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Sustainability assessment of palm oil-based refinery systems for food, fuel, and chemicals

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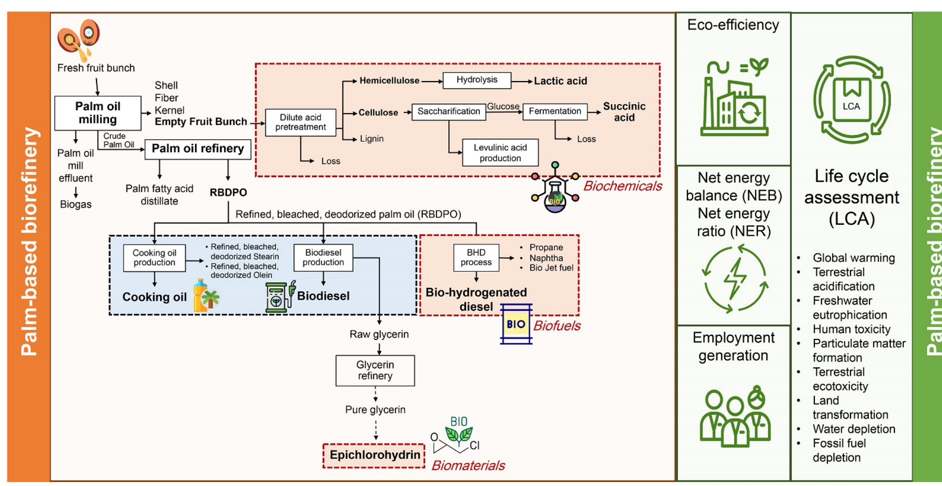
HIGHLIGHTS

➢Value-added products increase economic returns from palm biorefinery.
➢Value-added products increase overall environmental impacts from palm biorefinery.
➢Palm biorefinery with succinic acid production has the highest eco-efficiency.
➢Palm biorefinery with bio-hydrogenated diesel has the best energy performance.

GRAPHICAL ABSTRACT



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ABSTRACT

Palm-based biorefinery system has gained attention worldwide because of potentially high economic returns. However, environmental impacts also increase with the additional production. Therefore, this study aims to assess the sustainability of (1) current palm-based biorefinery system in Thailand, including cooking oil and biodiesel, and (2) palm-based biorefinery system with value-added products, i.e., succinic acid, lactic acid, bio-hydrogenated diesel (BHD), and epichlorohydrin (ECH) that represent biomaterial, biofuel, and biochemical products, respectively. Accordingly, seven palm-based biorefinery scenarios were designed, and their sustainability was assessed through life cycle assessment (LCA), net energy balance (NEB) and net energy ratio (NER), employment generation, and eco-efficiency. The results revealed that value-added production increased global warming impacts by around 3 – 79% compared with the current system. Although environmental impacts increased due to the additional processes related to the production of the value-added products, total product values also increased, especially for succinic acid, generally leading to higher eco-efficiency values. The current palm-based biorefinery system with succinic acid production had the highest eco-efficiency among all the scenarios considered. The BHD production scenario had the highest NEB and NER because the products were used for energy. Employment generation increased for all the scenarios between 2 – 86% compared with the current system.

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Contents

Abbreviations

1,3-DCH	1,3-Dichloropropan	LCA	Life cycle assessment
1,3-MCH	1,3-Monochloropropan	LCSA	Life cycle sustainability assessment
2,3-DCH	2,3-Dichloropropan	LT	Land transformation
2,3-MCH	2,3-Monochloropropan	MJ	Megajoule
AC	Terrestrial acidification	NEB	Net energy balance
B100	Biodiesel	NER	Net energy ratio
BCG	Bio-circular-green economy	Person-y	Person-year
BHD	Bio-hydrogenated diesel	PFAD	Palm fatty acid distillate
CPO	Crude palm oil	PMF	Particulate matter formation
ECH	Epichlorohydrin	POME	Palm oil mill effluent
EFB	Empty fruit bunch	RBDOL	Refined, bleached, deodorized palm olein
FD	Fossil fuel depletion	RBDPO	Refined, bleached, deodorized palm oil
FE	Freshwater eutrophication	RBDST	Refined, bleached, deodorized palm stearin
FFB	Fresh fruit bunch	RED	Renewable Energy Directive
GBEP	Global Bioenergy Partnership	RFS	Renewable Fuel Standard
Gg	gigagram	RSB	Roundtable on Sustainable Biomaterials
GHG	Greenhouse gas	SDGs	Sustainable development goals
GW	Global warming	SSF	Simultaneous saccharification and fermentation
HT	Human toxicity	THB	Thai Baht
kg	Kilogram	USD	US Dollar
kWh	kilowatt-hour	WD	Water depletion

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1. Introduction

Sustainable production of food and biofuels has been of interest worldwide. In 2020, approximately 72.3 million tonnes of palm oil products were produced globally, almost 85% in Indonesia and Malaysia (Murphy et al., 2021). The increment in palm oil demands (i.e., for cooking oil and biodiesel) has led to the rising in oil palm production, a highly productive crop used for food and energy, and value-added products, e.g., bio-acids from oil palm biomass (Akhtar et al., 2019; Bukhari et al., 2020) as well as the consideration of more advanced fuels such as bio-hydrogenated diesel and partially hydrogenated fatty acid methyl ester (Permpool et al., 2020; Boonrod et al., 2021). Thailand, the third-largest palm oil producer, produced around 16.2 million tonnes from 0.94 million hectares (OAE, 2021a), increasing about 51% from 2011 (OAE, 2021b). Palm oil has been promoted to be a potential source of renewable energy (Khatun et al., 2017; Jaroenkietkajorn and Gheewala, 2020); oil palm cultivation generates a huge of biomass (SAWIT, 2020), which is widely known as a renewable resource for value-added products (Hassan et al., 2019). The biomass composition (i.e., lignin, cellulose, and hemicellulose) can be reformed into chemical building blocks, which can be used for value-added products using the biorefinery concept (Akhtar and Idris, 2017).

A biorefinery system is an application of integrated processing technologies aiming to transform the biomass through physical, chemical, and/or biological processes into value-added products such as biofuels and bioenergy, biochemicals, degradable plastics, food, animal feed, cosmetics, and pharmaceuticals (Cherubini, 2010; Katakojwala and Mohan, 2021). The products from a biorefinery are consistent with bioeconomy, circular economy, and green economy perspectives, leading to the Bio-Circular-Green Economy (BCG Economy). Renewable resources (e.g., oil palm biomass) can increase product value and decrease agricultural waste. Also, biorefineries can be designed for additional unit processes such as materials, energy, or chemicals which are value-added products. Palm-based biorefineries have been developed and promoted continuously in response to the high oil palm production following a great demand from consumer markets (Ghazali et al., 2021) while also trying to reduce greenhouse gas (GHG) emissions which is an urgent global issue (IEA Bioenergy, 2020). However, including additional production processes for the biorefinery results in the escalation of environmental impacts as well as changing the social and economic impacts (Huailuek et al., 2019).

Various international strategies or standards were established for supporting the sustainable production of food and bio-based products, including from the oil palm value chain, e.g., Roundtable on Sustainable Palm Oil (RSPO) (RSPO, 2020), the US Renewable Fuel Standard (RFS) (EPA, 2022), the EU Renewable Energy Directive (RED) (EU, 2018), Global Bioenergy Partnership (GBEP) (FAO, 2011), Roundtable on Sustainable Biomaterials (RSB) (Fortin, 2017). Meanwhile, the evaluation of environmental, social, and economic impacts based on Sustainable Development Goals (SDGs) has been discussed in many studies (Hanafiah et al., 2021). Life cycle assessment (LCA) is a method used to assess environmental impacts over the life chain of a product or service (Goedkoop et al., 2008). The assessment is based on resources used and the emissions of the product/service system covering "Cradle-to-Grave", i.e., raw material acquisition process, production, use, and waste disposal. For the social sustainability assessment, employment generation or job creation is an indicator presenting a crucial component of national economic development and social and political stability. The number of workers or experts that works in any production can be represented by direct employment; direct employment relies on the expansion/reduction of the production process (Mendelson-Forman and Mashatt, 2007). Eco-efficiency is one of the indicators for evaluating economic sustainability; it relates to the effective use of resources to generate more goods and services and decrease waste and environmental pollution (UNESCAP, 2009). Life cycle sustainability assessment (LCSA) has been developed and used for assessing all environmental, social, and economic impacts throughout the life cycle (UNEP, 2011; Mondello and Salomone, 2020). LCSA does not only support sustainable production, which includes three pillars, but it also helps decision-making on sustainable agriculture, food, and bioenergy. Many studies have presented the sustainability of production systems by including various indicators that cover all three aspects. For example, the sustainability of palm biodiesel production in Thailand has been explained *via* GHG emissions, employment generation, gross domestic product, and trade balance improvement (Silalertruksa and Gheewala, 2013). The sustainability of valuable biochemical production has been illustrated by annual profit, global warming potential, fire explosion damage index, and toxicity damage index (Hafyan et al., 2020). As mentioned before, sustainability assessment, including the environmental, social, and economic pillars, can support the decision-making by policymakers and the private sector (Sitepu et al., 2020).

Therefore, to provide scientific supporting data for decision-making on the sustainability of palm-based biorefinery in Thailand, this study aims to assess the sustainability of the (1) current palm-based biorefinery system producing cooking oil and biodiesel and (2) proposed palm-based biorefinery systems with value-added products. Among several value-added products, succinic acid produced from empty fruit bunch (EFB), lactic acid produced from EFB, bio-hydrogenated diesel (BHD) produced from refined, bleached, deodorized palm oil (RBDPO), and epichlorohydrin (ECH) produced from glycerin are selected in this study. The selection of these four value-added products is based on covering all categories of oleochemical products, i.e., biomaterial, biofuel, and biochemical products, and the current market situation. Sustainability is being emphasized in the global market, and the production of bio-based chemical building blocks has gained interest. Accordingly, succinic, lactic acid, and ECH are good options for consideration. Succinic and lactic acid are promising precursors for various industrial chemicals and consumer products such as polyurethane, glue, polymers and resin, nylon, fibers, non-woven fabrics, plastic films, cosmetics, etc. (Hassan and Idris, 2016; Akhtar and Idris, 2017), while ECH is the most important building block in the manufacturing of epoxy resins and is used to produce various products such as polymer, plastic, rubber, textiles, inks, paper strengthening agents, etc. (Pembere et al., 2017; Lari et al., 2018). BHD has been promoted worldwide because of its better blending properties with diesel and environmental advantages (Boonrod et al., 2017; Permpool et al., 2020).

2. Methodology

2.1. Scope of this study

This study aimed to present the sustainability of palm-based biorefinery production by assessing the life cycle sustainability of current and potential palm-based biorefinery systems in Thailand. This study included LCA, eco-efficiency assessment, and employment generation to cover the three pillars of sustainability, i.e., environmental, economic, and social. Besides, NEB and NER were also assessed in this study to present the production efficiency. These assessments were selected based on the study objectives and following well-established international standards (i.e., RSPO, GBEP, and RSB). The assessment started with oil palm plantation, palm oil milling, palm oil refinery, cooking oil production, and biodiesel production (B100). For the potential palm-based biorefinery, it covers biofuels, biomaterials, and biochemicals, including the production of (1) succinic acid from EFB, (2) lactic acid from EFB, (3) BHD from RBDPO, and (4) ECH from pure glycerin. The functional unit of this assessment is 1 tonne of fresh fruit bunch (FFB). **Figure 1** presents the system diagram of this study; the dotted boxes refer to the production of value-added products, i.e., succinic acid, lactic acid, BHD, and ECH.

2.2. Life cycle inventory

Life cycle inventory presents the quantities of inputs (e.g., raw materials, resources, energy, utilities, etc.) and outputs (e.g., products, co-products, emissions to air, emissions to water, etc.). Data sources include (1) upstream palm oil industries (i.e., oil palm plantation), (2) midstream palm oil industries and upstream oleochemical industries (i.e., palm oil milling and palm oil refinery), and (3) downstream palm oil industries and midstream oleochemical industries (i.e., cooking oil production, and biodiesel and glycerin production). The data was collected from Thai palm oil industries (primary data) and reliable secondary data such as National Life Cycle Inventory (Thai LCI database), Ecoinvent, environmental impact assessment reports, and research studies. Besides, data validation was also conducted by material balance calculation. This study includes the inventories of oil palm plantation, palm oil milling, palm oil refinery, cooking oil production, biodiesel production, succinic and lactic acid production, BHD production, and ECH production (**Tables S1–S19** in the Supplementary Material).

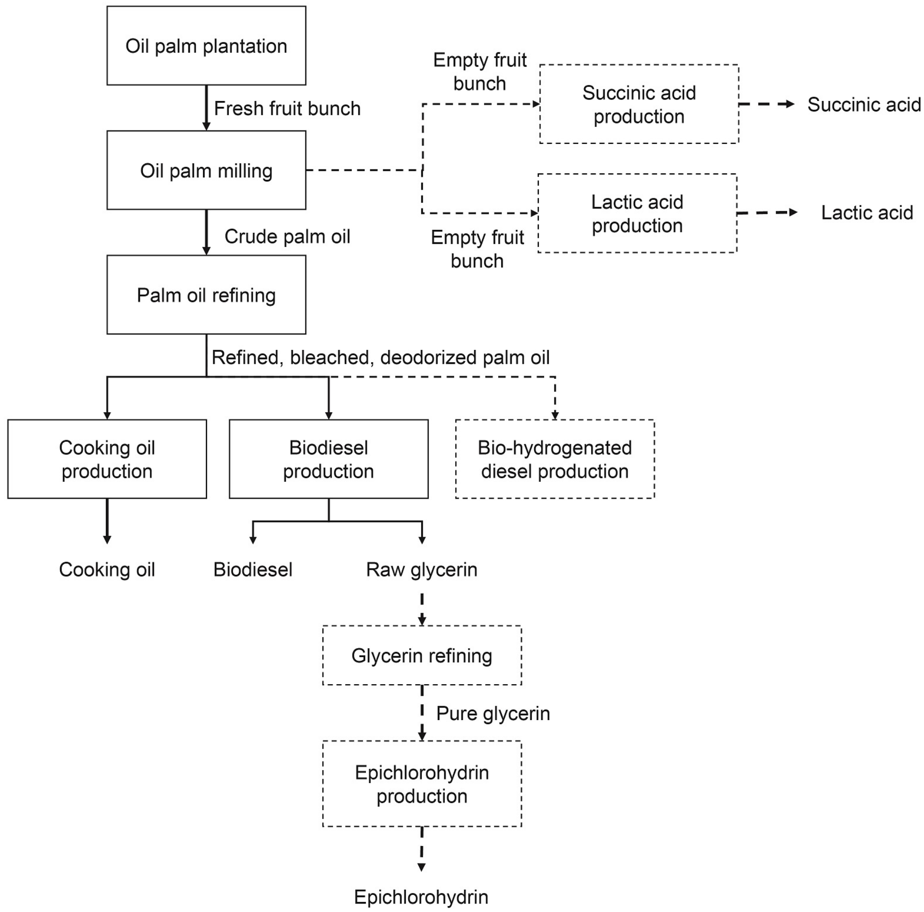

Fig. 1. System diagram of bio-based products from oil palm.

2.2.1. Oil palm plantation

Oil palm cultivation is separated into two main stages, i.e., oil palm seed production and oil palm plantation. Oil palm seed production comprises two minor steps; pre-nursery and main nursery. Pre-nursery covers almost four months, starting from sowing the seeds in a small poly bag that contains a mixture of soil, clay, mold, and other materials. Then, in the main-nursery stage, the seedlings are planted in large polyethylene bags for a year and brought to the cultivation area. Fertilizers and water are necessary for this step. Fertilizers must be applied for a couple of weeks while water is needed until planting in the cultivated areas. Oil palm cultivation starts with land preparation, followed by a selection of seedlings, planting and replanting, treatment, and harvest. The first harvest is when the oil palm is five years old and continues until it is around 25 – 30 years old, after which it is replanted. Currently, oil palm is harvested manually in Thailand.

2.2.2. Palm oil milling

Crude palm oil (CPO) is the main product of the milling process (wet extraction), and the major biomass residues include the kernel (5–15%), fiber (10–14%), shell (1–17%), and EFB (17–24%). Decanter cake and palm oil mill effluent (POME) are wastes from the wet extraction process. The oil extraction rate is in the range of 14–18%, which is similar to Malaysia (Subramaniam et al., 2010). In the palm oil mill, fiber and shell are used as renewable energy sources for steam and electricity production, and biogas from treating POME by anaerobic digestion process is used for electricity production. The steam and electricity are mainly used in the plant; however, the excess electricity can be sold back to the grid. The dry kernel is sold to a palm kernel oil mill, and the remaining EFB, in addition to what is used in oil palm plantations, is also sold as a biomass fuel or a feedstock for producing other products. In particular, it may be used for ethanol production to supplement the ethanol from cassava and sugarcane (Saswattecha et al., 2016).

2.2.3. Palm oil refinery

RBDPO is a product of the physical refining process, conducted by high-temperature steam under a vacuum to eliminate free fatty acids. This process includes three steps; (1) degumming, (2) bleaching, and (3) deodorization. This palm oil refining process can produce RBDPO with 90–96% yield and 4–9% of Palm Fatty Acid Distillate (PFAD) as a by-product.

2.2.4. Cooking oil production

Cooking oil or refined, bleached, deodorized palm olein (RBDOL) is produced by a dry fractionation process. This process converts RBDPO to RBDOL and refined, bleached, deodorized palm stearin (RBDST) with 70% and 30% yields, respectively.

2.2.5. Biodiesel (B100) production

Biodiesel production is based on a transesterification process through which the oil reacts with methanol as reactants producing biodiesel as the main product and glycerin as a by-product. In this study, RBDPO is the main feedstock for biodiesel production.

2.2.6. Succinic and lactic acid production

Succinic and lactic acids are produced from EFB using the same production process called "simultaneous saccharification and fermentation (SSF)"; however, the main feedstocks for producing these two acids are different. Succinic acid is produced from cellulose, while hemicellulose is used to produce lactic acid. Even though cellulose and hemicellulose together with lignin are obtained by separating the lignocellulosic content of EFB, the extraction of cellulose or hemicellulose requires different chemicals (Hassan and Idris, 2016; Chotirotsukon et al., 2019). Therefore, succinic and lactic acid cannot be simultaneously produced from the cellulose and hemicellulose obtained in the same batch of the EFB extraction process. Currently, the production of the two bio-based acids is still under research and development in Thailand to increase production efficiency and decrease production loss.

The production of succinic acid from EFB includes four stages; (1) SSF media preparation, (2) EFB drying process, (3) pretreatment and cellulose production, and (4) succinic-SSF process (Akhtar and Idris, 2017), as illustrated in the Supplementary Material (**Tables S10–S13**, respectively). The production of lactic acid is similar to succinic acid production; the difference is that lactic acid production does not include the EFB drying process. Lactic acid production comprises (1) SSF media preparation, (2) pretreatment and hemicellulose production, and (3) the lactic-SSF process (Hassan and Idris, 2016). Besides, the amount of extracted cellulose/hemicellulose from EFB is calculated based on the study by Chotirotsukon et al. (2019), which explains the cellulose extraction equation from EFB. Apart from these, data and information on the two bio-based acids from other biomass feedstocks are taken from existing commercial production platforms such as BioAmber and Mitsui & Co., PTT MCC Biochem Co., Ltd. (Cok et al., 2013).

2.2.7. Bio-hydrogenated diesel (BHD) production

BHD production from RBDPO is based on a hydrogenation process that requires the addition of hydrogen to RBDPO using palladium with activated carbon as a catalyst. BHD is obtained as the main product (around 97.6%), along with 1.0% fuel gas and 1.4% bio-gasoline as co-products (Permpool et al., 2020).

2.2.8. Epichlorohydrin (ECH) production

ECH production from pure glycerin is based on two steps; the hydrochlorination of glycerin and the production of ECH. A mixture of 1,3-Dichloropropan (1,3-DCH) and 2,3-Dichloropropan (2,3-DCH) is obtained from the first step. These chemicals are then dehydrochlorinated into ECH in the second step. The production of ECH from glycerin has not yet been commercialized in Thailand; data and information are from the commercial production of ECH in Taiwan (Wang et al., 2016).

2.3. Sustainability assessment

2.3.1. Life cycle impact assessment

This study assessed the mid-point environmental impacts using ReCiPe 2016 (version 1.13), as presented in **Table 1**.

Table 1.
Environmental impact categories considered in the study.

Impact Categories	Abbreviation	Unit
Global warming	GW	kg CO_2 eq
Terrestrial acidification	AC	kg SO_2 eq
Freshwater eutrophication	FE	kg P eq
Human toxicity	HT	kg 1,4-DB eq
Particulate matter formation	PMF	kg PM_{10} eq
Terrestrial ecotoxicity	TE	kg 1,4-DB eq
Land transformation	LT	m^2
Water depletion	WD	m^3
Fossil fuel depletion	FD	kg oil eq

The production process also generates co-products, which are utilizable and valuable. Hence, the economic-based allocation technique (Cherubini et al., 2011) was selected for sharing the environmental burdens from the production process between the main products and the co-products, as shown in **Table 2**. Meanwhile, this study assumed the waste generated as part of the production process would be adequately managed and considered the environmental impacts arising from the waste management process as well.

2.3.2. Net energy balance (NEB) and net energy ratio (NER)

NEB and NER are related to energy inputs and outputs of a production system, estimated by **Equations 1** and **2**. The total amount of fossil fuels (inputs) and products and co-products (outputs) from the palm-based biorefinery system are listed in *Supplementary Material* (**Tables S1–S19**). The energy of inputs and outputs is presented in **Table 3**.

$$NEB(MJ) = \Sigma Energy\ Output\ (MJ) - \Sigma Energy\ Input(MJ) \qquad \text{Eq. 1}$$

$$NER = \frac{\Sigma Energy\ Output\ (MJ)}{\Sigma\ Energy\ Input\ (MJ)} \qquad \text{Eq. 2}$$

Table 2.
Environmental impact categories considered in the study.

Palm-based biorefinery system	Product	Allocation factor	Co-products	Allocation factor
Oil palm cultivation	Fresh fruit bunch (FFB)	1.0000	-	-
Palm oil milling	Crude palm oil (CPO)	0.9140	Palm kernel	0.0704
			Fiber	0.0004
			Shell	0.0138
			Empty fruit bunch (EFB)	0.0014
Palm oil refining	RBDPO	0.9417	PFAD	0.0583
Cooking oil production	Cooking oil	0.6690	RBDST	0.3310
Biodiesel production	Biodiesel (B100*)*	0.9482	Raw glycerin	0.0518
Pure glycerin production	Pure glycerin	1.0000	-	-
BHD production	BHD	0.9403	Biofuels	0.0063
			Bio-gasoline	0.0534
Succinic acid production	Succinic acid	1.0000	-	-
Lactic acid production	Lactic acid	1.0000	-	-

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where; *NEB* is the net energy balance, *NER* is the net energy ratio, *ΣEnergy input* is the total energy consumption of the system (MJ), and *ΣEnergy output* is total energy from products and by-products (MJ).

Table 3.
Energy per unit product of palm-based biorefinery system.

Materials	Energy/Unit product (MJ/kg)
Fresh fruit bunch (FFB)	43.30
Fiber	11.40
Shell	16.90
Empty fruit bunch (EFB)	7.24
Crude palm oil (CPO)	40.10
Refined, bleached, deodorized palm oil (RBDPO)	37.60
Palm fatty acid distillate (PFAD)	36.00
Palm kernel oil (PKO)	35.56
Crude glycerin	18.05
Pure glycerin	18.05
Biodiesel (B100)	32.14
Steam (low pressure, 3 bar)	0.212
Electricity	3.60
Cooking oil (RBDOL)	54.14
Succinic acid	12.6
Lactic acid	15.11
Bio-hydrogenated diesel (BHD)	33.13
Epichlorohydrin (ECH)	0.42

2.3.3. Employment generation assessment

The assessment of employment generation in palm-based biorefinery production was assessed using employment coefficients. The employment generation is considered from oil palm plantation until the production of the four value-added products. The coefficients are estimated based on each product's direct employment per 1,000 tonnes (Gg).

Production capacity and the number of workers in cooking oil and biodiesel production listed in **Table 4** are based on primary data collected from 9 palm oil mills, 4 palm oil refineries, and 4 palm oil-based biodiesel plants. The results of the four value-added products are based on secondary data taken from pilot st udies and existing commercial production.

Table 4.
Production capacity and the number of workers for each product.

Production	Workers (Person)	Production capacity (Gg)
Cooking oil	25 – 396	44.8 – 416
Biodiesel (B100)	63 – 173	85.8 – 429
Bio-hydrogenated diesel (BHD)	23 – 314	400 – 800
Epichlorohydrin (ECH)	61	100
Succinic acid	60 – 64	13.6 – 30
Lactic acid	24 – 33	50 – 500

2.3.4. Eco-efficiency assessment

Eco-efficiency considers economic value per unit of the environmental impact caused, as expressed in **Equation 3**; a greater eco-efficiency value indicates more sustainable performance (Ehrenfeld, 2005). Higher economic value with lower environmental impacts can lead to a greater eco-efficiency value. Accordingly, current and potential palm-based biorefineries are assessed *via* the eco-efficiency indicator. The total economic value of all products occurring in each palm-based biorefinery is based on the market price of the products, as shown in **Table 5**. Due to the impacts of GHG emissions on the environment, society, and the economic system, global warming, one of the environmental issues of concern, is recommended to provide information on eco-efficiency (UNCTAD, 2004). Global warming is considered a proxy for the environmental impacts associated with each palm-based biorefinery.

$$Eco-efficiency = \frac{Total\ economic\ value\ of\ a\ product\ system}{Environmental\ impact\ of\ a\ product\ system} \qquad \text{Eq.3}$$

where, *total economic value* is estimated in Thai Baht (THB)/kg of product, and the global warming impact of a product system is assessed in kg CO_2 eq/kg of product.

Table 5.
Market prices of palm-based biorefinery products.

Products	Market price (USD/kg)
Palm kernel	0.90
Fiber	0.01
Shell	0.05
EFB	0.0013
Bio-electricity	0.11
Palm fatty acid distillate	0.70
Biodiesel	1.03
Cooking oil	0.87
Stearin	1.02
Raw glycerin	0.40
Pure glycerin	0.58
Succinic acid	2.65
Lactic acid	1.24
Bio-hydrogenated diesel	1.37
Fuel gas	0.85
Bio-gasoline	5.26
Epichlorohydrin	0.93

2.4. Current and potential palm-based biorefinery scenarios

Seven palm-based biorefinery scenarios were designed based on current and potential products, as illustrated in **Figure 2**. Figures of all scenarios, including inventories per tonne of FFB input, are provided in *Supplementary Material* (**Figs. S1–S7**).

2.4.1. Scenario 1: Current situation (cooking oil and biodiesel production)

In 2020, Thailand produced 2.9 million tonnes of CPO from 16 million tonnes of FFB entering palm oil mills. This total production of CPO consists of 19% domestic stock, 9% export, and 72% domestic consumption. The share of domestic consumption is divided into 52% for producing edible cooking oil and supplying it to other industries as raw materials and 48% for producing biodiesel.

The process of palm oil extraction yields 17% CPO along with 6% kernels, 13% fiber, 5% shell, 21% EFB, 1% POME, 3% decanter cake, and 34% loss (moisture, etc.). These biomass residues can be utilized and turned into profit, as detailed in *Section 2.2.2*. **Table 6** shows a summary of biomass utilization in palm oil mills.

2.4.2. Scenario 2: Current situation with succinic acid production

As detailed in **Table 6**, about 90% of the total amount of EFB remaining from the palm oil mills is sold. Thus, this amount of EFB is considered for producing succinic acid in this scenario to make it more beneficial. In the pretreatment and cellulose production stage, about 66% of the total amount of EFB is cellulose, with the remaining 33% of lignin and hemicellulose lost. About 0.85 kg of succinic acid can be obtained per kg of cellulose *via* the succinic-SSF process (Akhtar and Idris, 2017; Chotirotsukon et al., 2019).

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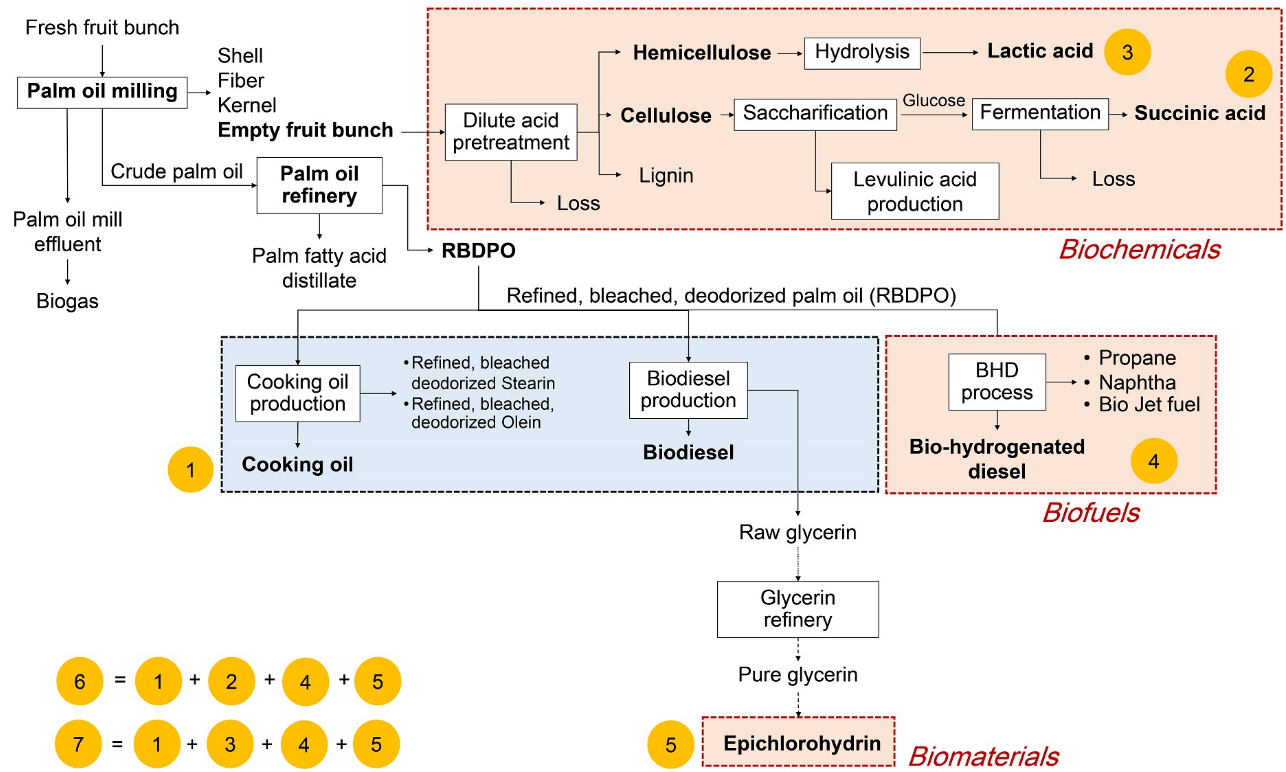

Fig. 2. Current and potential palm-based biorefinery scenarios.

Table 6.
Utilization of biomass residues from the palm oil mills.

Biomass residues (%)	Utilized within the factory (%)	Sold to other industries (%)
Kernels (6)	3	3
Fiber (13)	12	1
Shell (5)	0.1	4.9
EFB (21)	2	19
POME (1)	1	-

2.4.3. Scenario 3: Current situation with lactic acid production

Lactic acid production is based on the same amount of EFB (90% of total EFB) as for Scenario 2. Although lactic acid is produced using the same processes as succinic acid production (described in *Section 2.2.6*), making EFB ready for hemicellulose extraction is targeted for the pretreatment process, and converting hemicellulose into lactic acid is performed by the lactic-SSF process. Approximately 13% of hemicellulose can be obtained together with 87% loss as lignin and cellulose. About 0.17 kg of lactic acid can be obtained per kg of hemicellulose (Hassan and Idris, 2016; Chotirotsukon et al., 2019).

2.4.4. Scenario 4: Current situation with bio-hydrogenated diesel (BHD) production

This scenario assumed that BHD production is from 9% of the exported CPO, as presented in Supplementary Material (**Fig. S1**). Thus, the potential export of palm oil is slightly reduced compared to 2020.

2.4.5. Scenario 5: Current situation with epichlorohydrin (ECH) production

Epichlorohydrin is produced from pure glycerin, which is refined from raw glycerin. Raw glycerin is the by-product of biodiesel production. About 0.95 kg of ECH can be obtained per kg of pure glycerin (Wang et al., 2016).

2.4.6. Scenarios 6 and 7: Current situation with bioenergy, biochemical, and biomaterial

Both scenarios combine Scenario 1 (current situation) with three value-added products. Scenario 6 includes the production of cooking oil, biodiesel, BHD (bioenergy), ECH (biochemical), and succinic acid (biomaterial). Meanwhile, Scenario 7 includes the production of cooking oil, biodiesel, BHD (bioenergy), ECH (biochemical), and lactic acid (biomaterial).

2.5. Uncertainty analysis

Uncertainty analysis is conducted using a data quality assessment matrix to present the robustness of the results. Data quality indicators include Reliability, Completeness, Temporal correlation, Geographical correlation, and Technological correlation (Weidema and Wesnæs, 1997). Reliability represents the data collection or/and data estimation. Completeness relates to the quantity of data sampling and the period of sampling. Temporal correlation shows the age of data. Geographical correlation focuses on the areas of data collection. Finally, technological correlation considers processes, materials, and production technologies. The data quality score for each indicator varies from 1 (best) to 5 (worst). The uncertainty is then assessed using the Monte Carlo technique with a 95% confidence interval using the SimaPro software.

3. Results and Discussion

3.1. Environmental impact assessment

The environmental impact results provided in **Table 7** were calculated for each product accounted for in the palm-based biorefinery. The processes starting from oil palm plantation until the final products being produced, are included in the environmental impact assessment of palm-based biorefinery products.

Table 7.
Environmental impacts of palm-based biorefinery products.

Impacts	Unit	CPO	RBDPO	Cooking oil	B100	BHD	ECH	Succinic acid	Lactic acid
GW	kg CO_2 eq	9.45×10^{-1} ± 5.87×10^{-2}	1.07 ± 6.85×10^{-2}	1.04 ± 6.76×10^{-2}	1.26 ± 6.05×10^{-2}	1.02 ± 2.06×10^{-1}	2.61 ± 9.55×10^{-1}	9.54×10^{-1} ± 3.66×10^{-1}	3.09 ± 8.53×10^{-1}
AC	kg SO_2 eq	4.76×10^{-3} ± 2.55×10^{-4}	5.29×10^{-3} ± 3.11×10^{-4}	5.09×10^{-3} ± 3.26×10^{-4}	6.23×10^{-3} ± 2.80×10^{-4}	5.10×10^{-3} ± 1.01×10^{-3}	1.16×10^{-2} ± 4.24×10^{-3}	6.71×10^{-3} ± 2.40×10^{-3}	2.00×10^{-2} ± 5.63×10^{-3}
FE	kg P eq	8.05×10^{-5} ± 4.95×10^{-5}	8.80×10^{-5} ± 6.97×10^{-5}	8.50×10^{-5} ± 7.15×10^{-5}	1.02×10^{-4} ± 6.76×10^{-5}	7.93×10^{-5} ± 6.85×10^{-5}	1.78×10^{-4} ± 2.97×10^{-4}	7.24×10^{-5} ± 2.97×10^{-4}	2.28×10^{-4} ± 3.36×10^{-4}
HT	kg 1,4-DB eq	4.54×10^{-2} ± 5.52×10^{-2}	5.05×10^{-2} ± 7.88×10^{-2}	4.84×10^{-2} ± 8.41×10^{-2}	7.76×10^{-2} ± 6.47×10^{-2}	5.10×10^{-2} ± 7.39×10^{-2}	3.80×10^{-1} ± 3.71×10^{-1}	1.23×10^{-1} ± 2.92×10^{-1}	8.31×10^{-1} ± 4.90×10^{-1}
PMF	kg PM_{10} eq	1.40×10^{-3} ± 6.08×10^{-5}	1.66×10^{-3} ± 8.13×10^{-5}	1.59×10^{-3} ± 8.90×10^{-5}	2.04×10^{-3} ± 7.49×10^{-5}	1.57×10^{-3} ± 3.11×10^{-4}	4.75×10^{-3} ± 1.73×10^{-3}	2.87×10^{-3} ± 1.07×10^{-3}	7.87×10^{-3} ± 2.19×10^{-3}
TE	kg 1,4-DB eq	2.84×10^{-3} ± 1.86×10^{-4}	2.89×10^{-3} ± 2.11×10^{-4}	2.77×10^{-3} ± 2.17×10^{-4}	2.85×10^{-3} ± 1.88×10^{-4}	2.54×10^{-3} ± 5.59×10^{-4}	2.48×10^{-3} ± 9.61×10^{-4}	1.16×10^{-4} ± 4.19×10^{-5}	3.50×10^{-3} ± 9.37×10^{-4}
LT	m^2	3.30×10^{-4} ± 1.01×10^{-4}	3.40×10^{-4} ± 1.03×10^{-4}	3.26×10^{-4} ± 9.64×10^{-5}	3.74×10^{-4} ± 9.63×10^{-5}	3.00×10^{-4} ± 1.13×10^{-4}	5.29×10^{-4} ± 2.14×10^{-4}	2.90×10^{-5} ± 7.61×10^{-5}	4.37×10^{-4} ± 1.18×10^{-4}
WD	m^3	4.73×10^{-2} ± 7.46×10^{-2}	5.91×10^{-2} ± 1.09×10^{-1}	6.17×10^{-2} ± 1.03×10^{-1}	6.30×10^{-2} ± 1.01×10^{-1}	5.33×10^{-2} ± 9.91×10^{-2}	7.09×10^{-2} ± 8.09×10^{-2}	4.82×10^{-2} ± 4.00×10^{-1}	5.15×10^{-1} ± 2.09×10^{-1}
FD	kg oil eq	1.57×10^{-1} ± 8.50×10^{-3}	1.94×10^{-1} ± 1.10×10^{-2}	1.93×10^{-1} ± 1.13×10^{-2}	3.21×10^{-1} ± 1.02×10^{-2}	2.34×10^{-1} ± 3.84×10^{-2}	7.47×10^{-1} ± 2.73×10^{-1}	2.94×10^{-1} ± 1.09×10^{-1}	9.75×10^{-1} ± 2.71×10^{-1}

FFB is the main raw material for producing CPO, which is processed to RBDPO and used for cooking oil, biodiesel, and BHD production; therefore, the environmental burdens of FFB are significantly associated with these five palm-based biorefinery products. The key contributors to the environmental impacts of FFB production are fertilizer and chemical applications. Nitrogen and potassium fertilizer application is the major contributor to all environmental impacts, especially for terrestrial ecotoxicity and land transformation. In addition, the use of chemical pesticides or insecticides has the potential to cause harm to terrestrial organisms and may lead to species loss in the long term (Huijbregts et al., 2016). Accordingly, reducing the environmental impacts from the oil palm plantation stage can be achieved *via* proper fertilizer and chemical application management. The studies of Silalertruksa and Gheewala (2012) and Jaroenkietkajorn and Gheewala (2020) revealed that the appropriate quantities of fertilizers and chemicals help not only to reduce GHG emissions but also other environmental impacts. Apart from the raw material production, the environmental impact results of palm-based biorefinery products are from the processing of the product itself. Using kaolin is the main contributor to the milling process at the palm oil mill. Meanwhile, steam and chemicals play an important role in the palm oil refinery. For cooking oil production, energy consumption (*viz.*, steam and electricity) is the main cause of all impacts. In the cases of biodiesel and BHD production, chemicals (i.e., citric acid, methanol, sodium methoxide, and hydrochloric acid) and energy (i.e., steam) uses are the key contributors to environmental impacts.

The environmental impacts of ECH are primarily from the environmental burdens of raw glycerin, which is obtained as a co-product of biodiesel production. This raw glycerin needs to be purified by refining before producing ECH. While producing ECH, several intermediates, *viz.*, 1,3-DCH, 2,3-DCH, 1,3-MCH, and 2,3-MCH, occur and circulate within the production process. The total electricity consumption of these two processes plays a secondary role in the environmental impact results of ECH.

As EFB, whose environmental burdens are very less than FFB, is the main raw material for both succinic and lactic acid, the environmental impacts of these two acids are mainly from the production processes. For succinic acid production, the EFB drying process contributes more than 80% to all environmental impact results due to electricity use. Additionally, the use of chemicals, particularly sodium hydroxide and sulfuric acid, used in the pretreatment and cellulose production stages is a key factor affecting the environmental impacts of succinic acid. In the case of lactic acid production, the SSF media preparation process is the major contributor to the environmental impacts, which is affected by chemicals, water, and electricity consumption.

The GHG emissions of FFB in this study are 0.156 kg CO_2 eq/kg FFB; these emissions are within the range of values found in the literature – 0.093 to 0.190 kg CO_2 eq/kg FFB (Choo et al., 2011; Ma et al., 2022). As FFB is the main raw material for all the biorefinery products, their GHG values are higher than FFB, as shown in **Table 7**. The GHG emissions of CPO in the literature range from 0.5 – 1.164 kg CO_2 eq/kg CPO (Hosseini and Abdul Wahid, 2015; Ma et al., 2022). The GHG emissions of biodiesel are 1.84 kg CO_2 eq/kg B100, similar to the study by Wahyono et al. (2022).

The GHG emissions of succinic acid produced from various sources of raw materials such as bread waste (Gadkari et al., 2021), corn (Cok et al., 2013), sorghum (Moussa et al., 2016), sugarcane bagasse (Shaji et al., 2021), and fossil fuel (Cok et al., 2013) have been compared with that from EFB as shown in **Figure 3**. Producing bio-based succinic acid emits GHGs ranging from 0.87 to 1.39 kg CO_2 eq/kg bio-based succinic acid. These are 28–55% lower than those of fossil-based succinic acid. Electricity consumption is the main contributor to succinic acid from all the different raw materials considered. GHG emissions from EFB-based lactic acid (**Table 7**) are much lower than those of the fossil-based one (4.34 kg CO_2 eq/kg product) (Daful et al., 2016). Once again, the main contributor is electricity use in the pretreatment and hemicellulose production stages.

The current and potential palm-based biorefinery scenarios illustrated in **Figure 2** are based on the same quantity of FFB at 1,000 tonnes entering the system, as described in *Section 2.4*. The environmental impact results of all scenarios are provided in **Table 8**.

Scenario 6 (producing cooking oil, biodiesel, BHD, ECH, and succinic acid) has the highest impacts, whereas Scenario 1 (producing cooking oil and biodiesel) has the lowest impacts. This is because of the additional processes for producing value-added products (BHD, ECH, succinic acid, and lactic acid), leading to the escalation of environmental impacts. The production technologies of the value-added products affect the overall productivity, and the use of electricity and chemicals contributes to the environmental impacts. Thus, the environmental impacts of Scenarios 2 and 6, producing succinic acid, are higher than the other scenarios. The use of electricity, especially in the EFB drying process, and the use of chemicals in the pretreatment and cellulose production are the key drivers of the environmental impacts of succinic acid. Scenario 5 has the lowest environmental impacts, followed by Scenarios 3 and 4, respectively. Although adding value-added products leads to increased environmental impacts, these bio-based products are in high demand for various applications in various industries. Also, these bio-based products can result in a more sustainable production process with less dependence on fossil fuels.

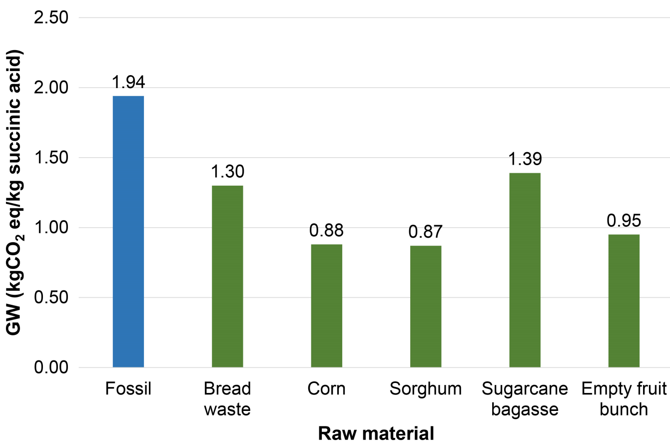

Fig. 3. Global warming (GW) results of succinic acid production from various raw materials.

Table 8.
Environmental impacts of palm-based biorefinery scenarios.

Environmental impacts	Unit	Scenarios						
		1	2	3	4	5	6	7
Global Warming	kg CO_2 eq	138	226	150	155	142	247	171
Terrestrial Acidification	kg SO_2 eq	0.68	1.30	0.76	0.76	0.69	1.39	0.86
Freshwater Eutrophication	kg P eq	0.01	0.02	0.01	0.01	0.01	0.02	0.01
Human toxicity	kg 1,4-DB eq	7.57	18.9	11.1	8.42	7.80	20.0	12.2
Particulate Matter Formation	kg PM_{10} eq	0.22	0.48	0.25	0.24	0.22	0.51	0.28
Terrestrial Ecotoxicity	kg 1,4-DB eq	0.34	0.35	0.35	0.38	0.34	0.39	0.39
Land transformation	m^2	0.04	0.05	0.04	0.05	0.04	0.05	0.05
Water depletion	m^3	7.37	12.1	8.46	8.26	7.39	13.0	9.36
Fossil Fuel Depletion	kg oil eq	30.5	57.8	34.5	34.3	31.7	62.8	39.6

3.2. Net energy balance (NEB) and net energy ratio (NER)

This study estimated NEB and NER in the case of scenarios that include both non-energy and energy products. It could be anticipated that the energy output of non-energy products would be lower than energy products, as also reflected in the obtained results. As seen in **Table 9**, the energy output of Scenario 4 is the highest because all the products and co-products are energy carriers (i.e., BHD, biofuels, and bio-gasoline). Meanwhile, Scenarios 2 and 6 consume higher energy for succinic production compared to other scenarios. However, although the NER of Scenarios 2–7 is lower than the current situation, the overall palm-based biorefinery system has an NEB higher than the current situation by 73 to 86%. Both indicators can indicate the efficiency of the system.

Positive NEB and NER values of more than 1 for the palm-based biorefinery scenarios presented in **Table 9** reveal positive results for all the scenarios. This means that the total energy content of palm-based biorefinery products and co-products is higher than the total energy required by the production processes. Scenario 4 has the highest energy output because BHD, its main product, and co-products, including fuel gas and bio-gasoline, are both energy products. Scenario 6 has the highest energy input due to the energy demand of succinic acid production. Although the NER of potential palm-based biorefinery scenarios (Scenarios 2–7) is lower than that of the current palm-based biorefinery scenario (Scenario 1), all potential scenarios, including a single or three value-added products lead to an increase in the energy output to a greater value than the energy input with an increase in the range 73 to 86%. These two indicators can help to evaluate the system's efficiency.

Table 9.
Net energy balance (NEB) and net energy ratio (NER) of different biorefinery scenarios.

Indicator	Unit	Scenarios						
		1	2	3	4	5	6	7
Energy input	MJ	1,280	2,426	1,448	1,441	1,333	2,639	1,661
Energy output	MJ	9,152	9,129	7,837	9,857	9,003	9,836	8,393
NEB	MJ	7,872	6,702	6,389	8,416	7,670	7,196	6,732
NER	-	7.15	3.76	5.41	6.84	6.75	3.73	5.05

3.3. Employment generation (direct employment results)

In 2021, approximately 16.56 million tonnes of FFB were produced, and the number of oil palm households was about 0.37 million; the employment coefficient shows that producing 1,000 tonnes of FFB requires 22 households annually. The employment coefficients per 1,000 tonnes for each commodity and per 1,000 tonnes FFB for each scenario are shown in **Tables 10** and **11**, respectively. The employment coefficient of CPO production is the highest among all products, as seen in **Table 10**; approximately 5 persons annually are needed for 1,000 tonnes of CPO produced. Meanwhile, about 1 person/yr is required to produce every 1,000 tonnes of RBDPO, cooking oil, and biodiesel. Producing succinic acid has the highest employment coefficient while producing BHD needs the least labor.

Table 10.
Employment coefficient of palm-based biorefinery products.

Products	Employment coefficient (Person-yr/1,000 tonnes of the product)
Crude palm oil	4.42 (2.74 – 9.31)
Refined, bleached, deodorized palm oil	0.54 (0.08 – 1.42)
Cooking oil	0.69 (0.08 – 1.42)
Biodiesel	0.59 (0.15 – 1.07)
Bio-hydrogenated diesel	0.23 (0.06 – 0.39)
Epichlorohydrin	0.61
Succinic acid	3.35 (2.00 – 4.71)
Lactic acid	0.35 (0.05 – 0.66)

Since the number of employees and production volume of the four value-added products (BHD, ECH, succinic, and lactic acid) are based on secondary data taken from pilot studies and existing commercial production, it must also be noted that production technology and economy of scale are significantly associated with those two parameters considered for estimating the employment coefficient. Even though increasing the production capacity would need more employees, adapting advanced technology would also require highly capable and skilled workers. Productivity can be improved by identifying suitable technology solutions, and expanding the industry can create more employment, as seen in the cases of succinic and lactic acid production. Moreover, it can be noticed that the employment coefficient of the value-added production scenarios (Scenarios 2–7) is higher than the current situation varying between 2 to 86% (**Table 11**).

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Table 11.
Employment coefficient of palm-based biorefinery products.

Products	Employment coefficient (Person-yr/1,000 tonnes of FFB)						
	1	2	3	4	5	6	7
Cooking oil	460	460	460	460	460	460	460
Biodiesel	566	566	566	566	566	566	566
Bio-hydrogenated diesel	-	-	-	60	-	60	60
Epichlorohydrin	-	-	-	-	46	46	46
Succinic acid	-	5,960	-	-	-	5,960	-
Lactic acid	-	-	25	-	-	-	25
Total employment (Person-yr)	1,026	6,987	1,051	1,086	1,072	7,092	1,157

3.4. Eco-efficiency

The eco-efficiency assessment revealed that the total economic value of all the potential scenarios (Scenarios 2–7) was greater than that of the current scenario (Scenario 1), as seen in **Table 12**. This implies that all the potential scenarios can help increase the system's economic value. The market price and production volume are the key drivers of the economic value system, as can be seen from the results of Scenarios 2 and 6. These two scenarios have a total economic value exceeding 16,000 THB/tonne of FFB due to the contribution of succinic acid, which has a very high price. The price of lactic acid is about half that of succinic acid, and its production volume accounts for only around 4% of that of succinic acid. As a result, the total economic value of Scenario 2 (succinic acid) is greater than that of Scenario 3 (lactic acid). Apart from succinic acid, another high-priced product is bio-gasoline, a co-product of BHD production (produced in Scenarios 4, 6, and 7). Although the price of bio-gasoline is high, the production volume is less at around 1.4% of BHD production. Thus, the total economic value of Scenario 4 is greater than that of Scenario 1 by approximately 12%. The production of bio-gasoline in addition to BHD leads to a higher total economic value of Scenario 4 compared to Scenarios 3 and 5, which produce only one value-added product, lactic acid and ECH, respectively.

Table 12.
Eco-efficiency of different biorefinery scenarios.

Indicator	Unit	Scenarios						
		1	2	3	4	5	6	7
Total economic value	THB/t FFB	5,997	16,715	6,188	6,852	6,031	17,605	7,077
Global warming	kg CO_2 eq/t FFB	138	226	150	155	142	247	171
Eco-efficiency	THB/kg CO_2 eq	43.6	73.9	41.2	44.3	42.6	71.3	41.4

The eco-efficiency values of Scenarios 2 and 6 are quite close and higher than those of other scenarios due to the production of succinic acid. Even though the contribution of succinic acid production to global warming impact is larger than that of other value-added products, the price of this acid is also greater than others. Comparing these two scenarios with the current scenario (Scenario 1), the increases in the global warming impact results are 39% for Scenario 2 and 44% for Scenario 6, while the increase in total economic value is 65% for both scenarios.

The eco-efficiency values of Scenarios 3 and 5 are lower than that of Scenario 1; meanwhile, the eco-efficiency of Scenario 4 is higher than that of Scenario 1. The additional production of value-added products and market price and production volume play important roles in the eco-efficiency results of Scenarios 3–5. Even though the price of lactic acid (Scenario 3) is higher than that of cooking oil and biodiesel (Scenario 1), the production volume of lactic acid in Scenario 3 is low. Thus, the total economic value of Scenario 3 exceeds that of Scenario 1 by 3%. For Scenario 5, even though the contribution of ECH production to the global warming impact is lower than that of lactic acid (Scenario 3), the price of ECH is close to the prices of cooking oil and biodiesel, leading to the total economic value increasing by 1% against Scenario 1. The global warming impact of BHD production in Scenario 4 is greater than that of lactic acid and ECH production in Scenarios 3 and 5; however, the prices of BHD and its co-products increase the total economic value of Scenario 4 by 12% compared to Scenario 1.

Increasing the production volume of value-added products will bring about the need for investment associated with several factors such as production technology, employment, location, etc. Hence, the estimation of cost-effectiveness should be considered to support the decision on the investment. Klein et al. (2017) reported that the cost of succinic acid production from bagasse was 79 THB/kg (2.32 USD/kg), based on fixed and variable costs. Lactic acid is mainly produced from corn and needs bacteria, fungi, and yeast for fermentation. Hassan and Idris (2016) reported that the cost of producing lactic acid by bacteria is 40,000 THB/tonne (1,181 USD/tonne), with an annual production capacity of about 0.1 million tonnes. More than 50% of production costs come from raw materials, followed by energy and resource consumption (approximately 30%), and 20% from wastewater treatment costs and labor (Manandhar and Shah, 2020). Currently, BHD is mainly produced by two companies, Neste Oil and UOP Honeywell, which have branches in many countries. However, investment value throughout the production process is not publicly reported. ECH is produced using Epicerol technology using pure glycerin, mostly imported; the production capacity is approximately 0.1 million tonnes/yr. The lowest product value (world market price) of ECH is about 35 THB/kg (0.94 USD/kg), and the maximum product value is about 130 THB/kg (3.51 USD/kg), depending on the purity of the produced ECH (ChemAnalyst, 2020). In summary, although value-added production leads to an increment in environmental impacts and investment, total revenue also increases, similar to the study of Abdullah and Hussein (2021), which concluded that the economic aspects could be improved by the development of biochemical and biomaterial products from oil palm. Thus, the future decision on appropriate value-added production should rely on social, economic, and environmental aspects.

3.5. Practical implications and limitations of the present study

Based on the overall results obtained from the current and potential palm-based biorefinery scenarios, findings and insights could be summarized as follows:

- To increase the production volume of both succinic and lactic acid, research and development should focus on the production technology and biomass waste utilization. This will reduce not only the environmental impacts but also negative externalities related to the production of both acids.

- The integration of value-added products into the current palm-based biorefinery should be promoted along with the supply chain as elaborated below:
    - The production of succinic and lactic acid is recommended at the palm oil mill to avoid the environmental impacts of raw material transportation and get extra support on the renewable electricity from the biomass generated in the palm oil mill
    - The production of BHD and pure glycerin, the main raw materials for ECH production, should be considered at the biodiesel plants. This is because RBDPO is used for producing both biodiesel and BHD, and raw glycerin is a by-product of biodiesel production. Therefore, this kind of expansion would offer flexibility and opportunity to the existing biodiesel plants to produce several valuable products.

- The major contributor to the environmental impacts of all palm-based biorefinery products is the production of FFB rather than using energy and chemicals in the production processes. The recommendations below could lead to reducing the environmental impacts.
    - The application of fertilizer and chemicals used in oil palm plantations should be controlled or minimized based on soil and leaf analysis results.

- The transition of both the palm oil mill and the palm oil refinery to 100% renewable electricity could lead to a decrease in the environmental impacts of their products. The palm oil mill should move to 100% electricity generated from biomass and biogas, and the palm oil refinery should also follow a similar route.

3.5.1 Practical implications

The overall results obtained from the current and potential palm-based biorefinery scenarios reveal some practical implications for improving the sustainability of the current palm-based biorefinery. As the oil palm plantation is the key contributor to the environmental impacts, support could be provided by the government or the palm oil mills to the oil palm farmers to manage fertilizer application based on soil and leaf analysis. Moving to 100% electricity generated from biomass and biogas could drive not only the current palm oil mill but also other downstream activities toward a green industry. If the palm oil refinery is close to the palm oil mill, excess electricity from the palm oil mill could support the operation of the palm oil refinery. As for the value-added products proposed in this study, a pilot-scale BHD production was established under a collaboration of the two biggest companies in Thailand several years ago; however, there has been no further progress ever since. On the other hand, there is only a single company producing ECH. The conversion of EFB into cellulose and hemicellulose to produce succinic and lactic acid is still at the laboratory scale, although other feedstocks have been used commercially in other countries. The obtained results will also create or attract more opportunities to support the sustainable commercialization of BHD, ECH, succinic acid, and lactic acid production.

3.5.2. Uncertainty analysis

Figure 4 illustrates the uncertainty analysis results conducted based on the overall environmental performances of CPO, RBDPO, biodiesel,

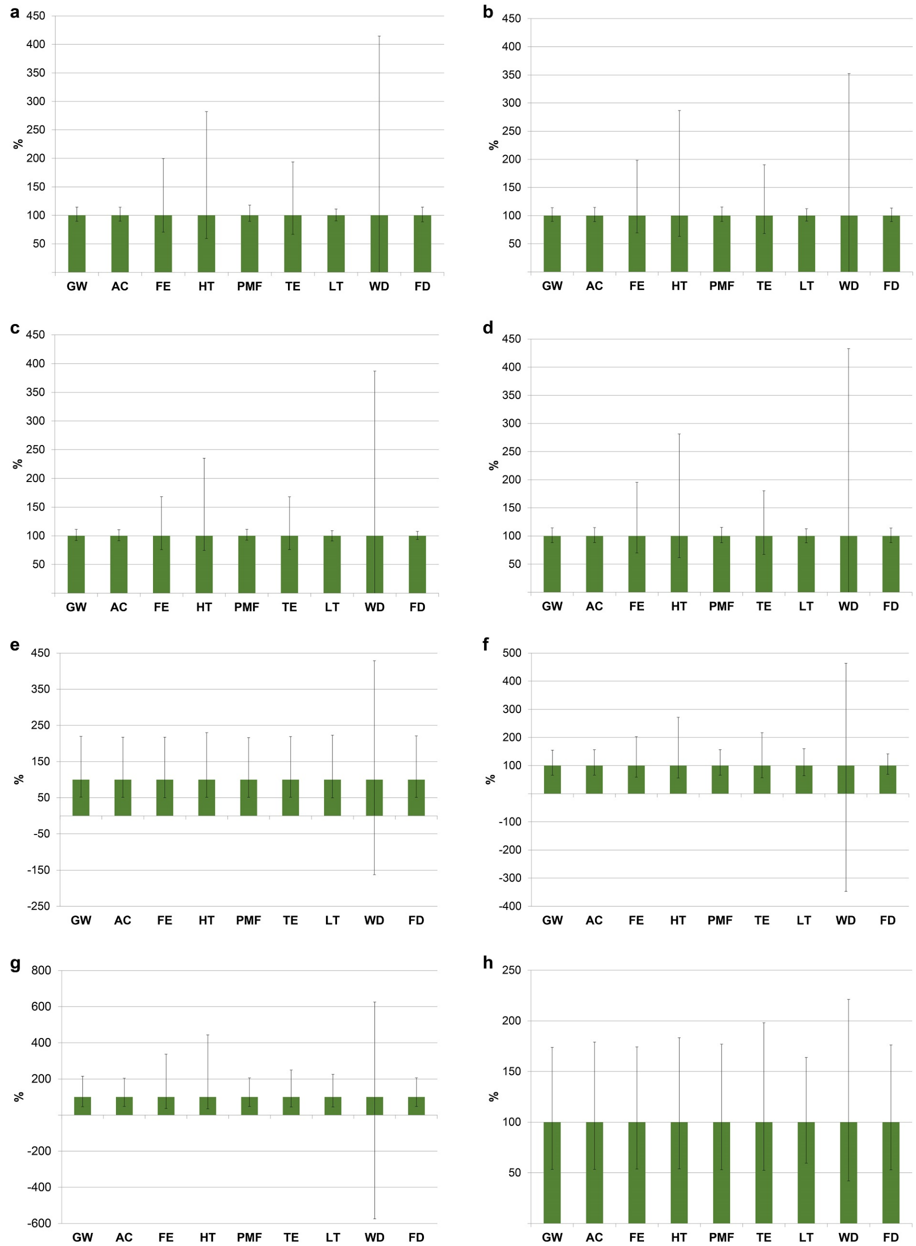

Fig. 4. Uncertainty analysis results; **(a)** Crude palm oil, **(b)** Refined, bleached, deodorized palm oil, **(c)** Biodiesel, **(d)** Cooking oil, **(e)** Bio-hydrogenated diesel, **(f)** Epichlorohydrin, **(g)** Succinic acid, **(h)** Lactic acid. Abbreviations: GW: global warming; AC: Terrestrial acidification; FE: freshwater eutrophication; HT: human toxicity; PMF: particulate matter formation; TE: terrestrial ecotoxicity; LT: land transformation; WD: water depletion; and FD: fossil fuel depletion.

cooking oil, BHD, ECH, succinic acid, and lactic acid. The results show less uncertainty concerning the impacts of CPO, RBDPO, biodiesel, and cooking oil production compared to the value-added products (i.e., BHD, ECH, succinic acid, and lactic acid). This is because the data of CPO, RBDPO, biodiesel, and cooking oil were collected directly from the value chain enterprises (primary data). On the other hand, the data of all value-added products were collected from various reliable literature (secondary data). It can also be seen that the global warming impact values have the least uncertainty compared to the other impacts. As the eco-efficiency calculations (**Eq. 3**) considered global warming, hence, the results can be considered relatively robust.

3.5.3. Limitations

Although this study's scope starts from oil palm plantation until the production of value-added products, intermediate transportation was not included. Moreover, the primary data was collected only from existing palm oil mills and palm oil refineries in Thailand, whereas the secondary data was applied for all value-added products (succinic acid, lactic acid, BHD, and ECH) considered in the potential palm-based biorefinery system due to confidentiality and there being no existing manufacturing industries in Thailand. The production of succinic and lactic acid is based on experimental data, while the BHD and ECH production data was obtained by computer simulations. It should be noted that there is a difference in data inventory between the laboratory scale and the commercial scale. In addition, the capacity and workforce of these four products were taken from existing manufacturing industries in other countries.

Other than that, all six scenarios in this study were based on the current demands for CPO as 19% domestic stock, 9% export, and 72% domestic consumption. If there is a change in CPO demand in the future, the configuration of palm-based biorefinery must be re-evaluated. There is a need for further research on optimizing supply and demand in the whole palm-based biorefinery system. This will enable stakeholders in the palm oil industry to secure more sustainable production and consumption. In addition, cost-benefit analysis and location assessment for the value-added products are expected to address the limitation of this study.

4. Conclusions and prospects

This study aimed to assess the sustainability of palm-based biorefinery, including the current situation (i.e., cooking oil and biodiesel) and the potential scenarios with value-added products, i.e., succinic acid, lactic acid, BHD, and ECH by considering the overall palm value chain. These value-added products represent biomaterial, biofuel, and biochemical products. Accordingly, seven palm-based biorefinery scenarios were considered, and their impacts were assessed through LCA, NEB, NER, employment generation, and eco-efficiency.

The two-potential palm-based biorefineries, including the current palm-based biorefinery with succinic acid production (Scenario 2) and the current palm-based biorefinery with succinic acid, BHD, and ECH production (Scenario 6), showed the most positive results toward sustainable palm-based biorefinery; the production of succinic acid was the key player in these two scenarios due to the highest results in all environmental impacts and the highest market price. The current palm-based biorefinery with BHD production (Scenario 4) showed lower environmental impacts than in Scenarios 2 and 6.

Adding the production of value-added products to the current palm-based biorefinery led to an increase in the environmental impacts of that potential palm-based biorefinery due to the use of raw materials and energy in the production processes. Meanwhile, market price and production volume increased the total economic value system. Eco-efficiency, as well as NEB and NER results, were affected by market price, production volume, and energy content of the product and co-products obtained from potential palm-based biorefinery. As production technology plays an important role in the production processes and volume of value-added products, it should be noted that revising the assessment results will be required once the production technologies of succinic acid, lactic acid, BHD, and ECH change. Thus, the decision on suitable value-added production in the future should consider the potential investment of the industrial sector, environmental impacts aspect, and total revenue from the added value.

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Supplementary Material

Table S1.
Inventory of oil palm nursery (Gheewala et al., 2014).

Details	Quantity/kg Product	Unit
Input		
Electricity	4.23×10^{-5}	kWh
Diesel	2.82×10^{-5}	L
Polybag	1.48×10^{-5}	kg
Water	1.06×10^{-2}	L
Nitrogen fertilizer	3.59×10^{-6}	kg
Phosphorus fertilizer	1.83×10^{-6}	kg
Potassium fertilizer	1.48×10^{-6}	kg
Thiocarbamate	7.89×10^{-8}	kg
Pyrethroid	2.49×10^{-8}	kg
Organophosphate	1.41×10^{-7}	kg
Dithiocarbamate	6.77×10^{-7}	kg
Unspecified Pesticide	9.51×10^{-9}	kg
Urea/Sulfonylurea	1.53×10^{-7}	kg
Glyphosate	6.27×10^{-8}	kg
Land	7.04×10^{-6}	ha-yr
Product		
Oil palm nursery	1.00	trees
Output		
CO_2 eq emission (from Nitrogen fertilizer)	1.19×10^{-5}	kg CO_2 eq
Carbon dioxide (CO_2)	7.60×10^{-5}	kg
Methane (CH_4)	3.08×10^{-9}	kg
Nitrous oxide (N_2O)	6.16×10^{-10}	kg
Carbon monoxide	2.82×10^{-7}	kg
Oxides of nitrogen	1.89×10^{-7}	kg
Particulate matter 2.5 µm	5.63×10^{-8}	kg
Particulate matter 10.0 µm	5.92×10^{-8}	kg
Polycyclic aromatic hydrocarbons 4	9.01×10^{-12}	kg TEQ
Sulfur dioxide 3	4.79×10^{-10}	kg
Total volatile organic compounds 5	2.31×10^{-8}	kg
Unspecified Pesticide	1.15×10^{-6}	kg
N leaching to river	5.39×10^{-9}	kg

Table S2.
Inventory of oil palm plantation (Gheewala et al., 2014).

Details	Quantity/kg Product	Unit
Input		
Nursery plant	2.85×10^{-4}	trees
Occupation land; agricultural land	5.71×10^{-5}	ha-yr
Nitrogen fertilizer	6.87×10^{-3}	kg
Phosphorus fertilizer	4.42×10^{-3}	kg
Potassium fertilizer	1.17×10^{-2}	kg
Organic fertilizers: Cow manure, pig manure, chicken manure	4.92×10^{-2}	kg
Soil improvement materials: lime, furadan, boron, etc.	4.38×10^{-3}	kg
Diesel	1.68×10^{-4}	L
Benzene	1.03×10^{-3}	L
LPG	2.08×10^{-7}	kg
Diesel	7.20×10^{-6}	L
Benzene	3.20×10^{-7}	L
Natural gas	4.12×10^{-3}	kg
LPG	4.91×10^{-4}	kg
Electricity	2.39×10^{-5}	kWh
Glyphosate	2.28×10^{-4}	L
Paraquat	1.85×10^{-4}	L
Others herbicides	1.55×10^{-6}	L
Bennyl (Benomyl)	5.46×10^{-8}	L
Unspecified chemicals	3.00×10^{-8}	kg
Cypermethrin	2.61×10^{-7}	L
Pesticides/Insecticides	1.06×10^{-6}	L
Groundwater	1.74×10^{-4}	m^3
Lake, irrigation water	4.01×10^{-3}	m^3
Tap water	5.27×10^{-5}	m^3
Product		
Fresh Fruit Brunches; FFB	1.00	kg
Output		
CO_2 eq emission (from N fertilizer)	2.81×10^{-2}	kg
CO_2 (on-road)	1.09×10^{-3}	kg
CH_4 (on-road)	1.21×10^{-6}	kg
N_2O (on-road)	1.65×10^{-8}	kg
CO_2 (off-road)	2.70×10^{-3}	kg
CH_4 (off-road)	2.62×10^{-6}	kg
N_2O (off-road)	2.40×10^{-7}	kg
Carbon monoxide	1.75×10^{-6}	kg
Oxides of nitrogen	1.17×10^{-6}	kg
Particulate matter 2.5 µm	3.50×10^{-7}	kg
Particulate matter 10.0 µm	3.68×10^{-7}	kg
Polycyclic aromatic hydrocarbons 4	5.61×10^{-11}	kg TEQ
Sulfur dioxide 3	2.98×10^{-9}	kg
Total volatile organic compounds 5	1.44×10^{-7}	kg
Unspecified Pesticide	6.22×10^{-4}	kg
N leaching to river	1.03×10^{-5}	kg

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Table S3.
Inventory of palm oil milling (crude palm oil production)*.

Details	Quantity/kg Product	Unit
Input		
Fresh fruit bunch (FFB)	6.01	kg
Steam	2.99	kg
Freshwater	1.96×10^{-3}	m^3
Electricity grid mix	3.75×10^{-2}	kWh
Electricity-Boiler unit (steam turbine)	8.37×10^{-2}	kWh
Electricity (POME-WWTP to biogas)	8.24×10^{-3}	kWh
Kaolin	0.29×10^{-1}	kg
Product		
Crude palm oil (CPO)	1.00	kg
Co-product		
Dry kernel: sell	2.09×10^{-1}	kg
Fiber: sell	3.91×10^{-2}	kg
Shell: sell	2.87×10^{-1}	kg
Empty fruit bunch (EFB)	1.15	kg
Output		
POME	3.74×10^{-2}	m^3
Decanter cake	2.06×10^{-1}	kg

* Primary data

Table S4.
Inventory of crude palm kernel oil production*.

Details	Quantity/kg Product	Unit
Input		
Dry kernel	2.21	kg
Electricity grid mix	1.91×10^{-1}	kWh
Electricity-Boiler unit (steam turbine)	2.11×10^{-2}	kWh
Electricity (POME-WWTP to biogas)	2.85×10^{-3}	kWh
Product		
Crude palm kernel oil (CPKO)	1.00	kg
Output		
Palm kernel cake (PKC)	1.09	kg

* Primary data

Table S5.
Inventory of anaerobic wastewater treatment*.

Details	Quantity/kg Product	Unit
Input		
Raw water	1.43	m^3
Electricity-Boiler unit (steam turbine)	1.53	kWh
Polymer	2.89×10^{-4}	kg
PAC/Alum	1.15×10^{-1}	kg
RO (Antiscalant Flocon 135)	7.92×10^{-4}	kg
Brom Pam-9A	1.40×10^{-4}	kg
Chlorine	2.03×10^{-2}	kg
Sodium hydroxide	2.70×10^{-2}	kg
Product		
Treated water	1.00	m^3
Output		
Wastewater	4.34×10^{-1}	m^3

* Primary data

Table S6.
Inventory of steam production from boiler*.

Details	Quantity/kg Product	Unit
Input		
Fiber	2.42×10^{-1}	kg
Shell	2.72×10^{-3}	kg
Raw water	1.21×10^{-3}	m^3
Product		
Steam	1.00	kg
Co-product		
Electricity-Boiler unit (steam turbine)	3.31×10^{-2}	kWh
Output		
Wastewater	1.17×10^{-4}	m^3
Ash	8.21×10^{-3}	kg

* Primary data

Table S7.
Inventory of palm oil refinery*.

Details	Quantity/kg Product	Unit
Input		
Crude palm oil	1.08	kg
Phosphoric acid	1.11×10^{-3}	kg
Bleaching earth	1.06×10^{-2}	kg
Silica	2.67×10^{-4}	kg
Activated carbon	3.45×10^{-7}	kg
Sodium hydroxide	2.00×10^{-4}	kg
Steam	1.93×10^{-1}	kg
Electricity grid mix	1.16×10^{-2}	kWh
LPG	2.49×10^{-3}	kg
Water	1.10×10^{-4}	m^3
Product		
RBDPO	1.00	kg
Co-product		
PFAD	6.85×10^{-2}	kg
Output		
Spent earth	1.96×10^{-2}	kg
Silica (used)	2.67×10^{-4}	kg
Wastewater	5.73×10^{-4}	m^3

* Primary data

Table S8.
Inventory of palm olein (cooking oil) production*.

Details	Quantity/kg Product	Unit
Input		
RBDPO	1.43	kg
Anti-crystallizer	3.92×10^{-5}	kg
Electricity grid mix	2.50×10^{-2}	kWh
Steam	1.36×10^{-1}	kg
Soft water for the chiller	1.42×10^{-4}	kg
Product		
Cooking oil (RBDOL)	1.00	kg
Co-product		
Palm stearin (RBDST)	4.25×10^{-1}	kg

* Primary data

Table S9.
Inventory of biodiesel (B100) production*.

Details	Quantity/kg Product	Unit
Input		
RBDPO	9.21×10^{-1}	kg
RBDPO (purchased)	1.49×10^{-2}	kg
Stearin (purchased)	1.01×10^{-2}	kg
Methanol	1.25×10^{-1}	kg
Sodium hydroxide	1.04×10^{-2}	kg
Citric acid	2.52×10^{-2}	kg
Hydrochloric acid	3.58×10^{-3}	kg
Sodium methoxide	9.68×10^{-3}	kg
Phosphoric acid	1.84×10^{-4}	kg
Steam	7.01×10^{-2}	kg
Electricity grid mix	1.98×10^{-2}	kWh
Product		
Biodiesel (B100)	1.00	kg
Co-product		
Raw glycerin	1.44×10^{-1}	kg
Output		
Sterol Glucosides (SG)	4.67×10^{-3}	kg
Acid oil/Fatty acid oil	3.03×10^{-3}	kg
Wastewater	9.78×10^{-6}	m^3

* Primary data

Table S10.
Inventory of SSF media preparation (Succinic acid production) (Akhtar and Idris, 2017).

Details	Quantity/kg Product	Unit
Input		
Inoculum media	2.50×10^{-6}	kg
Cellulose	7.00×10^{-2}	kg
Yeast extract	2.00×10^{-2}	kg
Corn steep liquor (CSL)	2.00×10^{-2}	kg
Sodium acetate	1.50×10^{-3}	kg
Monosodium phosphate ($Na_2H_2PO_4$)	1.50×10^{-3}	kg
Dipotassium phosphate ($K_2H_2PO_4$)	1.50×10^{-3}	kg
Magnesium chloride	2.00×10^{-4}	kg
Calcium chloride ($CaCl_2$)	2.00×10^{-4}	kg
Magnesium carbonate ($MgCO_3$)	6.50×10^{-2}	kg
Product		
SSF media	1.00	L

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Table S11.
Inventory of EFB drying process (Succinic acid production) (Akhtar and Idris, 2017).

Details	Quantity/kg Product	Unit
Input		
Empty fruit bunch	1.67	kg
Electricity-Boiler unit (steam turbine)	2.40	kWh
Product		
Dried EFB	1.00	kg
Output		
Waste	6.70×10^{-1}	kg

Table S12.
Inventory of pretreatment and cellulose production (Succinic acid production) (Akhtar and Idris, 2017).

Details	Quantity/kg Product	Unit
Input		
Empty fruit bunch	1.52	kg
Sulfuric acid	6.06×10^{-1}	L
Water	15.20	L
Electricity-Boiler unit (steam turbine)	*3.42*	kWh
Sodium hydroxide	1.52	kg
Product		
Cellulose	1.00	kg
Output		
Lignin and hemicellulose	5.15×10^{-1}	kg

Table S13.
Inventory of Succinic-SSF process (Succinic acid production) (Akhtar and Idris, 2017).

Details	Quantity/kg Product	Unit
Input		
SSF media	6.51	L
Electricity-Boiler unit (steam turbine)	1.55×10^{-1}	kWh
Product		
Succinic acid	1.00	kg
Output		
Waste	1.71×10^{-1}	kg

Table S14.
Inventory of SSF media preparation (Lactic acid production) (Hassan and Idris, 2016).

Details	Quantity/kg Product	Unit
Input		
Hemicellulose	5.00×10^{-2}	kg
Urea (CH_4N_2O)	2.50×10^{-3}	kg
Dipotassium phosphate ($K_2H_2PO_4$)	6.00×10^{-4}	kg
Magnesium sulfate ($MgSO_4$)	2.50×10^{-4}	kg
Zinc sulfate ($ZnSO_4$)	8.80×10^{-4}	kg
Electricity-Boiler unit (steam turbine)	3.08	kWh
Product		
SSF media	1.00	L

Table S15.
Inventory of pretreatment and hemicellulose production (Lactic acid production) (Hassan and Idris, 2016).

Details	Quantity/kg Product	Unit
Input		
Empty fruit bunch	7.67	kg
Sodium hydroxide	1.53×10^{-3}	g
Water	76.70	L
Electricity-Boiler unit (steam turbine)	3.08	kWh
Product		
Hemicellulose	1.00	kg
Output		
Lignin and cellulose	6.68	kg

Table S16.
Inventory of Lactic-SSF process (Lactic acid production) (Hassan and Idris, 2016).

Details	Quantity/kg Product	Unit
Input		
Electricity-Boiler unit (steam turbine)	6.17	kWh
Hemicellulose	1.25	kg
SSF media	83.30	L
Product		
Lactic acid	1.00	kg
Output		
Waste	4.77	kg

Table S17.
Inventory of bio-hydrogenated diesel (BHD) production (Permpool et al., 2020).

Details	Quantity/kg Product	Unit
Input		
RBDPO	9.25×10^{-1}	kg
Palladium	2.20×10^{-1}	mg
Activated carbon	3.92	mg
Hydrogen	4.19×10^{-2}	kg
Electricity from biomass	4.41×10^{-2}	kWh
Product		
BHD	1.00	kg
Co-product		
Fuel gas	1.01×10^{-2}	kg
Bio-gasoline	1.41×10^{-2}	kg

Table S18.
Inventory of pure glycerin production*.

Details	Quantity/kg Product	Unit
Input		
Raw glycerin	1.74	kg
Electricity grid mix	1.22×10^{-1}	kWh
Hydrochloric (HCl)	6.90×10^{-2}	kg
Sodium hydroxide (NaOH)	4.00×10^{-3}	kg
Activated carbon	1.00×10^{-3}	kg
Steam	1.92	kg
LPG	1.8×10^{-2}	kg
Water	6.6×10^{-2}	m^3
Product		
Pure glycerin	1.00	kg
Output		
Yellow	8.6×10^{-2}	kg
MONG**	1.11×10^{-1}	kg
Activated carbon (used)	1.00×10^{-3}	kg
Salt	4.1×10^{-2}	kg
Wastewater	1.6×10^{-2}	m^3

* Primary data
** MONG: matter organic non-glycerin

Table S19.
Inventory of Epichlorohydrin (ECH) production (Wang et al., 2016).

Details	Quantity/kg Product	Unit
Input		
Hydrochloric acid	1.050	kg
Water	1.780	kg
Pure glycerin	1.380	kg
Electricity grid mix	0.020	kWh
Epichlorohydrin*	1.000	kg
Output		
Water	1.260	kg
1-MCH	0.000	kg
Pure glycerin (loop in the system**)	0.000	kg
1-MCH (loop in the system)	0.170	kg
2-MCH (loop in the system)	0.060	kg
Acetic acid (loop in the system)	0.160	kg
Hydrochloric acid (loop in the system)	0.000	kg
Water (loop in the system)	0.030	kg
1,3-DCH (loop in the system)	0.010	kg

* 1,3-DCH:ECH is 1.39: 1.00
** Outputs that are reused in the first stage of production.

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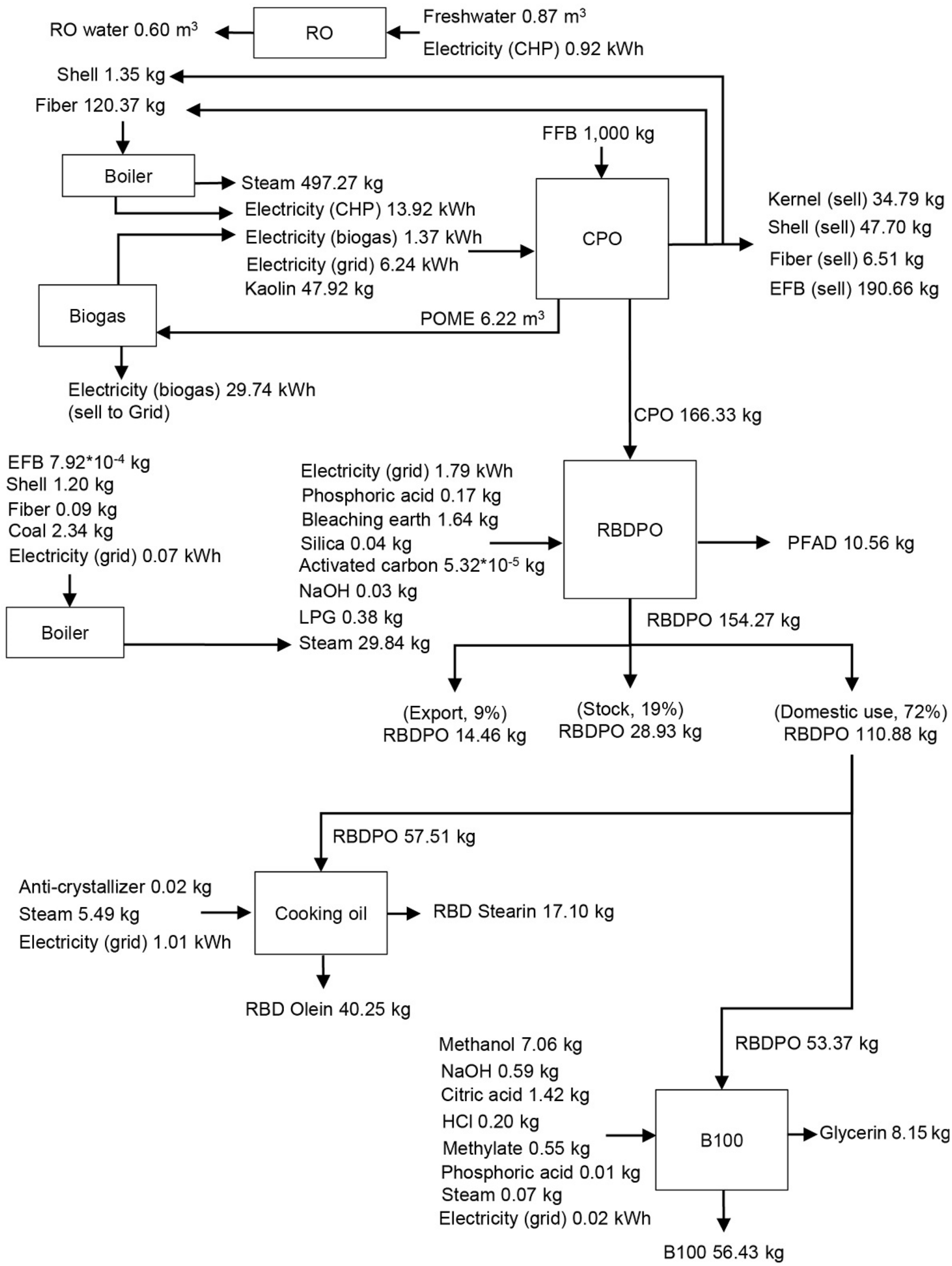

Fig. S1. Current situation (cooking oil and biodiesel production), represented Scenario 1.

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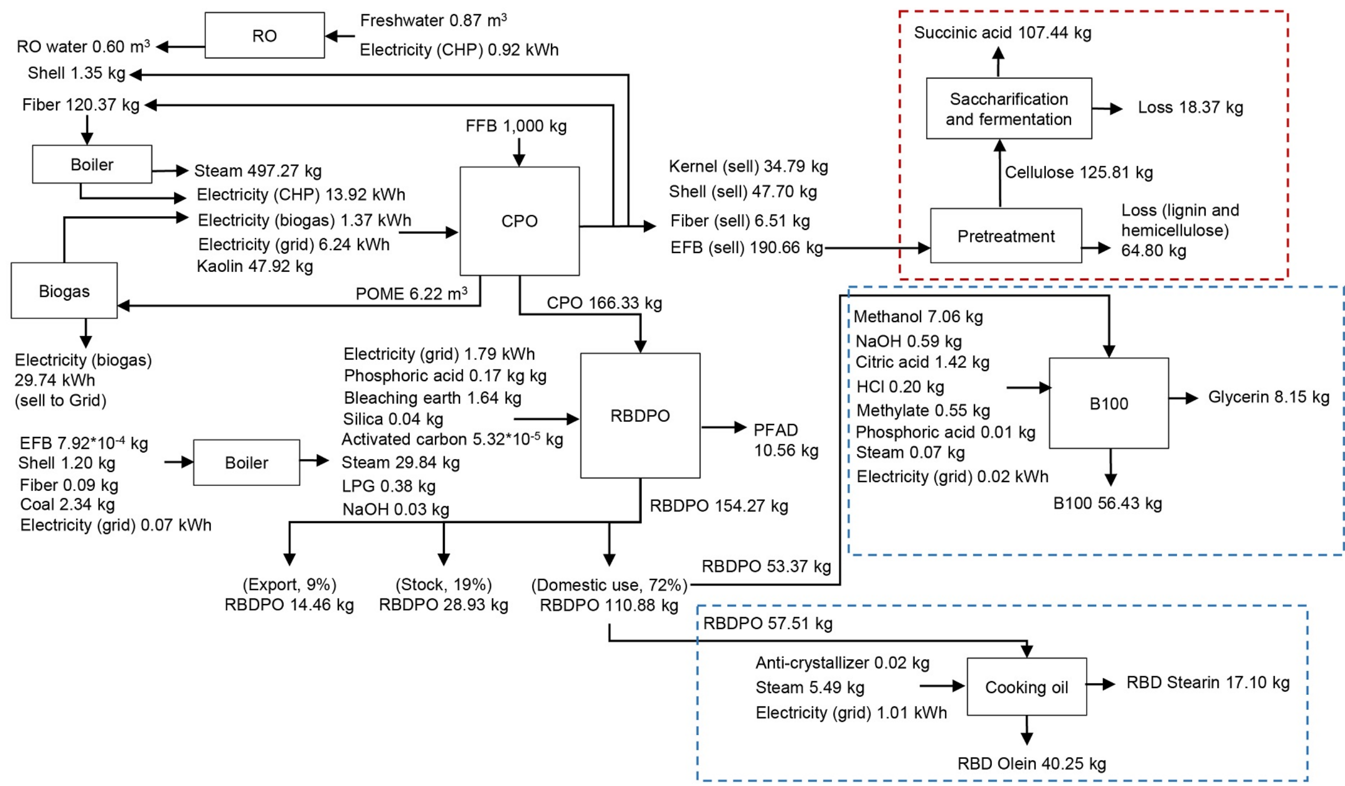

Fig. S2. Current situation with succinic acid production (Scenario 2).

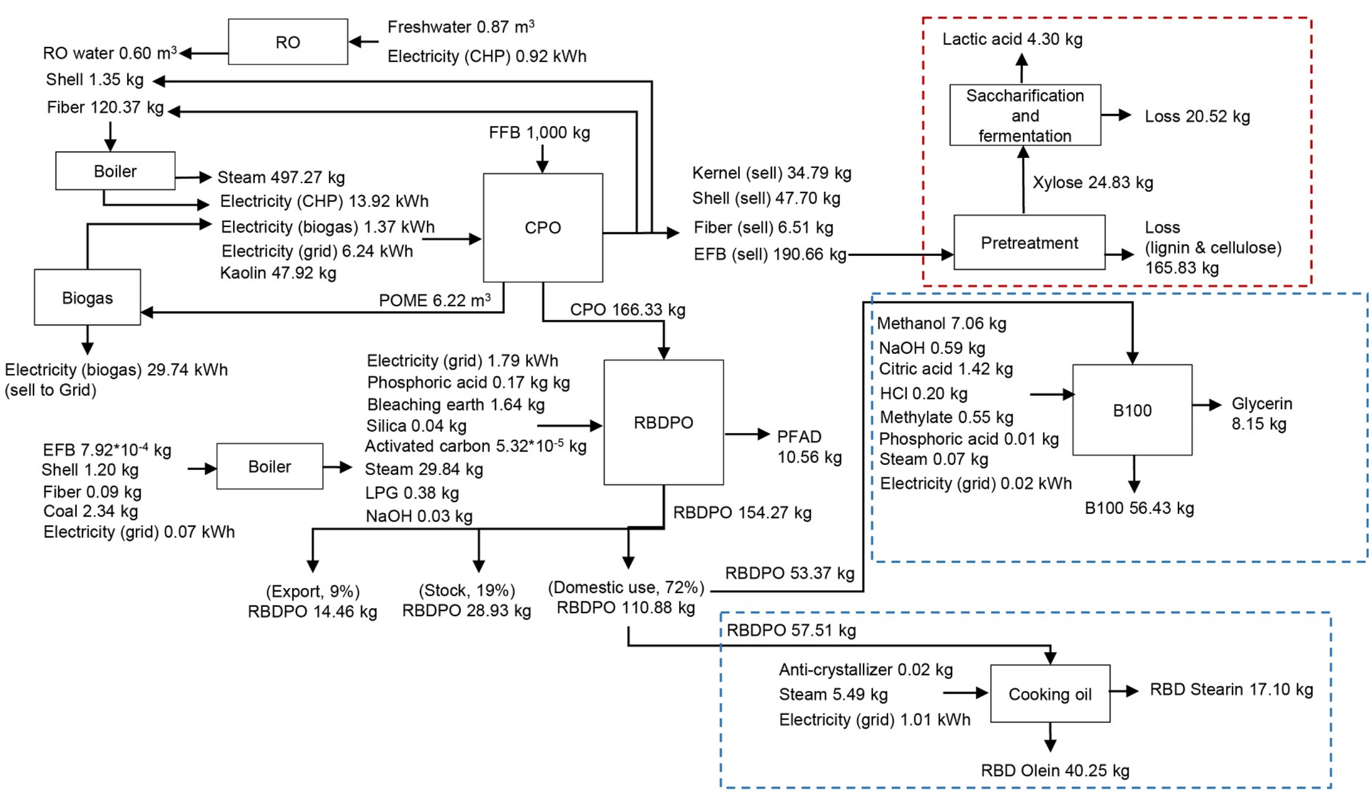

Fig. S3. Current situation with lactic acid production (Scenario 3).

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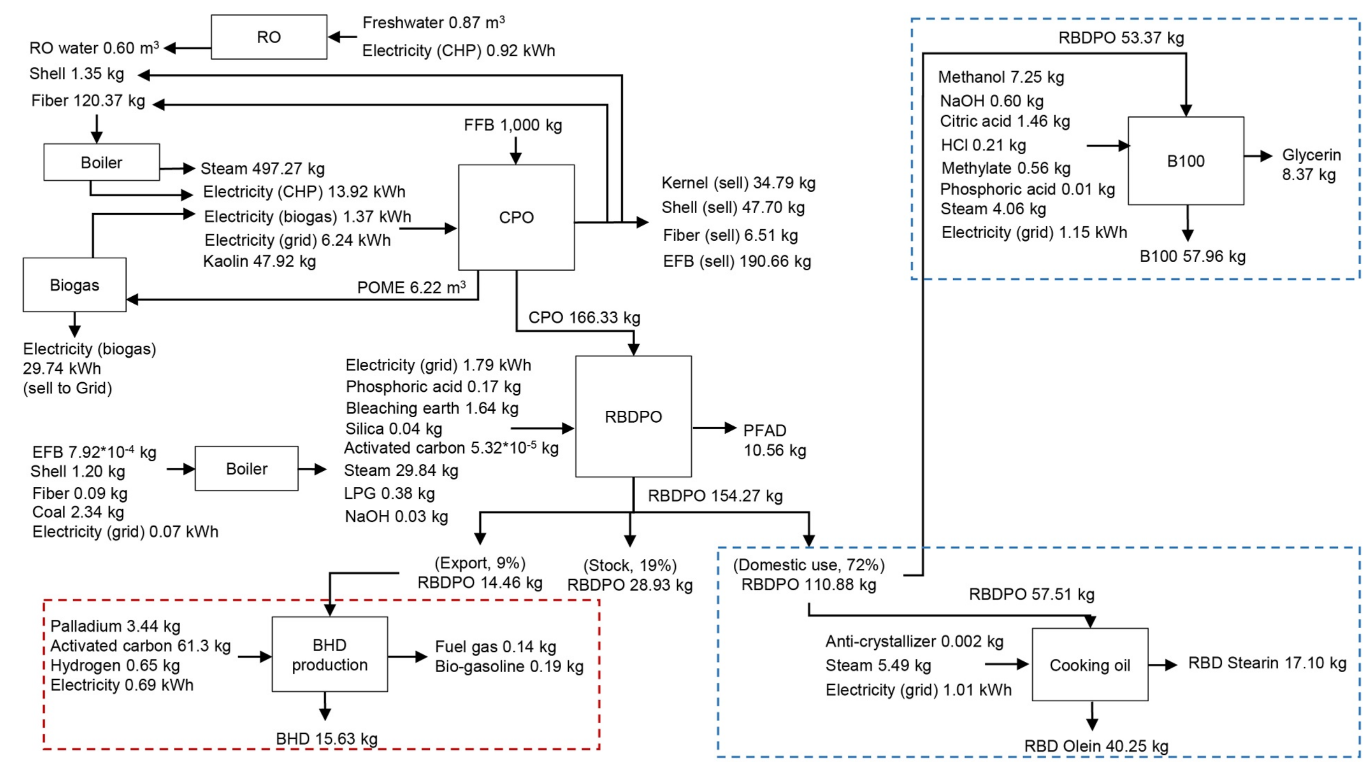

Fig. S4. Current situation with bio-hydrogenated diesel (BHD) production (Scenario 4).

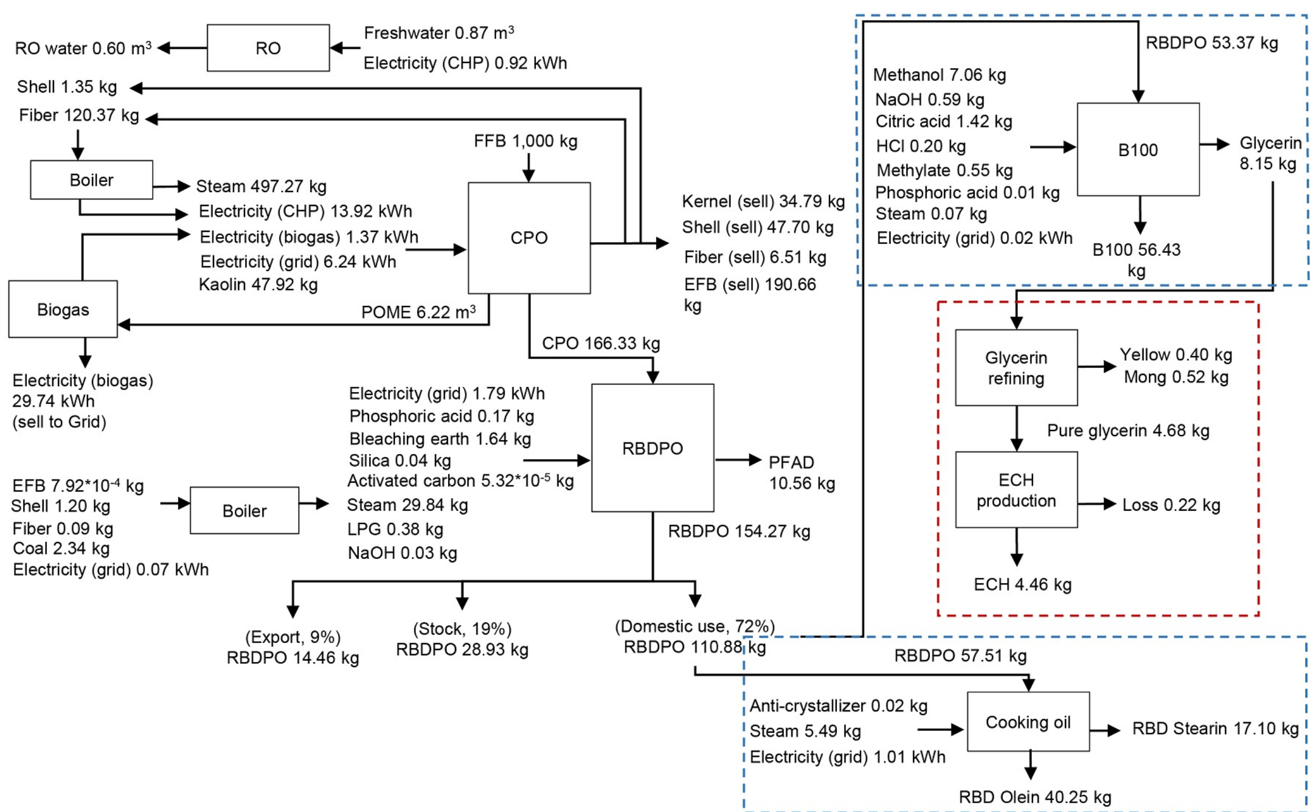

Fig. S5. Current situation with epichlorohydrin (ECH) production (Scenario 5).

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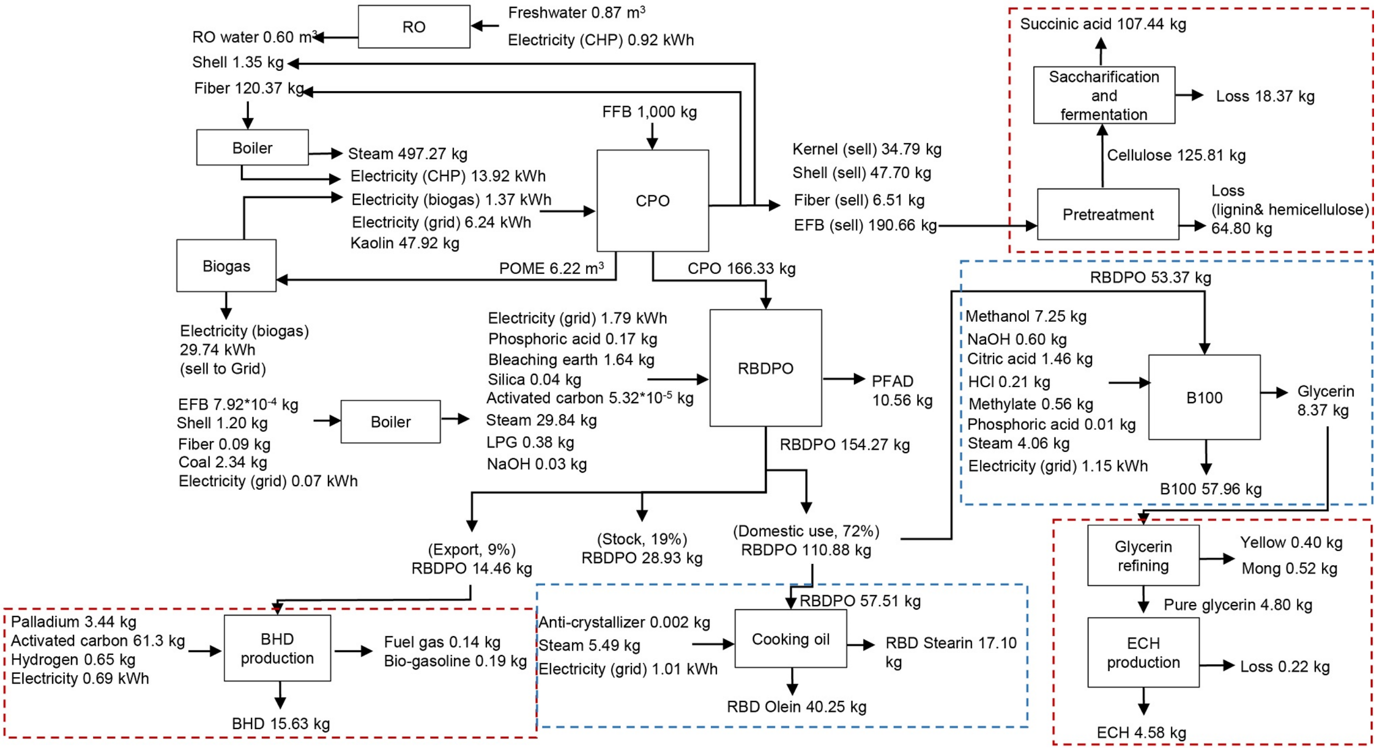

Fig. S6. Current situation with BHD, ECH, and succinic acid production (Scenario 6).

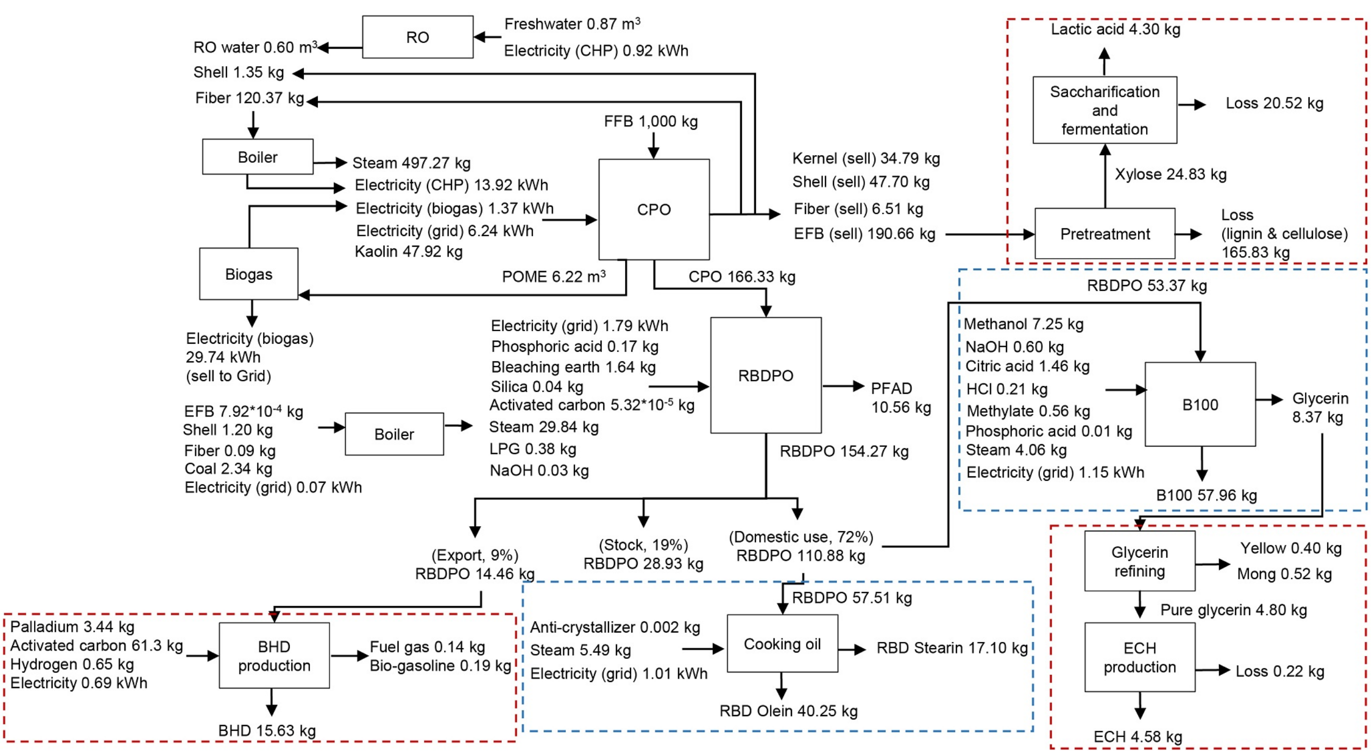

Fig. S7. Current situation with BHD, ECH, and lactic acid production (Scenario 7).