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# Life cycle assessment of coconut plantation, copra, and charcoal production

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## ABSTRACT

**BACKGROUND AND OBJECTIVES:** Coconuts and their derivatives, such as copra and charcoal, are leading commodities of Indonesia contributing to local consumption and exports. Life cycle assessment is a tool for evaluating the inputs, outputs, and potential impacts of a product system throughout its life cycle and is associated with product sustainability. The cradle-to-gate life cycle assessment of copra and coconut shell charcoal aims to determine the impacts of coconut, copra, and charcoal production from copra byproducts quantitatively and identify scenario improvements to reduce the impacts and enhance sustainability.
**METHODS:** Field observations were conducted in tall coconuts in Agrabinta, South Cianjur, and in copra and coconut shell charcoal factories in Sukabumi, West Java, Indonesia. The life cycle assessment method comprises the following four stages: goal and scope definition, inventory analysis, impact assessment, and interpretation. The scope of this study was based on land preparation, nurseries, planting, fertilization, harvesting of mature coconuts, transportation of mature coconuts, copra production, transportation of coconut shells, and charcoal production. Ten impacts were calculated using the Center of Environmental Science of Leiden University Impact Assessment baseline method with Simapro software.
**FINDINGS:** This study obtained ten impact categories, not only the global warming potential impact similar to most studies of perennial crop products in Indonesia. Normalization results showed that the category with enormous impacts on humans from coconut cultivation and copra processing activities had terrestrial ecotoxicity potential. The largest impact on charcoal production was on the human toxicity potential. Separated coconut factories from plantations have a high impact because of high fuel transportation. Four recommendation scenarios were formulated: 1) utilization of smoke from pyrolysis into liquid, 2) implementation of organic coconut cultivation practices, 3) integration of coconut plantations with copra and charcoal processing plants and processing smoke into liquid, and 4) combining scenarios 1, 2, and 3. In scenario 3, seven of ten impacts showed the lowest value among other scenarios. This scenario potentially decreases the impact from 68.35 to 99.62 percent. The human toxic potential of coconut shell charcoal decreased from $2.92 \times 10^5$ to 109.43 kilogram 1,4-dichlorobenzene equivalent, terrestrial ecotoxicity potential decreased from 59 to 19 kilogram 1,4-dichlorobenzene equivalent, and the global warming potential decreased from 1753.55 to 93.03 kilogram carbon dioxide equivalent.
**CONCLUSION:** Life cycle assessment can evaluate the impacts of copra and coconut shell charcoal from the coconut cultivation to the production stages. Opportunities for improvement can be identified from the interpretation and hotspots. Scenario analysis results showed the potential of developing integrated coconut agroindustry with coconut plantations, copra factories, and charcoal factories to produce liquid smoke in one location. This integration markedly reduces the impact due to the reduction of transportation fuel and emissions and the treatment of air pollution from pyrolysis.



| NUMBER OF REFERENCES | NUMBER OF FIGURES | NUMBER OF TABLES |
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## INTRODUCTION

Coconuts (*Cocos nucifera* L.), one of the most important commodities of Indonesia, have a significant economic impact. Coconut is a plantation commodity with the third-largest area of production and productivity in Indonesia, after palm oil and rubber. According to the Food and Agriculture Organization (FAO), Indonesia was the largest coconut producer in 2019 and 2020, with a total production of 17.07–16.82 million tons of nuts, followed by the Philippines at 14.77–14.49 million tons and India at 14.68–14.69 million tons (FAO, 2021). The coconut area in the world was around 11.63 million ha in 2019, 79.1% of which are found in three countries, namely the Philippines (31.4%), Indonesia (29.3%), and India (18.5%) (ICC, 2022). The Directorate General of Estate Crops (DGEC) reported that Indonesia has 3.4 million ha of coconut farms, which comprise 3.27 million hectares (ha) of tall coconut plantations and the remainder being hybrid coconut plantations (DGEC, 2022). Approximately 99.4% of tall coconut plantations are smallholder plantations cultivated by farmers in gardens and their yards in monocultures or mixed gardens, involving approximately 6.1 million coconut farming families. The coconut production in Indonesia is approximately 2.86 million tons, which is equivalent to copra, or approximately 14.3 billion coconuts assuming that 1 kg of copra is obtained from five coconuts (DGEC, 2022). The largest coconut plantation areas in Indonesia are found in the following provinces: Riau, North Sulawesi, East Java, Central Sulawesi, Central Java, North Maluku, and West Java (DGEC, 2022). Cianjur is a crucial coconut production area in West Java, with 8042 ha and 4252 tons, particularly in southern Cianjur. Coconut plants can be harvested from immature and mature plants. Immature coconuts are directly consumed while mature coconuts can be used as raw materials in various products. The coconut fruit comprises 35% coconut coir, 28% endosperm, 25% coconut water, and 12% coconut shells (Mawardi *et al.*, 2016). The final production of coconut meat in Indonesia is divided into the following: copra (42.5%), coconut oil (46.9%), desiccated coconut (4.7%), and others (5.9%) (ICC, 2022). Almost every part of the coconut palm can be utilized to make high-value products; thus, the coconut is known as the “tree of life.” However, the productivity of coconuts in Indonesia is still low. Therefore, increasing production by replanting unproductive palms, promoting good agricultural practices, and introducing high value in coconut plantations and products is necessary (Alouw *et al.*, 2020). Regarding coconut exports, India, Indonesia, and the Philippines export 11, 9, and 13 types of coconut products, respectively (ICC, 2022). Copra and coconut shells are among the most exported products in Indonesia. The export of coconut shell derivative products in Indonesia is still dominated by nonactivated shell charcoal because it does not require activation processes. Charcoal can be used as a raw material for other derivative products, such as activated charcoal, biogas, bio-pellets, and bio-briquettes, which can be used for various applications (Yavari *et al.*, 2021). Copra is a coconut intermediate product obtained by drying coconut meat and is typically used for cooking oil, food, beverages, and cosmetics. In 2019, 108.3 tons of copra were exported to various destination countries, such as Sri Lanka, Pakistan, and Malaysia (DGEC, 2022), increasing copra export from 2022 to 155.65 tons. A total of 0.81 tons of coconut shell can be obtained as a byproduct from 1 ton of copra (Kaseke, 2016). At the farm level, burning coconut shells into charcoal produces gas and dust pollutants, which can reduce the ambient air quality of the surrounding environment. Incomplete combustion produces various emissions, such as carbon oxide (CO), methane ($CH_4$), ethylene ($C_2H_4$), and other volatile organic compounds (VOCs) (Arena *et al.*, 2016). Thus, controlling the environmental impact of charcoal production throughout its life cycle is necessary. Environmental impacts can be calculated using the life cycle assessment (LCA) method. LCA is a compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle (ISO, 2006). Climate change, followed by extreme weather patterns, is a considerable challenge for the entire agricultural system, including coconut plantations. Climate impacts are expected to become prominent by 2050 and will affect availability and utility (Pathiraja *et al.*, 2015). Thus, a coconut development system and its derivatives must be environmentally friendly (Maliangkay and Matana, 2018). Sustainability and environment-friendly products are essential for building consumer confidence. One is the application of ecolabels (Riyanto *et al.*, 2018). Ecolabel identifies the overall environmental performance of a product

Table 1: Scope and impact categories of LCA studies in perennial crop products in Indonesia

| Reference | Commodity | Scope | Impact categories | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | GWP | AP | EP | ADP | ADP-FF | HTP | TEP | FAP | POP | ODP |
| Suprihatin *et al.* (2015) | Palm oil | Cradle-to-gate | √ | | | | | | | | | |
| Siregar *et al.* (2015) | Palm oil | Cradle-to-gate | √ | | | | | | | | | |
| Siregar *et al.* (2015) | Jatropha | Cradle-to-gate | √ | | | | | | | | | |
| Yusuf *et al.* (2019) | Sago | Cradle-to-gate | √ | | | | | | | | | |
| Diyarma *et al.* (2019) | Arabica coffee | Cradle-to-gate | √ | | | | | | | | | |
| Pramulya *et al.* (2022) | Gayo arabica coffee green bean | Cradle-to-gate | √ | | | | | | | | | |
| Gunawan *et al.* (2019) | Sugarcane | Cradle-to-gate | √ | | | | | | | | | |
| Parameswari *et al.* (2019) | Quinine | Cradle-to-gate | √ | √ | √ | | | | | | | |
| Mila *et al.* (2020) | Green tea | Cradle-to-gate | √ | √ | √ | | | √ | | √ | √ | |
| **This study** | Coconut | Cradle-to-gate | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ |

Note: abiotic depletion potential (ADP), abiotic depletion potential (fossil fuels) (ADP FF), global warming potential (GWP), ozone layer depletion potential (ODP), human toxicity potential (HTP), freshwater aquatic ecotoxicity potential (FAP), terrestrial ecotoxicity potential (TEP), photochemical oxidation potential (POP), acidification potential (AP), eutrophication potential (EP).

or service based on life cycle considerations (Setiawan *et al.*, 2019). The results of the LCA calculations can be used as the basis for type III ecolabel or environmental product declaration (EPD). An LCA study of copra and coconut shell charcoal products should be conducted at the cultivation stage (cradle-to-gate). Most LCA studies on plantation products in Indonesia have been conducted on palm oil (Suprihatin *et al*., 2015; Siregar *et al*., 2015), quinine (Parameswari *et al*., 2019), jatropha (Siregar *et al*., 2015), sago (Yusuf *et al*., 2019), and arabica coffee (Diyarma and Bantacut, 2019). The impact categories from other studies generally only considered global warming potential, acidification, and eutrophication. Thus, this study considered additional impact categories, such as ecotoxicity and human toxicity potential. Table 1 shows the impact categories and scope used in the LCA study of perennial crop products.

Except for the impact categories, minimal attention has been provided to the agronomic aspects of perennial or plantation crops in LCA because of the limited data available and the lack of methodological guidelines to explain the entire life cycle, especially the agricultural/plantation aspects. Calculating the entire lifespan of perennial crops within the LCA is necessary (Diyarma and Bantacut, 2019; Bessou *et al.*, 2013). LCA studies of coconut-derived products in Indonesia have been limited to gate-to-gate or production aspects, such as coconut shell liquid smoke (Yuliansyah, 2019). As a leading export product, evaluating the environmental impact of copra and charcoal products is important to improve their environmental performance such that they can increase product competitiveness and can be promoted as environmentally friendly products. This study can also be a reference to the LCA of other derived products, such as coconut cooking oil, activated carbon, bio-briquette, and bio-pellet. This study aimed to analyze inventory by identifying inputs and outputs, calculating the impacts of coconuts, copra, and coconut shell charcoal using the LCA approach, and identifying improvement scenarios to reduce these impacts and improve sustainability. This study was conducted on coconut plantations in Agrabinta, South Cianjur, and a copra-charcoal factory in Sukabumi, West Java, Indonesia, from 2020 to 2021.

## MATERIALS AND METHODS

This study was based on the LCA framework following the ISO 14044 guidelines, which comprises several stages: 1) goal and scope definition, 2) life cycle inventory (LCI), 3) life cycle impact assessment (LCIA), and 4) interpretation followed by improvement recommendations.

### *Goal and scope definition*

An LCA study was conducted to quantify the impacts of coconuts on farms, copra, and coconut charcoal. This study aimed to identify hotspots and opportunities for improvement. The scope of this study was cradle-to-gate, starting from preparation of coconut land and nurseries, planting, fertilization, and harvesting mature coconuts, which had been conducted for 42 years, to transporting coconuts from farm to factory, copra production in the factory, and charcoal production (Fig. 1). Forty-two years was considered to be the coconut age because it is necessary to calculate the entire lifespan of the perennial crop within the LCA (Bessou *et al.*, 2013).

### *Life cycle inventory (LCI)*

The LCI stages include data collection, calculation, validation, and linkage with process and function units based on mass and energy balances. The data comprised primary (foreground) data from plantations and secondary (background) data from the literature, Ecoinvent 3.5, and agri-footprint databases. The Technical Instructions for Tall Coconut Cultivation of the Palma Plantation Research Institute (PPRI) collected data on planting, fertilization, and maintenance of coconut plants (PPRI, 2015). The output comprised primary products, co-products, and emissions. Inventory analysis also addresses allocation mechanisms to discover the processes shared with different production systems. The mass balance determines allocation. The inventory analysis of this LCA study used 1 ha of land for coconut plantations as the basic unit for the unit function of a 1 ton mature coconut on the farm. The impact study normalized the unit function based on the plantation yield of 1 ton of copra and 1 ton of coconut charcoal.

### *Life cycle impact assessment (LCIA)*

According to ISO 14044, the mandatory elements of LCIA include the selection of impact categories, classification of LCI results, and characterization or calculation of category indicator results. The characterization is calculated using Eq. 1 (Heijungs *et al.*, 2004).

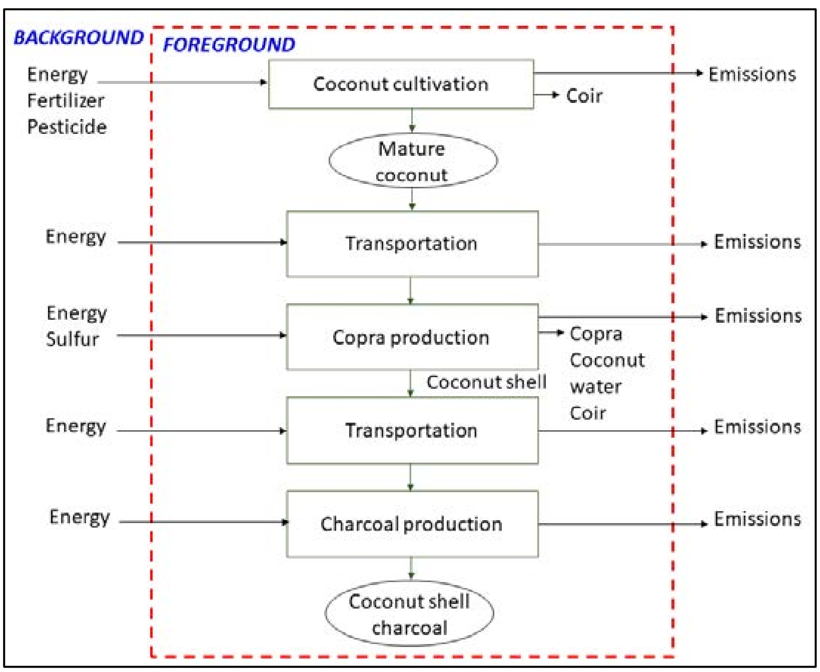



Fig. 1: System boundary (scope) of the LCA (cradle-to-gate)

$$IRc = \sum_{s} CFcs \times ms, \quad (1)$$

where:

$IR_c$ : indicator results for impact category c;

$CF_{cs}$ : characterization factor that connects inventory s with impact category c;

$m_s$ : amount or mass of inventory s.

The impact assessment calculation was performed using SimaPro software version 9.3, Faculty License. The selected impact assessment method was the Center of Environmental Science of Leiden University Impact Assessment (CML 2001-IA baseline) because it is the most widely used impact calculation method in LCA studies in the agriculture and food product (agri-food) sectors (Merchan and Combelles, 2012). CML 2001 uses a midpoint approach, which includes all emission- and resource-related impacts (Guinee, 2002). The mandatory impacts (baseline) in the CML 2001-IA baseline comprise 11 midpoint categories: ADP, ADP-FF, GWP100, ODP, HTP, FAP, marine aquatic ecotoxicity potential (MAP), TEP, POP, AP, and EP. MAP was excluded from this study because the characterization model of this impact category is still debatable due to the absence of evidence regarding increased pollutants in seawater caused by atmospheric emissions (Wiloso *et al.*, 2019; Heijungs *et al.*, 2004). A normalization procedure was performed to identify the most significant impact categories for humans.

*Interpretation and recommendation*

The results of the LCI and LCIA stages should be interpreted considering the objectives and scope of the study. During the interpretation stage, inferences were made from the resultant hotspots, specifically the stages with the most substantial impact categories that played the most significant role. Scenarios for improvement were also identified, and the impact reduction was calculated.

## RESULTS AND DISCUSSION

*Life cycle inventory*

The data revealed that 1 hectare (ha) of tall coconut plantations has generated an average of 1235 mature coconuts/ha/year since the sixth year of planting. The weight of each tall coconut was approximately 1.4 kg, which is equal to 1729 tons/ha/year. Table 2 shows the input and output data from the Inventory of Tall Coconut cultivation for one cycle (42 years) within the scope of the cradle-to-farm gate. These activities begin with land preparation, nurseries, planting, fertilization, and harvesting, including transportation to the warehouse and coconut husk stripping. The distance between the plantation and the warehouse was 6.2 km. The production site is in the same area as the coconut plantation; thus, the transportation of supporting materials, such as fertilizers and pesticides, is zero (0).

Land preparation comprised several stages: land clearing, establishment of plant lines, and creation of planting holes. The initial land for the Tall Coconut Plantation at the Agrabinta Plantation was an acacia wood secondary forest. Land clearing is performed by chopping trees using an ax to cut shrubs and small trees and a chainsaw to cut down giant trees. The average time to cut down acacia trees using a chainsaw on a 25% sloping topography is 0.06 h/tree (Wulan *et al.*, 2020). The number of acacia trees per 1 ha was 647; therefore, chopping an acacia tree on 1 ha of land takes 38.82 h. Logging was performed using a gasoline-fueled chainsaw with a requirement of 3 L/h and mixed with oil at a ratio of 25:1 (Dulsalam *et al.*, 2018; Faqih *et al.*, 2018). The following process involved land preparation using a diesel-fueled four-wheeled tractor with a disk plow, which takes 7.5 h/ha with a diesel fuel consumption of 6.498 L/h (Murti *et al.*, 2016). Processing 1 ha of land requires as much as 49 L of diesel fuel. The polybag used for seedlings was black polyethylene with a length of 40 cm, a height of 50 cm, and a thickness of 0.18–0.10 mm (16–17 pieces of polybag/kg). Plating 160 seeds over 1 ha took 160 polybags weighing 10 kg. Fertilization was performed until the seedlings were eight months old based on the PPRI guidelines. Table 3 shows the dosage of fertilizers during seedlings, and Table 4 shows the dosage during fertilization after planting. The types of fertilizers used are Urea (Nitrogen source), $P_2O_5$ or SP-36 (phosphor source), KCl (Potassium source), Kieserite (Magnesium source), and Borax (Boron source). Intensive fertilization only lasts until the fourth year, after which poultry manure is given annually at the rate of 5 kg/tree/year.

The primary outputs of tall coconut cultivation are coconut bunches and biomass from coconut leaves and fallen leaf midribs. The amount of fallen leaves is estimated to be 5 kg/ha/year, with the leaf midrib

Table 2: Inventory input of coconut cultivation (1 ha in one cycle – 42 years)

| Process stage | Input/output | Amount | Unit |
|---|---|---|---|
| Input | | | |
| Land preparation | Gasoline fuel | 116.46 | L |
| | Oil | 4.66 | L |
| | Diesel fuel | 49 | L |
| Nursery/ seedlings | Polybag | 10 | kg |
| | Coconut seeds | 160 | pcs |
| | Urea | 10.4 | kg |
| | Phosphorous pentoxide ($P_2O_5$) | 7.2 | kg |
| | Potassium chloride (KCl) | 18.4 | kg |
| | Kieserite | 4.8 | kg |
| | Herbicide | 0.6 | kg |
| | Insecticide | 0.6 | kg |
| | Fungicide | 0.6 | kg |
| Planting | $P_2O_5$ | 4.8 | kg |
| Fertilization | Urea | 272 | kg |
| | $P_2O_5$ | 192 | kg |
| | KCl | 464 | kg |
| | Kieserite | 80 | kg |
| | Borax | 9.6 | kg |
| | Poultry Manure | 15,200 | kg |
| Harvesting | Fuel | 2,901.6 | L |
| Output | | | |
| Harvesting | Coconuts | 62,244 | ton |
| | - Coconut grains | 41,349 | ton |
| | - Coconut coir | 20,895 | ton |
| Biomass | Coconut leaves | 95,020 | ton |
| | Coconut midrib | 52,053 | ton |

Table 3: Fertilizers dosage during seedlings (PPRI Guideline)

| Fertilizers (g/seed) | Seedling age (month) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Urea | 5 | 5 | 5 | 10 | 10 | 10 | 10 | 10 |
| $P_2O_5$ | 0 | 0 | 15 | 0 | 0 | 0 | 0 | 0 |
| KCl | 10 | 10 | 10 | 15 | 15 | 15 | 20 | 20 |
| Kiserit | 5 | 0 | 5 | 0 | 10 | 0 | 10 | 0 |

Table 4: Fertilizers dosage during fertilization (PPRI Guideline)

| Fertilizers | Amount (g/tree/year) | | | |
|---|---|---|---|---|
| | Year I | Year II | Year III | Year IV |
| Urea | 250 | 250 | 500 | 700 |
| $P_2O_5$ | 175 | 175 | 350 | 500 |
| KCl | 350 | 350 | 700 | 1500 |
| Kieserite | 50 | 100 | 150 | 200 |
| Borax | - | 10 | 20 | 30 |

weighing up to 188.56 kg/tree. The biomass falls to the ground and decomposes if left unmanaged. The harvested coconuts were transported to a copra factory in Sukabumi, West Java. Copra-processing inventories were justified on the basis of the number of coconuts per hectare in one cradle-to-gate cycle. The activity began by transporting raw materials from the coconut warehouse in the Agrabinta plantation to the copra factory at a distance of 142 km. The total input of coconut grains used was 41,349 tons.

Table 5: Inventory data of copra product (unit function: 1-ton copra)

| Process | Input/Output | Amount | Unit (Per 1 ton of Copra) |
|---|---|---|---|
| Transportation of harvested coconut (142 km) | Input | | |
| | - Mature coconut | 4.168 | ton/ton |
| | - Diesel fuel | 0.045 | GJ/ton |
| | Output | | |
| | - Mature coconut | 4.168 | ton/ton |
| Transportation of sulfur (110 km) | Input | | |
| | - Sulfur | 0.001 | ton/ton |
| | - Gasoline | 0.036 | GJ/ton |
| | Output | | |
| | - Sulfur | 0.001 | ton/ton |
| Production of copra | Input | | |
| | - Mature coconut | 3.182 | ton/ton |
| | - Sulfur | 0.001 | ton/ton |
| | - Electricity | 0.023 | GJ/ton |
| | Output | | |
| | - Copra | 1.000 | ton/ton |
| | - Water vapor | 0.953 | ton/ton |
| | - Coconut water | 0.752 | ton/ton |
| | - Coconut coir | 0.161 | ton/ton |
| | - Coconut shell | 0.989 | ton/ton |

Coconut grains that arrive at the factory are sorted and cleaned from the remaining fibers in the coconut shell. The coconut was split and dried in a drying chamber. Fumigation was conducted on the first and second days of drying using 0.2 kg of sulfur for each drying room with a capacity of approximately 2000 coconuts. Fumigation aims to clean and prevent fungal contamination in dried coconut meat (Najamuddin *et al*., 2020). Table 5 presents the inventory data for the copra products.

Table 5 shows that the highest material inventory hotspot was mature coconuts at 4.168 tons/ton copra. The entire copra production is traditionally processed; machines or equipment that require large amounts of energy are not used. The use of energy in the form of electricity in copra production shows a small ratio to copra products because it is only used for lighting. Coconut shell charcoal is produced by burning coconut shells sourced from the byproducts of copra processing. The coconut shell used as a raw material for charcoal affects the mass allocation of the copra. Table 6 reveals that the highest inventory hotspot is the use of coconut shells and fibers, which is 5601 tons/ton of charcoal.

Pyrolysis produces charcoal, ash, and combustible substances containing various compounds. Of the charcoal products produced, 11% are raw or immature charcoal (Darmawan *et al.*, 2015). Ash is produced from charcoal processing fuel because the furnace in which the fuel is only partially closed is still in operation. The burning substances from smoke due to pyrolysis contain various compounds, such as water vapor, gases, and VOCs. Odor emissions and the formation of photochemically reactive species are the most influential impacts associated with VOCs in the environment (Reyes *et al.,* 2020). During fuel combustion, the combustible substances contain only $CO_2$ and dihydrogen oxide ($H_2O$). $H_2O$ and gas-containing components CO, $CO_2$, hydrogen (H), $CH_4$, and $C_2H_4$ were produced during pyrolysis as much as 18.97%, 35.63%, 0.23%, 4.02%, and 2.30%, respectively, and other volatile matter as much as 18.24% of the charcoal (Fagbemi *et al.,* 2001). The amounts of combustible substances in the charcoal are listed in Table 7.

*Life cycle impact assessment (LCIA)*

The environmental impact analysis of coconut cultivation comprised 10 impacts based on the CML 2001-IA baseline method. Table 8 shows the potential impacts of mature coconuts in this study compared with Indonesia, India, and the Philippines from the Agri footprint.

The Agri-footprint 6 database (a, b, c) uses economic

Table 6: Inventory data of coconut charcoal product (unit function: 1-ton coconut shell charcoal)

| Process | Input/output | | Amount | Unit (Per 1-ton charcoal) |
|---|---|---|---|---|
| Transportation of coconut shell from copra factory to charcoal factory (11 km) | Input | | | |
| | | - Coconut shell + coconut coir | 7.337 | ton/ton |
| | | - Gasoline | 1.305 | GJ/ton |
| | Output | | | |
| | | - Coconut shell + coconut coir | 7.337 | ton/ton |
| Charcoal production | Input | | | |
| | | - Coconut shell | 3.069 | ton/ton |
| | | - Coconut shell (firing) | 1.498 | ton/ton |
| | | - Coconut coir (firing) | 0.105 | ton/ton |
| | | - Electricity | 0.150 | GJ/ton |
| | Output | | | |
| | | - Coconut charcoal | 1.000 | ton/ton |
| | | - Half-baked coconut charcoal | 0.111 | ton/ton |
| | | - Ash of coconut shell | 0.020 | ton/ton |
| | | - Ash of coconut coir | 0.020 | ton/ton |
| | | - Burning substance from firing | 1.651 | ton/ton |
| | | - Burning substance from pyrolysis | 1.958 | ton/ton |

Table 7: Composition of burning substance (smoke) from charcoal production per 1-ton charcoal

| Substances | Amount (ton) |
|---|---|
| Burning substance from firing | |
| - $CO_2$ | 1.486 |
| - $H_2O$ | 0.166 |
| Burning substance from pyrolysis | |
| - $H_2O$ | 1.161 |
| - CO | 0.190 |
| - $CO_2$ | 0.356 |
| - H | 0.002 |
| - $CH_4$ | 0.040 |
| - $C_2H_4$ | 0.023 |
| - VOC | 0.182 |

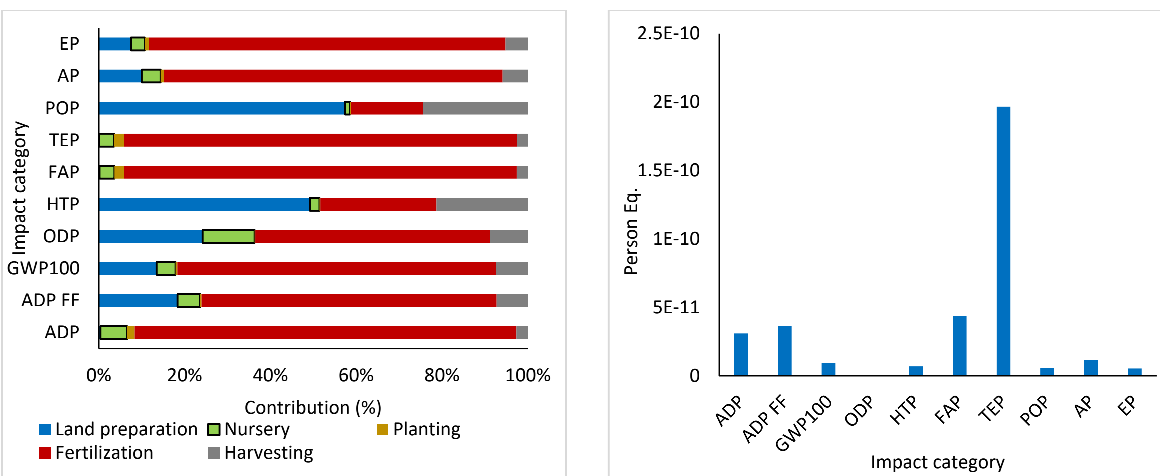
Table 8: Potential value of impact categories per 1 ton of coconut

| Impact category | Units | Coconut (this study) | Coconut (Indonesia)[a] | Coconut (India)[b] | Coconut (Philippines)[c] |
|---|---|---|---|---|---|
| ADP | kg Sb eq | $2.58x10^{-3}$ | $2.43x10^{-4}$ | $3.36x10^{-3}$ | $2.83x10^{-4}$ |
| ADP FF | MJ | 434.19 | 363 | $3.87x10^{3}$ | 481 |
| GWP100 | kg $CO_2$ eq | 40.02 | $1.06x10^{3}$ | 413 | 344 |
| ODP | kg CFC-11 eq | $5.41x10^{-6}$ | $3.35x10^{-6}$ | $3.42x10^{-5}$ | $4.05x10^{-6}$ |
| HTP | kg 1,4-DB eq | 50.69 | 5.87 | 61.1 | 11.6 |
| FAP | kg 1,4-DB eq | 22.40 | 67.5 | 289 | 318 |
| TEP | kg 1,4-DB eq | 9.53 | 5.45 | 22.9 | 23.6 |
| POP | kg $C_2H_4$ eq | 0.05 | $-6.52x10^{-3}$ | -0.49 | $-5.35x10^{-3}$ |
| AP | kg $SO_2$ eq | 0.26 | 0.32 | 8.74 | 0.431 |
| EP | kg $PO_4$ eq | 0.06 | 0.78 | 5.36 | 0.66 |

[a]Agri-footprint 6 database (coconuts at orchard {ID}, economics)
[b]Agri-footprint 6 database (coconuts at orchard {IN}, economics)
[c]Agri-footprint 6 database (coconuts at orchard {PH}, economics)

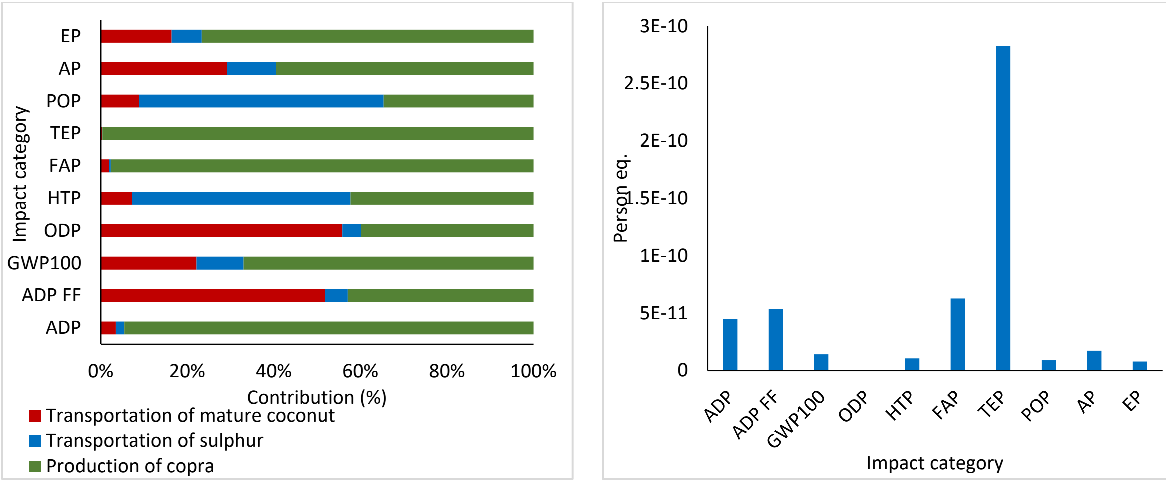
allocation, whereas the current study utilizes the mass allocation method for the LCI. This database covers various natural resources, such as water, land occupation, land transformations, and inputs, which include fertilizers, lime, capital goods, and energy use for field management and irrigation. Specific fertilizer amounts were quantified on the basis of the total NPK and the relative amounts of fertilizer consumed by type in Indonesia by the International Fertilizer Association (IFA, 2021). The total pesticide use in the Agri-footprint database is based on a pesticide model specific to crop–country combinations. Describing coconut plant varieties is necessary; thus, this study used an inventory based on PPRI guidelines for tall coconuts and live field observations. The crop yields of Agri-footprint 6 were derived from FAO statistics using a five-year average (2014–2018). This study covers land preparation and harvesting for up to 42 years. The length of the crop cycle is a key parameter that must be considered in the LCA of perennial crops (Bessou *et al.*, 2013). Fig. 2a shows the percentage impact at each stage of the coconut production process. By contrast, Fig. 2b shows the normalization results for the most influential coconut cultivation activities. LCA contribution analysis of coconut cultivation showed that fertilization was the most critical contributor to these impacts.

Fig. 2 shows that the value of any impact is unrelated to the relevance of the effect because each impact has a unique unit. Normalization was performed in accordance with the ISO 14044:2006 standard. Ranking categories with the same unit based on their influence on person-equivalent is feasible. According to the normalization, TEP has the most significant impact of 9.53 kg 1,4-DB eq/ton harvested coconut. The 1,4-DB (dichlorobenzene) eq unit is the normalized outcome of the ecotoxicity impact and is used to compute the emissions of each dangerous substance in 1,4-DB equivalent units (Singh *et al.*, 2018). TEP and FAP encompass the effects of toxicity on the environment, specifically in terrestrial and freshwater environments. Toxicity impacts involve various indicators that cause environmental harm based on the inherent toxicity and potential exposure to a compound (Tagliaferri and Lettieri, 2019). Fertilization causes the most significant ecotoxicity effects due to various chemical fertilizers (Merchan and Combelles, 2012). The effects of TEP are the most severe because they are linked to chemical fertilizers and pesticides, which directly impact the plantation land. Land exposed to chemical fertilizers for an extended period can leave harmful residues on the soil. The ADP FF impact represents the amount of energy in MJ for fossil resources utilized as energy or fuel. By contrast, ADP is expressed in stibium equivalent units (Sb eq), representing elements of abiotic energy. The stages of fertilization and land preparation primarily influenced this effect. This category of environmental consequences is impacted mainly by the rate at which nonrenewable or finite resources are extracted (Farinha *et al.*, 2019). The impact of ADP is mainly influenced by chemical fertilizers and land preparation by heavy equipment using fossil fuels. The next potential impact is acidification caused by the sulfur dioxide ($SO_2$) reaction with water in the atmosphere (Acero *et al.*, 2017). Acid-deposition gases include ammonia ($NH_3$), nitrogen oxides (NOx), sulfur oxides (SOx), and HCl.




(a) (b)

Fig. 2: Impact of coconut cultivation a) Percentage of the contribution of the coconut cultivation process, b) Normalization of impact category




(a) (b)

Fig. 3: Impact of copra production a) Percentage of the contribution of copra production, b) Normalization of impact category

Acidification also refers to lowering the soil pH by adding nitrogen, which can have various direct and indirect effects on plant growth (Clark *et al.*, 2013). Coconut has a relatively low GWP100 value when compared to other plantation crops, such as palm oil, jatropha, and quinine salt, with 1378 kg $CO_2$ eq/ton palm oil, 817.25 kg $CO_2$ eq/ton jatropha (Siregar *et al.*, 2015), and 1533 kg $CO_2$ eq/ton quinine (Parameswari *et al.*, 2019). Coconut plants do not require extensive maintenance after fruiting, particularly with chemical fertilizers and pesticides. The coconuts were analyzed at 42 years of age; thus, the age of the crop cycle also affected the degree of impact (Bessou *et al.*, 2013). Crops produce additional fruits as age increases. The influence of crops on the cultivation period was relatively minimal. The copra production system involves transporting raw coconut grains from the warehouse, transferring sulfur-supporting materials from the producer, and processing coconuts into copra. The percentage impacts of the transportation and copra production stages are shown in Fig. 3a. Meanwhile, the normalization results are presented in Fig. 3b.

The use of sulfur in the fumigation process caused a high impact on processing. By contrast, the magnitude of the impact on transportation was due to the use of gasoline to transport coconuts from the warehouse to a copra factory. The number of impact categories is listed in Table 8. The normalization results in Fig. 3b show that the categories of impacts with the most significant influence were almost the same as those on cultivation activities. TEP still demonstrated the most significant impact because most impacts were still influenced by coconut cultivation activities. The system limitation in copra production is cradle-to-gate; therefore, the impact of coconut cultivation is included in the copra product system. The ADP FF impact category remained the next most important factor due to the use of fossil fuels in the copra production system. The energy used in copra production comes from the gasoline utilized for transporting raw materials, supporting materials, and lighting. ADP FF increased to 1683.58 megajoules (MJ)/ton of copra from 434.19 MJ/ton of coconut grains. Another impact was observed for acidification. The use of sulfur in the fumigation process influences this potential impact. The potential impact of acidification has almost doubled from 0.26 kg $SO_2$ eq/ton coconut to 0.48 kg $SO_2$ eq/ton copra. The use of sulfur also affects the category of HTP impact, which increases by 30.73 kg 1.4 DB eq. Burning sulfur produces $SO_2$ gas, which harms human health because it can cause respiratory problems and lung damage considering long-term exposure (Cahyono, 2011). Excess sulfur can irritate the cornea and cause blindness (Najamuddin *et al.*, 2019). The subsequent impact was GWP, which has the potential global impact. The gases that affect

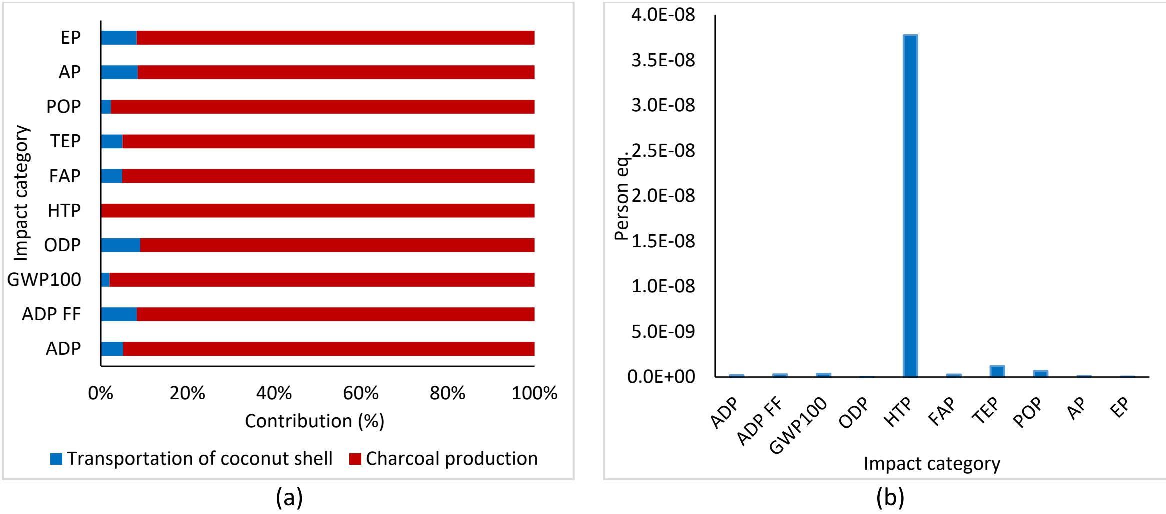



Fig. 4: Impact of coconut shell charcoal production a) Percentage of the contribution of coconut shell charcoal production, b) Normalization of impact category

Table 9: Potential value of impact categories per 1 ton of copra and 1 ton of coconut shell charcoal

| Impact category | Units | Copra | Coconut shell charcoal |
|---|---|---|---|
| ADP | kg Sb eq | $3.78 \times 10^{-3}$ | 0.02 |
| ADP FF | MJ | 1,683.58 | 8,651.17 |
| GWP100 | kg $CO_2$ eq | 70.74 | 1,753.55 |
| ODP | kg CFC-11 eq | $1.87 \times 10^{-5}$ | $9.47 \times 10^{-5}$ |
| HTP | kg 1,4-DB eq | 81.42 | 292,487.52 |
| FAP | kg 1,4-DB eq | 32.50 | 140.96 |
| TEP | kg 1,4-DB eq | 13.72 | 58.50 |
| POP | kg $C_2H_4$ eq | 0.08 | 5.58 |
| AP | kg $SO_2$ eq | 0.48 | 2.58 |
| EP | kg $PO_4$ eq | 0.10 | 0.54 |

GWP include carbon dioxide ($CO_2$), methane ($CH_3$), nitrogen oxides ($NO_2$), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6) (IPCC, 2006). The analysis shows that copra production produces a GWP100 of 70.74 kg $CO_2$ eq/ton of copra in a cradle-to-gate. If copra is only seen from the gate-to-gate scope, from raw material transportation to product processing, then GWP100 emissions are only 30.72 kg $CO_2$ eq/ton of copra. Copra production has a low impact because it uses traditional methods and is primarily performed by manpower. In the Republic of Fiji, copra production through solar drying with manual labor contributes zero emissions (Charan, 2020). For consumption in the UK, copra emissions are 270 kg $CO_2$ eq/ton copra (Audsley *et al.*, 2009). Differences in technique and process technology, use of materials and energy, and the effect of transportation distance cause variations in impact. Charcoal production comprises shell transportation from the copra factory to the charcoal factory and shell processing into charcoal. Based on the LCIA, the processing of the shell into charcoal had a substantially significant impact compared with the transportation stage for all the impact indicators. The percentage of impact from the transportation and coconut–shell charcoal production stages is shown in Fig. 4a, and the normalization results are depicted in Fig. 4b. The potential values for each impact are presented in Table 9.

On a cradle-to-gate basis, charcoal production uses copra byproduct shells as the raw material, with 23.72% of the coconut grains processed into copra. The existence of an allocation method may affect the processes of previous stages. The calculation results of potential impacts in Table 9 show that all impact categories increased, particularly HTP. The toxic impact of charcoal preparation is obtained from the accumulation of coconut cultivation, coconut transportation, copra production, and shell transportation because the scope of this study is cradle-to-gate.

Normalization was performed for the 10 impact categories to assess the importance of the different impact categories (Wagner and Lewandowski, 2017). The order of impact (from highest to lowest) was HTP, TEP, POP, GWP100, ADP FF, FAP, ADP, AP, EP, and ODP, with person-equivalent values as shown in Fig. 4b. HTP is the impact category with the largest influence on the charcoal product system, which is mostly due to pyrolysis. HTP is a calculated index that reflects the potential hazard of a chemical unit released into the environment and is based on the inherent toxicity of a compound and its potential dose (Acero *et al.*, 2017). During pyrolysis, smoke is released through kiln-drum smoke containing compounds or emissions, including CO, $CO_2$, H, $CH_4$, $C_2H_4$, and VOCs. CO emissions provide significant contributions under scarce oxygen, poor mixture preparation, air entrainment, and incomplete combustion in traditional pyrolysis processes (Gunasekar *et al.*, 2020). Smoke was immediately released into the air because pollution control was not conducted. This uncontrolled air pollutant is similar to biomass burning in the open field, producing primary organic aerosols and VOCs in the atmosphere (Fang *et al.*, 2021). Biomass burning is a significant air pollution source, with global, regional, and local impacts on air quality, public health, and climate (Chen *et al.*, 2017). Water vapor is produced by burning raw materials and ash from coconut shells and fiber fuels. The smoke produced from pyrolysis harms human health and the environment because it can interfere with breathing and vision (Supraptiningsih, 2020). Exposure to coconut shell charcoal smoke can cause skin, eye, and gastrointestinal irritation (Abdollahi and Hosseini, 2014). The small particle can reach the alveolar region of the respiratory system depending on the inhaled particle size distribution. The fine particles penetrate the alveolar region and might be absorbed into the bloodstream of the human body (Chen *et al.*, 2017). This impact leads to charcoal factories that are located far from copra factories and settlements to avoid exposure to pollution in the wide community. HTP is also affected by the use of fossil fuels for transportation and fossil-fueled electricity production (Acero *et al.*, 2017). In the activated carbon production from coconut shells, HTP also has the highest impact (Arena *et al.*, 2016). The impact significantly increased photochemical oxidation potential (POP), which increased to 5.58 kg $C_2H_4$ eq/ton coconut shell charcoal. Photochemical oxidant formation occurs in relatively stagnant air under sunlight, low humidity, nitrogen oxides, and VOCs (Wang *et al.*, 2021). The GWP100 in the charcoal product system also increased to 1.75 tons $CO_2$ eq/ton coconut shell charcoal. The gas emissions due to pyrolysis significantly affect the GWP potential. By contrast, the GWP study of coconut shell charcoal in other factories within the gate-to-gate scope resulted in an impact of 0.18 tons $CO_2$ eq/ton of coconut shell charcoal (Yuliansyah, 2019). The charcoal production system was limited to transporting coconut shells from the market to a factory located 17 km away. In pyrolysis, a kiln drum connected to a condenser produces liquid smoke. The smoke from the pyrolysis results is accommodated in the condenser using this technology such that the emissions do not pollute the environment and the resulting impact is negligible.

*Interpretation and improvement recommendations*

An enormous percentage of contribution to the impact of environmental pollution (hotspots) occurred at the charcoal production stage, particularly during the pyrolysis process, based on LCI and LCIA. HTP was the most significant impact category for charcoal production. The high impact of HTP is due to exhaust gas emissions in the form of smoke during pyrolysis. Copra production has negligible potential impact because the process is still traditional and does not require significant resources or energy. Compared with other plantation crops, coconuts have minimal impact because of the slightly intensive cultivation and maintenance processes and a large amount of production due to the plant age. The impact allocation is small because it uses a cradle-to-gate system limitation from the beginning of land preparation to the harvesting of a 42-year-old coconut plant due to the large number of coconuts produced. Opportunities to reduce the impacts of the coconut shell charcoal are still available based on the interpretation. Therefore, a baseline scenario, existing conditions, and four improvement scenarios were developed without considering the technical and economic aspects. Improvement scenarios were identified for all activities, including coconut cultivation, copra production, and charcoal production. Several formulation improvement scenarios are presented as: 1) utilizing pyrolysis smoke for liquid smoke production, 2) implementing organic coconut farming, 3) developing decentralized coconut plantations integrated with a copra–charcoal factory and producing liquid smoke, and 4) applying scenarios 1, 2, and 3. The 10 impacts considered in this scenario analysis are presented in Fig. 5. Normalization was performed for the four scenarios to identify the influence level of each impact category. The normalization results show that compared with the existing condition, the effect of each impact category on the person equivalent is significantly reduced (Table 10).

In Scenario 1, the smoke from pyrolysis was processed into liquid smoke. The decrease in impact was due to the pyrolysis of smoke containing $H_2O$, CO, $CO_2$, H, $CH_4$, $C_2H_4$, and VOCs connected to the condenser. The GWP of liquid smoke from coconut charcoal was studied, and the impact of pyrolysis was found to be 0.075 tons $CO_2$ eq/ton charcoal. This impact is smaller than that in the current study, which produced 1.65 tons of $CO_2$ eq/ton charcoal. The calculation results show that scenario 1 can potentially reduce the impact of GWP to 0.2 tons $CO_2$ eq/ton coconut shell charcoal (cradle-to-gate scope). In addition to controlling air pollution and reducing emissions, liquid smoke can also increase the added value of coconut derivatives. Coconut coir, which is another byproduct, can be used as tar adsorbent in liquid smoke (Sari *et al.*, 2021). The liquid smoke condensation process is disregarded because it is not included in the coconut shell charcoal product system. In Scenario 2, organic farming was applied to coconut cultivation. Organic coconut farming can produce organic-based products that increase with rising health awareness among people (Alouw *et al.*, 2020). Ecotoxicity and human toxicity in organic and low-input farming systems are lower than that in conventional farming systems (Alaphilippe *et al.*, 2013). The fertilization stage in coconut cultivation significantly contributed to almost all impact categories due to the LCA under existing conditions. Petroleum fuel can also be replaced with fuel from vegetable oil (bioenergy) at the land preparation stage. Gasoline and oil for cutting trees were replaced with biofuel and bio-oil (lube oil), whereas diesel used for cultivating land with tractors was replaced with biodiesel. Scenario 2 showed a decrease in most of the impacts compared to the current conditions, but the impact categories of acidification and eutrophication increased. These results indicate that manure increases the incidence of $SO_2$ emissions, which causes acidification, and raises the amount of N and P nutrients, which cause eutrophication. Similarly, applying organic farming to apple plantations also raises acidification due to the use of compost (Alaphilippe *et al.,* 2013). Scenario 3 applied the concepts of integrated coconut plantations, copra factories, and coconut-shell charcoal factories. Coconut plantations were maintained under conventional conditions in this scenario. The integrated coconut agroindustry is developed near the warehouse of harvested coconut, which is 6.2 km away from the coconut plantation. The copra and charcoal factories are located in one area, that is, the warehouse; thus, does not require transportation. This concept aims to reduce the use of fuel oil for the transportation of coconut grains to the copra factory and shell transportation from the copra factory to the charcoal factory. Transportation is an activity that significantly contributes to the impact, especially ADP FF. This scenario still considers the transportation of sulfur from producers in Bandung to plantations in Agrabinta at a distance of 162 km. The emission reduction from charcoal production was achieved by producing liquid smoke. If liquid smoke is produced, then the smoke due to pyrolysis containing various gas emissions will be accommodated in the condensation pipe to prevent its entrance in the air and avoid potential impacts. Liquid smoke affects the LCA only for the usage of smoke from pyrolysis, but the production process of liquid smoke is not included in the system product of charcoal LCA. Scenario 4 combines the concepts of Scenarios 1, 2, and 3. The impact analysis results in Scenario 4 also decreased the impact but required additional implementation effort. Further implementation can also utilize charcoal as biochar to replace herbicides (Yavari *et al*., 2022). Table 10 shows that the highest level of influence changed from the HTP to the TEP in all scenarios. The decrease in HTP in the individual units was due to reduced toxic chemicals from fertilizers, fossil fuels, and various gas emissions

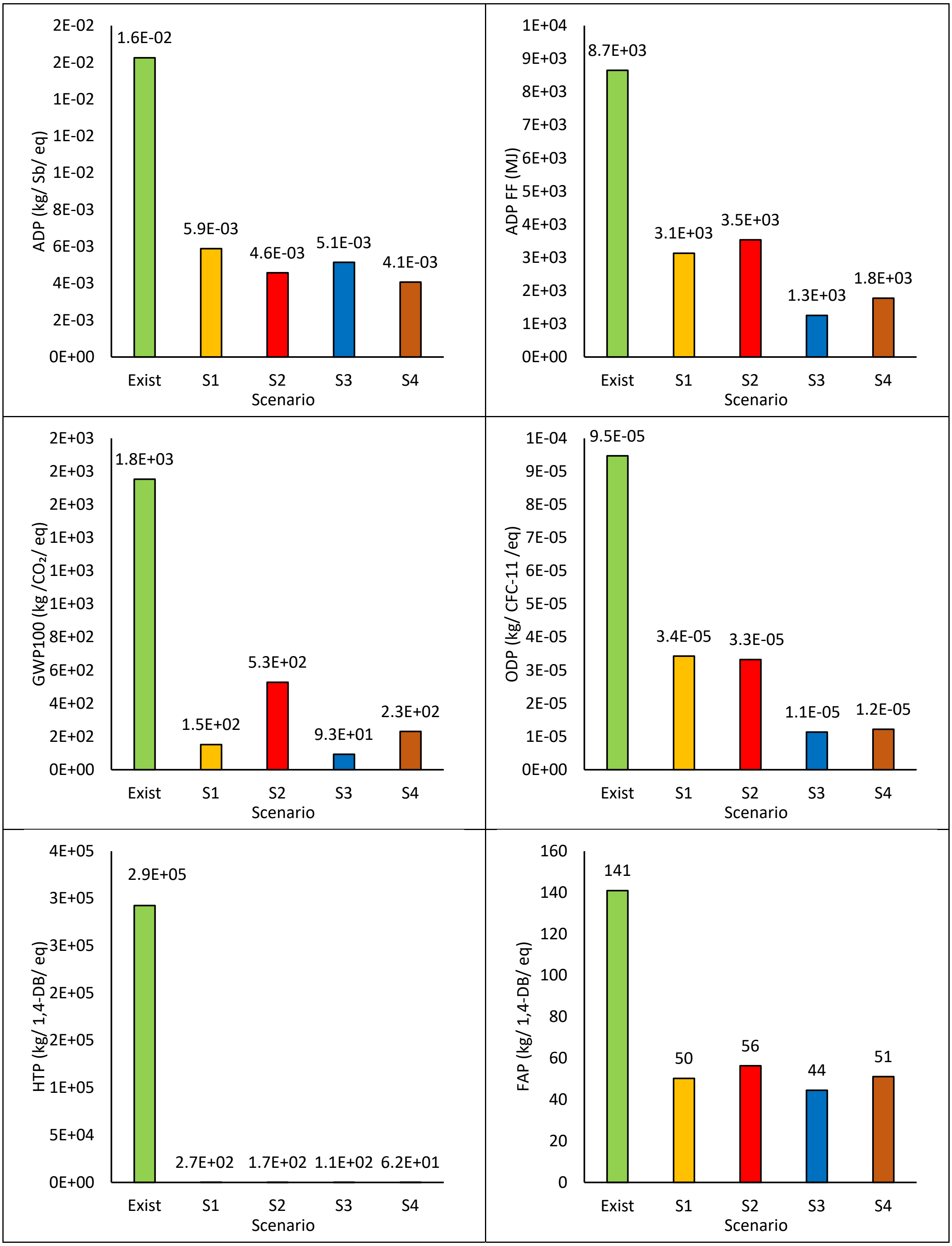
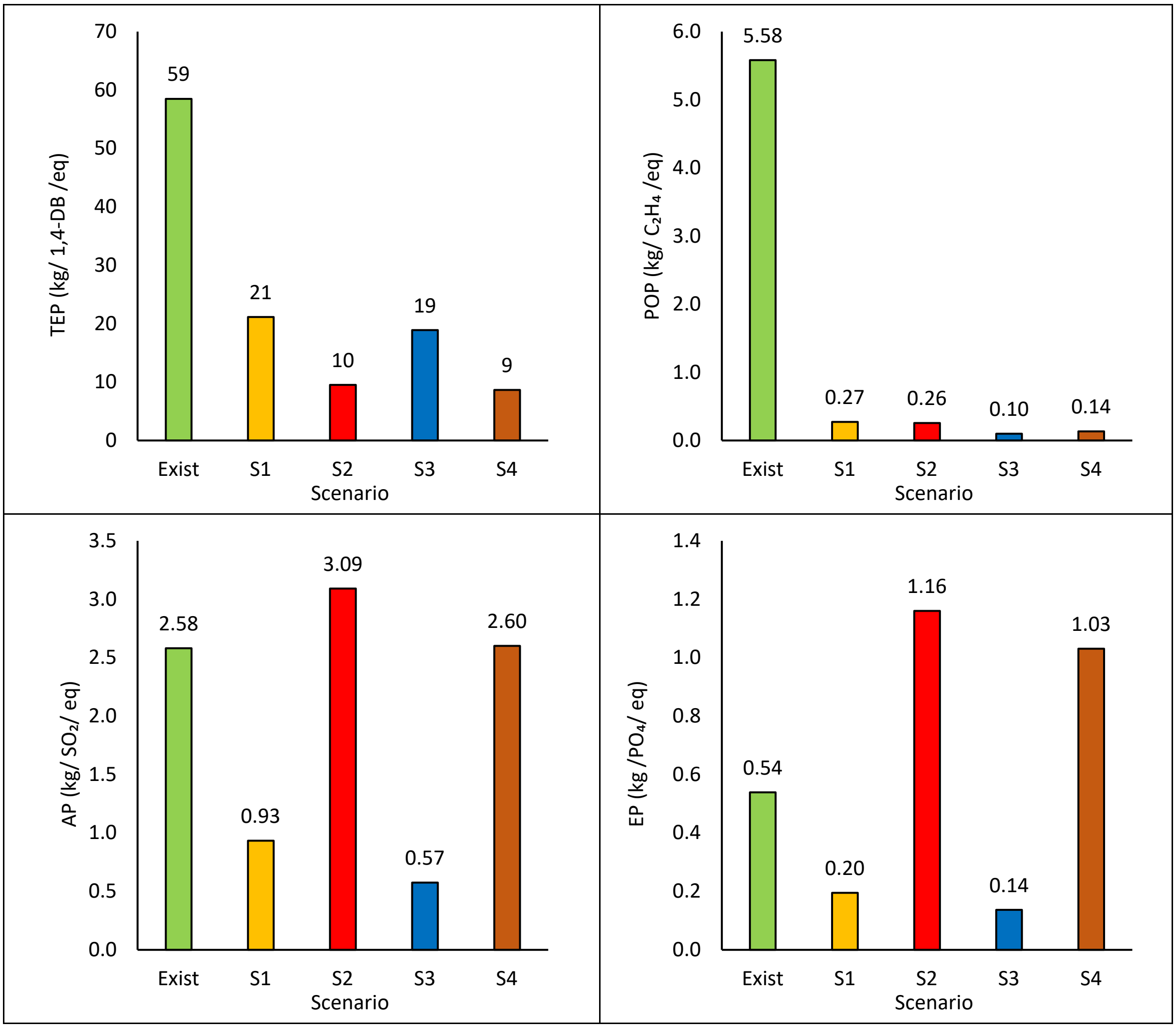



Fig. 5: Ten impact potential categories of coconut shell charcoal from each scenario compared with the existing condition




Continued Fig. 5: Ten impact potential categories of coconut shell charcoal from each scenario compared with the existing condition

Table 10: Normalization of impact category from each scenario compared with the existing condition

| Impact category (*Person eq.*) | Exist | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Decrease in scenario 3 (%) |
|---|---|---|---|---|---|---|
| ADP | 1.92E-10 | 6.94E-11 | 5.40E-11 | 6.07E-11 | 4.80E-11 | 68.35 |
| ADP FF | 2.75E-10 | 9.96E-11 | 1.12E-10 | 4.00E-11 | 5.65E-11 | 85.47 |
| GWP100 | 3.49E-10 | 3.03E-11 | 1.05E-10 | 1.85E-11 | 4.59E-11 | 94.69 |
| ODP | 1.06E-12 | 3.84E-13 | 3.72E-13 | 1.27E-13 | 1.37E-13 | 88.01 |
| HTP | **3.77E-08** | 3.52E-11 | 2.18E-11 | 1.41E-11 | 7.99E-12 | 99.96 |
| FAP | 2.72E-10 | 9.71E-11 | 1.09E-10 | 8.59E-11 | 9.86E-11 | 68.43 |
| TEP | 1.21E-09 | 4.36E-10 | 1.96E-10 | 3.89E-10 | 1.78E-10 | 67.70 |
| POP | 6.59E-10 | 3.22E-11 | 3.03E-11 | 1.19E-11 | 1.60E-11 | 98.19 |
| AP | 9.16E-11 | 3.32E-11 | 1.10E-10 | 2.04E-11 | 9.24E-11 | 77.73 |
| EP | 4.09E-11 | 1.48E-11 | 8.79E-11 | 1.04E-11 | 7.81E-11 | 74.64 |

due to pyrolysis. Scenario 3 demonstrated the most significant reduction in the impact categories among all the scenarios. Scenario 3 had the lowest 7 of 10 impacts among other scenarios, namely ADP-FF, GWP100, ODP, FAP, POP, AP, and EP (Fig. 5 and Table 10). Scenario 3 integrated coconut plantations, copra factories, charcoal factories, and coconut shell liquid smoke in one location without implementing organic coconut cultivation. Conventional farming practices for coconut cultivation are currently considered beneficial because coconut cultivation does not require intensive care and is highly resistant to pests or diseases. Coconut plants can generally last for a sufficiently long period of up to 60 years. The impacts decrease when the accumulation of manufactured products increases. Organic coconut cultivation can be applied if organic certification of coconut-derived products, such as virgin coconut oil and coconut sugar, is necessary. This implementation can increase product competitiveness, especially for consumers concerned about organic products. Coconut derivatives that generally require organic certification include virgin coconut oil and coconut sugar. Under conventional conditions, integrating coconut plantations, copra factories, charcoal factories, and liquid smoke production can lower the impacts through the following: reducing transportation fuels, removing emissions to air from pyrolysis, reducing time, cost, and handling risks, lessening byproducts, and increasing value-added products. Coconut-based agroindustry can be a promising sector for integrated industrial development while implementing the zero waste concept as an important part of a sustainable industry. The environmental performance of copra and coconut shell charcoal can be declared as EPD or Type III ecolabel.

## CONCLUSION

Potential impact analysis showed that the activity that produced the most significant impact (hotspot) in coconut cultivation was at the fertilization stage. Hotspot copra production occurs during the processing stage, whereas hotspot charcoal production transpires during pyrolysis. Pyrolysis for charcoal production had the largest impact on the three activities. The normalization results show that the most significant impact on humans from coconut cultivation and copra processing activities is TEP because of the use of fertilizers and transportation fuel. The largest influence of charcoal production was on the HTP because of emissions from pyrolysis. Improvement scenarios were formulated to reduce the environmental impact and improve sustainability. Scenario 1 converted the smoke due to pyrolysis into liquid smoke. Scenario 2 implemented organic coconut cultivation practices. Scenario 3 integrated coconut plantations with copra and charcoal processing plants and processed smoke into liquid smoke, and Scenario 4 combined all the scenarios. The results of the scenario implementation demonstrated the potential of developing an integrated coconut agroindustry that integrates coconut plantations, copra factories, charcoal factories, and liquid smoke in one location. The factors that affected the potential impact categories based on the scenario analysis were the type and amount of fertilizers and pesticides, transportation distance, amount of fuel, and treatment of emissions from pyrolysis. Scenario 3 can be implemented in the absence of organic farming because the cultivation of tall coconuts in Indonesia, especially in South Cianjur, West Java, does not require intensive care during its life cycle. Among all scenarios, Scenario 3 has the lowest 7 of 10 impact categories (ADP-FF, GWP100, ODP, FAP, POP, AP, and EP). The integration of coconut derivative production in one location significantly reduced the impact of fuel transportation and emissions. A further feasibility study should also consider the economic and technical aspects. The application of this scenario can help develop sustainable coconut agroindustry that produces environmentally friendly coconut derivative products and brand products using Type III ecolabel or EPD. This study can also be a reference for the next LCA of copra and shell charcoal derivatives, such as coconut cooking oil, virgin coconut oil from copra, activated carbon, bio-briquette, bio-pellet, and liquid smoke.

## AUTHOR CONTRIBUTIONS

T. Puspaningrum contributed to the data collection and observation, life cycle analysis, scenario analysis, and manuscript preparation and revision. N.S. Indrasti supervised the data collection and impact analysis, extended the discussion, and improvement recommendations. C. Indrawanto processed the coconut statistical data, sharpened the background, life cycle analysis deepened the discussion, and prepared the manuscript. M. Yani, the corresponding author, supervised the life cycle analysis, revised the discussion, and proofread the manuscript.

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## CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.



## PUBLISHER'S NOTE

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## ABBREVIATIONS

| | |
|---|---|
| *%* | Percent |
| *1,4-DB* | 1,4 – dichlorobenzene |
| *DGEC* | Directorate General of Estate Crops (*Direktorat Jenderal Perkebunan Republik Indonesia*) |
| *ADP* | Abiotic depletion potential |
| *ADP FF* | Abiotic depletion potential (fossil fuels) |
| *AP* | Acidification potential |
| *B* | Boron |
| $C_2H_4$ | Ethylene |
| *CFC-11* | Trichlorofluoromethane |
| $CH_4$ | Methane |
| *CML-IA* | Center of Environmental Science of Leiden University Impact Assessment |
| *CO* | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| *EP* | Eutrophication potential |
| *EPD* | Environmental product declaration |
| *Eq.* | Equation |
| *eq.* | Equivalent |
| *FAP* | Freshwater aquatic ecotoxicity potential |
| *GJ* | Gigajoule |
| *GWP100* | Global warming potential (100 years) |
| $H_2O$ | Hydrogen oxide |
| *H* | Hydrogen |
| *h* | Hour |
| *ha* | Hectare |
| HC | Hydrocarbon |
| HFCs | Hydrofluorocarbons |
| *HTP* | Human toxicity potential |
| *ICC* | International coconut community |
| *ID* | Indonesia |
| *IN* | India |
| *IPCC* | Intergovernmental Panel on Climate Change |
| *ISO* | International Organization for Standardization |
| *KCl* | Potassium chloride |
| *kg* | Kilogram |
| *km* | Kilometer |
| *L* | Liter |
| *LCA* | Life cycle assessment |
| *LCI* | Life cycle inventory |

| | |
|---|---|
| *LCIA* | Life cycle impact assessment |
| *MAP* | Marine aquatic ecotoxicity potential |
| *Mg* | Magnesium |
| *MJ* | Megajoule |
| *N* | Nitrogen |
| *$NO_2$* | Nitrogen dioxide |
| *NOx* | Nitrogen oxides |
| *ODP* | Ozone layer depletion potential |
| *P* | Phosphorus |
| *$P_2O_5$* | Phosphorus pentoxide |
| *Pcs* | Pieces |
| *PFCs* | Perfluorocarbons |
| *PH* | Philippines |
| *POP* | Photochemical oxidation potential |
| *PPRI* | Palma Plantation Research Institute |
| *S1* | First Scenario |
| *S2* | Second Scenario |
| *S3* | Third Scenario |
| *S4* | Fourth Scenario |
| *Sb* | Stibium |
| *SF6* | Sulfur hexafluoride |
| *S-LCA* | Social life cycle assessment |
| *SP-36* | Superphosphate (36% of Phosphorus) |
| *$SO_2$* | Sulfur dioxide |
| *TEP* | Terrestrial ecotoxicity potential |
| *VOCs* | Volatile organic compounds |

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