy can be used externally and thus substitute fossil-based energy carriers. In this study, it was assumed that an electricity mix and heat based on the combustion of natural gas were replaced. Thus, it is possible to generate energy for local consumption in addition to the production of biofuels for export markets. Under these assumptions, the carbon mitigation potential of the main product rubber seed-based biodiesel is around 55 g CO_2 eq. per MJ RSME for the *baseline by-product* scenario. The additional carbon mitigation potential through the utilization of the by-products is, however, considerably higher at 665 g CO_2 eq. per MJ RSME. Such large variations in results due to differences in handling of co-products have also been shown in other studies analysing the environmental performance of biofuel value chains [69].

The findings of the current study show that the utilization of rubber tree seeds for biodiesel production offers a significant carbon mitigation potential when substituting a fossil reference. This potential is still substantial when lower seed yields, higher fertilizer inputs or longer transport distances are assumed. A direct comparison with other biofuels however is complicated by the differences in allocation methods and system boundaries.

4.2. Rubber Seed-Based Biodiesel: An Opportunity for a Sustainable and Deforestation-Free Value Chain?

The implementation of a rubber seed-based biodiesel value chain offers the opportunity to exploit an economic and greenhouse-gas mitigation potential that so far remains untapped. This is particularly interesting for the most important rubber plantation areas, located mainly in Southeast Asia (in descending order of plantation area: Indonesia, Thailand, Malaysia, southern China, Vietnam, Myanmar, Laos, Philippines, Cambodia). This region alone has a rubber cultivation area of 9.0 million hectares [17,24], which would correspond to a theoretical total biodiesel energy yield of approximately 82.5 million GJ (average energy yield of 9208 MJ/ha) [55,56]. This is equivalent to over 2300 million litres of fossil diesel applying a calorific value of 35.77 MJ^{-1}.

This theoretical energy yield is in line with a study by Zhu et al. (2014) for SEA [70]. It would offer a substantial contribution to securing the regional and national energy supply. Applying the mitigation potential of 66.9 g CO_2 eq. per MJ calculated in the *baseline* scenario gives a theoretical mitigation potential of around 5.5 million tonnes of CO_2 eq. per year for the use of rubber seeds for biodiesel generation in SEA. The theoretical energy potential, however, needs to be put into perspective with recent findings [23,71,72] that suggest that the expansion of rubber tree plantations can lead to similar detrimental effects on ecosystem services to those reported for monocultural palm oil plantations [16,73,74]. These include conversion of pristine primary rainforests and other land cover types of high ecological importance such as long fallow-short rotational swiddening and agroforestry systems. The CO_2 emissions associated with such land cover change define the biofuel produced on these sites as unsustainable from an ecosystem service and GHG mitigation point of view [75,76]. Especially if natural forests are replaced by monocultural plantation systems, there is a high risk of carbon stock losses. These losses are caused in the short term by a sharp decrease in aboveground biomass and in the long term by a loss of belowground carbon [77]. For example, Guillaume et al. (2018) reported up to 96% carbon losses in the first fifteen years after forest biomass clearance in Indonesia, because a high proportion of the wood cleared is non-merchantable and used for energy production [71]. Extensive cultivation forms such as rubber agroforests (often referred to as 'jungle rubber') could be used instead [74]. Rubber agroforests are still very common in many parts of Indonesia and Malaysia and are usually managed by small-scale farmers as a means of farm income diversification. They are cultivated without any fertilizer or herbicide application. In addition, they have higher carbon stocks compared to monoculture rubber and oil palm stands [71,78]. However, their exploitation is limited and labour-intensive. The risk of land use change remains, as small-scale farmers may favour rubber tree monoculture plantations over rubber agroforests on account of the higher expected economic return. This trend is currently ongoing in many parts of Indonesia and Malaysia due to the continued high global demand for natural rubber [17,23,70]. It is important to acknowledge this fact when propagating the establishment of a rubber seed biodiesel value chain. Warren-Thomas et al. (2015) estimated that about fifty percent of the current rubber plantation area has been established in locations that were previously covered by primary forests or other land cover types of high ecological importance, e.g., biodiverse cropland-agroforestry-natural vegetation mosaics [17]. Accordingly, the theoretical rubber seed biodiesel potential mentioned above has to be reduced by about 50% to 41.2 million GJ and the GHG mitigation potential to about 2.8 million tonnes of CO_2 eq. per year. In this case, no land cover changes would need to be accounted for in the assessment. Thus, the authors recommend concentrating on existing rubber tree plantations that comply with land status and sustainability criteria, for example, as defined by the European Renewable Energy Directive [25]. This stipulates that rubber plantations must have been established in or before 2008 and not converted from primary tropical rainforests or other land cover types of high ecological value (i.e., long fallow-short rotational swiddening or agroforestry systems). The proposed rubber seed-based biodiesel chain would comply with these sustainability criteria and would not lead to deforestation of pristine tropical rainforest. This could be ensured through a certification system, as propagated for many industrial-scale commodities and already implemented for palm oil [79]. Ideally, such a certification system should not only acknowledge carbon- and other ecosystem service-based sustainability criteria, for example, no establishment of rubber tree plantations on steep slopes due to the high risk of soil erosion and landslides [80], but also socio-economic criteria [74].

A further option to improve the economic performance of a rubber seed-based biodiesel value chain is to identify *H. brasiliensis* clonal types that produce higher seed yields than the ones reported in the literature. Improving rubber seed yields is one of the key variables that ensure the long-term viability of a rubber seed-based biodiesel value chain [70]. An increase in rubber seeds yields, however, could also be at the expense of a declining latex yield due to competition for carbon into two different sinks [23]. This could lead to a trade-off decision for policy-making: either in favour of establishing a new biodiesel production chain or preserving the established latex production system. The implication of such a decision has been described as a 'competing claim' for biomass products [2], as the ultimate question would be how the various rubber tree plantation products (latex, seeds, wood, seed shells, press cake) can be most effectively utilized. This can be done either in the form of a cascade (latex > seeds > seed shells > press cake >> rubber wood at the end of a plantation cycle) or by using the variability of *H. brasiliensis* clonal types to focus on improving the latex or rubber seed yield performance. There are already several clones that favour wood over latex. Clonal types could then be planted in a single plantation stand generating products for two different value chains (rubber and biodiesel), with the further advantage of an income diversification for plantation owners.

In recent years, there has been growing interest in utilizing rubber tree seeds for biodiesel production but this is currently not done on a large scale. Reasons could be the lack of both experience in the use of rubber seeds as feedstock and of oil extraction plants and biodiesel factories. Yusup and Khan (2010) propose using CRSO in existing crude palm oil-based biodiesel production facilities as a solution [60].

5. Conclusions

The rise in atmospheric concentrations of carbon dioxide and other greenhouse gas (GHG) emissions forces society and policy-makers to acknowledge climate change as an eminent threat to human wellbeing and to accelerate the transition to a post-fossil society. One of the most promising and currently underutilized biodiesel feedstock alternatives is crude rubber seed oil, extracted by pressing the seeds of the rubber tree (*Hevea brasiliensis*). Rubber trees are cultivated on more than 11.4 million hectares worldwide, with the main and oldest plantations found in Southeast Asia. The results of the LCA methodology applied in this study show that the utilization of rubber tree seeds for biodiesel production offers a significant carbon mitigation potential when substituting fossil-based diesel and complies with international sustainability criteria. The mitigation potential of this novel biodiesel production pathway remains substantial even when lower seed yields, higher fertilizer inputs or longer transport distance are assumed. However, strong emphasis should be placed on the exclusive use of existing plantations so as not to promote the destruction of pristine primary tropical rainforest and ensure that the newly established biodiesel value chain is 'deforestation-free'.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/9/9/548/s1, Table S1: Calorific value of rubber seed shells and rubber wood, Table S2: Nutrient content of press cake and ash.

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