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Process design and life cycle assessment of furfural and glucose co-production derived from palm oil empty fruit bunches

Zi Wei Ng[1], Hui Xin Gan[1], Aditya Putranto[1*], M Akbar Rhamdhani[2] Sharif H. Zein[3], Oluwafemi Ayodele George[4], Jannata Giwangkara[4], Ivan Butar[5]

[1]Discipline of Chemical Engineering, School of Engineering, Monash University Malaysia, Bandar Sunway, Selangor 47500, Malaysia
[2]Department of Mechanical Engineering and Product Design Engineering, School of Engineering, Swinburne University of Technology, John St, Hawthorn VIC 3122, Australia
[3]Department of Chemical Engineering, Faculty of Science and Engineering, University of Hull, Kingston Upon Hull, HU6 7RX, UK
[4] Department of Systems Engineering, Faculty of Engineering, University of Lagos, Akoka, Nigeria
[5]Climateworks Centre, Level 27, 35 Collins St, Melbourne, VIC 3000, Australia
[6]Monash University, BSD, Serpong, Banten, Indonesia

*Corresponding author: aditya.putranto1@monash.edu

Abstract

In light of environmental issues, lignocellulosic empty fruit bunch (EFB) biomass is promoted as a carbon-neutral, environmentally friendly, and renewable alternative feedstock. A comprehensive environmental assessment of EFB biorefineries is critical for determining their sustainability in parallel with the bioeconomy policy. Nonetheless, no life cycle assessment (LCA) has been performed on co-producing food and biochemicals (furfural and glucose) derived from EFB biomass. This research is the first to evaluate the environmental performance of the furfural and glucose co-production processes from EFB biomass. Environmental analysis is conducted using a prospective gate-to-gate LCA for four impact categories, including global warming potential (GWP), acidification (ADP), eutrophication (EP), and human toxicity (HT). Aspen Plus is used to simulate the co-production process of furfural and glucose as well as generate mass and energy balances for LCA inventory data usage. The findings suggest that the environmental footprint in respect of GWP, ADP, EP, and HT is 4846.85 kg CO_2 equivalent per tonne EFB, 7.24 kg SO_2 equivalent per tonne EFB, 1.52 kg PO_4 equivalent per tonne EFB, and 2.62E-05 kg 1,4-DB equivalent per tonne EFB, respectively. The normalized overall impact scores for GWP, ADP, EP, and HT are 1.16E-10, 2.28E-11, 6.12E-10, and 2.18E-17 years/tonne of EFB, respectively. In summary, the proposed integrated plant is not only economically profitable but also environmentally sustainable. In the attempt to enhance the Malaysian economic sector based on the EFB, this study has the potential to serve as an indicator of the environmental sustainability of the palm oil industry.

Keywords: process design, empty fruit bunches, environment, life cycle assessment, glucose, furfural

Abbreviations

Abbreviation	Definition
EFB	Empty fruit bunches
LCA	Life cycle assessment
GWP	Global warming potential
ADP	Acidification
EP	Eutrophication
HT	Human toxicity
LNG	Liquified natural gas
GHG	Greenhouse gas
MYR	Malaysia Ringgit
USDA	United States Department of Agriculture
NRTL	Non-random two-liquid
UNIQUAC	Universal quasi-chemical
ISO	International Organization for Standardization

1. Introduction

Malaysia is endowed with an abundance of lignocellulosic biomass, particularly palm oil biomass such as empty fruit bunch (EFB) that consists of cellulose, hemicellulose, lignin, ash, and water, as shown in Table 1 **(Chiesa & Gnansounou, 2014; Mohd Yusof, Zakaria, et al., 2019)**. With increased downstream activities and the use of palm oil as a feedstock in different sectors, the palm oil industry promotes agriculture economics by up to 8%, providing Malaysia Ringgit (MYR) 80 billion in gross national revenue **(AIM, 2013)**. Despite this rapid increase, the sustainability of palm oil production remains a key problem due to the waste accumulation caused by the palm oil industry **(Lim & Biswas, 2019)**. Awalludin et al. **(2015)** estimate that only around 10% of cultivated oil palm trees are converted into commercial palm oil commodities. Despite their economic potential, 90% of the remaining palm oil crops are processed as biomass waste **(Dwi Prasetyo et al., 2020)**. Consequently, there is a potential to revive the palm oil sector by converting EFB biomass into food and chemicals with an integrated lignocellulosic biorefinery technology.

Table 1 *Composition of EFB* ***(Chiesa & Gnansounou, 2014)***

Components	Percentage (wt.%)
Cellulose	29.60
Hemicellulose	22.30
Lignin	22.90
Water	19.80
Ash	5.40

Biorefinery, a system comparable to a petroleum refinery, has been envisioned to valorize a variety of raw materials such as agricultural wastes, food crops, and municipal solid waste in an integrated industrial network **(Rizwan et al., 2019; Singh & Das, 2019)**. Studies have shown that transforming palm oil waste into marketable products (e.g., biodiesel, bioethanol, hydrogen, and electricity) in palm oil biorefineries may help improve sustainability **(Aristizábal, 2016; R. H. Hafyan et al., 2020)**. In recent years, the use of EFB biomass has gained increasing attention due to its abundance in Malaysia, lower prices than food crops, a decline in land-use change, and no disturbance to the food chain **(Abdulrazik et al., 2017; Chiew & Shimada, 2013; Rehman et al., 2021)**. In this context, environmental analyses of biorefinery systems based on EFB biomass are required to identify bottlenecks early on.

Many studies either focus on one single product, such as bioethanol using lignocellulosic feedstocks **(Lee et al., 2017; Sharma et al., 2020; Soleymani Angili et al., 2021)**, or on the techno-economic analysis of integrated plants without performing the environmental analysis **(Giuliano et al., 2018; Hossain et al., 2019; Zang et al., 2020)**. However, no attention is paid to the detailed environmental assessment of food and biochemical co-production in an integrated system using EFB biomass. Hence, this study proposes a plant that simultaneously co-synthesizes the suggested foods and biochemicals (i.e., furfural and glucose) derived from EFB and evaluates the plant’s environmental sustainability via life cycle assessment (LCA). In this aspect, furfural and glucose may be manufactured in a single facility with minimal equipment, which makes them ideal for integrated food and chemical processing plants. Furthermore, leftover lignin may be utilized as a fuel for boilers to provide heat energy. By utilizing EFB's potential, the plant's economic and environmental burdens are decreased.

Glucose is a type of sugar that is often employed as a foam stabilizer, sweetener, and humectant in the food industry **(Hull, 2010)**. According to the latest worldwide market study

2020/2021 from United States Department of Agriculture (USDA), global sugar production will increase to 181 million tonnes due to the growing sugar consumption in China, India, and Russia **(USDA FDS, 2021)**. On the other hand, furfural is now gaining appeal as a bio-based solvent, owing to growing public awareness of the need for more environmentally friendly chemicals. Furfural is extensively used in a variety of sectors, including agriculture, coatings, and medicines and construction industries as a feedstock for the manufacture of refractory materials such as ceramics and bricks **(Grand View Research, 2021)**. In parallel with the COVID-19 issue, the worldwide market for furfural, which was predicted to be worth US$ 971.1 million in 2020, is anticipated to expand to US$ 1.9 billion by 2027, rising at a 10.2% compound annual growth rate over the analyzed period 2020-2027 **(Cision PR Newswire, 2021)**.

LCA is a valuable environmental impact quantifying management approach to assess the environmental sustainability and viability of a proposed design **(Sevigné-Itoiz et al., 2021)**. Recently, LCAs on several products using biomass have been published, including those that use palm oil EFB as a feedstock to produce either bioethanol, bio-oil, xylitol, or levulinic acid **(Chan et al., 2016; Hafyan et al., 2019; R. Hafyan et al., 2020; Mohd Yusof, Roslan, et al., 2019)**. Also, numerous studies have incorporated LCA into their feasibility reports for glucose or furfural synthesis using traditional feedstocks such as woody biomass wastes or maize starch **(Blanco et al., 2020; Groslambert & Léonard, 2015; Salim et al., 2019)**. Nevertheless, no LCA has been conducted on furfural and glucose co-production in an integrated biorefinery using EFB biomass. Therefore, this research aimed to assess the environmental impacts of co-producing furfural and glucose in an EFB-based biorefinery via LCA. The novelty of this work primarily concentrates on addressing the research gap by conducting environmental analysis using gate-to-gate LCA, beginning with the arrival of EFB feedstock on-site and ending with the manufacturing of final products before distribution to the market.

2. Methodology

2.1 Process description of integrated plant

The environmental impact assessment was conducted on five integrated biorefinery units using the Aspen Plus model data for the co-production of furfural and glucose. The simplified flow diagrams in Fig. 1 illustrate various units with respective key inputs and outputs. In this research, a feedstock capacity of 111.11 kg/hr of EFB on a wet mass basis (100 kg dry EFB with 10 wt.% moisture) was employed at the EFB biomass biorefinery. Enzymatic hydrolysis and dehydration are used to produce glucose and furfural, respectively. To obtain the appropriate specification, it is followed by enzymatic hydrolysis for glucose production and dehydration for furfural synthesis, as well as purification and recovery of the products.

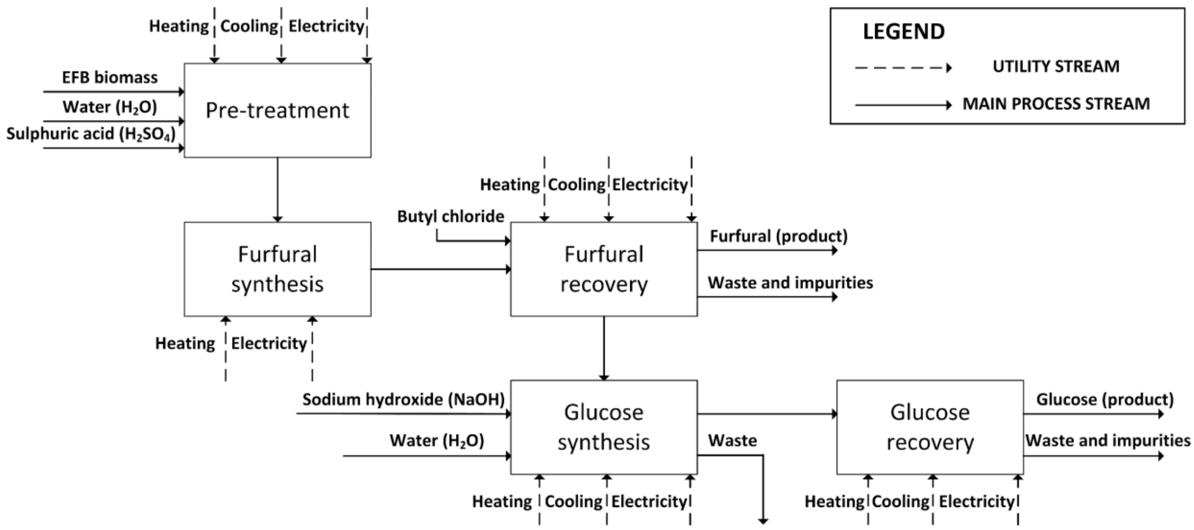

Fig. 1 *Block flow diagram showing an integrated biorefinery in co-production of furfural and glucose*

2.1.1 Pre-treatment

In the pre-treatment unit, an agitated mixing tank (M-1101) operates at room temperature and pressure (30°C and 1 atm). It mixes process water and 70 wt.% sulfuric acid (H_2SO_4) from their respective storage tanks as well as recycled water from the distillation column (C-1302) in the furfural recovery unit. Here, the water is used to dilute the H_2SO_4. The H_2SO_4 and process water flowrates are set to 30 wt.% of the solid loading, with 18 mg of H_2SO_4 per gramme of dry EFB **(Humbird et al., 2011)**. Afterwards, the mixture is heated (E-1101) to 158°C before being sent to a continuous stirred tank reactor (CSTR) (R-1101). Feedstock (EFB biomass) is then sent to R-1101 and stirred with acid mixtures for 5 minutes **(Humbird et al., 2011)**. Besides conversion of hemicellulose to xylose via acid hydrolysis, by-products are produced in other secondary reactions in the reactor, as indicated in Table A.1 of supplementary information **(Section A)**. The xylose mixture produced from the reactor is then cooled (E-1102) to 50°C and delivered to a decanter centrifuge (S-1101) for solid-liquid separation. The decanter centrifuge can filter solid particles ranging from 0.1 to 1 mm from the liquid by rotating horizontally, separating solids on the separator wall, and executing them via a screw conveyor **(Dolphin Centrifuge, 2021)**. The solid is eliminated with 5 wt.% moisture before sending to the glucose synthesis unit, whilst the liquid stream is sent to the furfural synthesis unit.

2.1.2 Furfural synthesis

In the furfural synthesis unit, the liquid stream from the decanter centrifuge of the pre-treatment unit is dehydrated to convert xylose to furfural, where the dehydration process is autocatalyzed by heat. Here, the liquid is pumped (P-1201) and heated (E-1201) to 8.8 atm and 70°C, respectively before sending to an insulated CSTR (R-1201) that is operating under a residence time of 20 minutes. With this regard, CSTR can convert xylose to furfural at up to 96.50% **(Mittal et al., 2017)**.

2.1.3 Furfural recovery

Further purification is required in the furfural recovery unit because the condensed liquid from the dehydration process in the furfural synthesis unit contains by-products other than furfural, such as water, H_2SO_4, and acetic acid. All of the by-products must be removed to obtain high purity furfural. Thus, the condensed liquid is supplied into a distillation column (C-1301), in which furfural and water are recovered at the top as distillate whilst diluted acid exits at the bottom of the distillation column. Furthermore, the distillate is cooled (E-1303) to 40°C before being routed to a liquid-liquid extraction column (C-1302), where butyl chlorine is used as a solvent to break up the azeotrope of furfural and water **(Nhien et al., 2021)**. In a mixer (M-1301), fresh butyl chloride from its storage tank is combined with recycled butyl chloride from the distillation column (C-1303). The butyl chloride is then heated (E-1304) to 40°C before being injected into C-1302. Here, the water exits at the bottom stream of C-1302 and is recycled to the pre-treatment unit, with 5 wt.% of the water being purged to prevent buildup in the production plant **(Nhien et al., 2021)**. The furfural-butyl chloride mixture extracted from the top of C-1302 is transported to the second distillation column (C-1303) to recover the butyl chloride solvent so that the purity of furfural can be recovered to 99.54 wt.%. After that, the purified furfural exiting from the bottom of C-1303 is cooled to 30°C before being delivered to the storage tank. The leftover solvent recovered from the top is recycled.

2.1.4 Glucose synthesis

In the glucose synthesis units, the diluted base (neutralizing liquid with 50 wt.% sodium hydroxide), process water, and recycled water from the distillation column (C-1601) of the glucose purification unit are pre-mixed in a mixing tank (M-1401) before being sent to a simultaneous mixing tank (M-1402). In the second mixing tank, the wet solid (5 wt.% moisture) from the decanter centrifuge (S-1101) of the pre-treatment unit is mixed with the mixture from M-1401. To achieve full neutralization of acetic acid, sodium hydroxide is added in excess of 10% mol **(Humbird et al., 2011)**. In this process, sulfuric and acetic acid are converted into sodium salt (i.e., sodium sulfate and sodium acetate). After acid neutralization, the pH of the slurry is elevated to 5, and it is then heated (E-1401) to 48°C **(Humbird et al., 2011)**. In addition, the heated slurry is fed into an insulated CSTR (R-1501) operating at 48°C and 1 atm for saccharification to synthesize glucose **(Humbird et al., 2011)**. With this regard, the cellulase enzyme is supplied into R-1501 from its storage tank and the enzymatic hydrolysis converts 95.20 wt.% of cellulose to glucose with a residence time of two consecutive days

(Humbird et al., 2011). The glucose slurry produced from R-1501 is transported through a decanter centrifuge (S-1501) for solid-liquid separation, where any solid particles with a moisture content of less than 5 wt.% are removed and delivered to the boiler feed unit as fuel stock, while the glucose liquid mixture is separated and sent to the glucose recovery unit.

2.1.5 Glucose recovery

Further purification is needed in the glucose recovery unit since the glucose mixture comprises glucose, water, and other contaminants. To obtain high purity glucose, the mixture is introduced into a distillation column (C-1601), in which the residual water is collected at the top as distillate. In contrast, the majority of the glucose may be recovered up to 96.67 wt.% at the bottom. For the top stream of C-1601, the residual water is cooled (E-1603) to 30°C and recycled to M-1401 of the glucose synthesis unit; for the bottom stream of C-1601, the glucose is cooled (E-1604) to room temperature (30°C) before being sent to the storage tank.

2.2 Aspen simulation

Aspen Plus incorporates a number of modules and thermodynamic databases for the purpose of modeling chemical processes **(Manual, 2001)**. In this regard, Aspen Plus V10 is used to model the integrated process of glucose and furfural generation from EFB (Fig. 2), using process conditions derived from literature studies **(Dolphin Centrifuge, 2021; Humbird et al., 2011; Kenthorai Raman & Gnansounou, 2015; Loh, 2018; Mittal et al., 2017; Nhien et al., 2021)**. There is a dearth of knowledge on the equipment design and operating parameters in certain large unit operations. As a result, the following assumptions are made in this work:

- EFB is dried and ground.
- The process is continuous and maintained in a constant state of equilibrium.
- There is no pressure or temperature loss between pieces of equipment or pipes.
- All transfer pumps are increased by 0.1 atm to accommodate pipeline pressure loss.
- Positive displacement pumps are utilized for streams with a capacity of less than 0.55 m^3/h and streams containing solid-liquid slurry, whereas centrifugal pumps are used for all other streams **(Liquiflo, 2016)**.

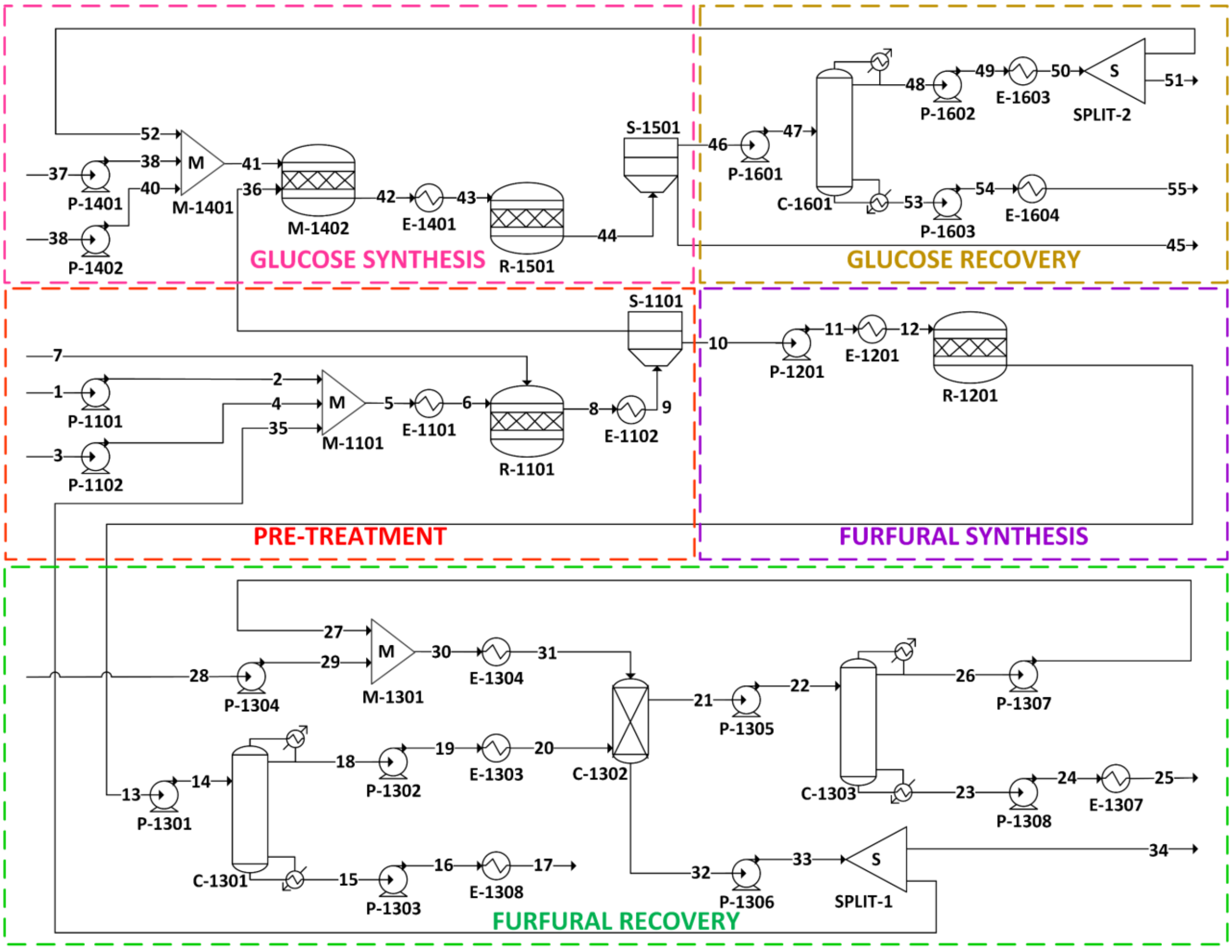

Fig. 2 ***Aspen simulation flowsheet of furfural and glucose co-production process***

2.2.1 Property method

This study adopts a non-random two-liquid (NRTL) model as the thermodynamic property package, which is consistent with other studies **(Humbird et al., 2011)**. Nonetheless, the universal quasi-chemical (UNIQUAC) model may be utilized for both vapor-liquid equilibrium (VLE) and liquid-liquid extraction (LLE) since the binary interaction between some components, such as butyl chloride and furfural, is not included in the NRTL package **(Manual, 2001)**. Therefore, in the Aspen Plus simulation, it was decided to use NRTL as the basic property technique and add UNIQUAC as the reference technique.

2.2.2 Define components

The Aspen database contains all liquid components. Nevertheless, the solid component, namely EFB, is missing from the Aspen database. As a result, it must be manually inserted by specifying the relevant molecular weight, solid enthalpy of formation, solid molar volume (VSPOLY-1), and solid head capacity (CPSPO1-1). This information is available in the literature **(Wooley & Putsche, 1996),** as indicated in Table A.2 of supplementary information **(Section A)**.

2.3 Life cycle assessment

The material and energy balance generated from the Aspen simulation is employed for LCA analysis, which is conducted in accordance with the stages outlined by the International Organization for Standardization (ISO) **(ISO, 2006)**. Their ISO 14041 series specifies the requirements and four procedures that should be conducted in LCA, including goal and scope definition, inventory analysis, life cycle impact assessment, and life cycle interpretation.

2.3.1 Goal and scope

The goal of this research is to evaluate the environmental viability of proposed furfural and glucose co-production systems from EFB. To minimize the complexity involved with substantial analysis, where environmental consequences become sensitive to potential policy measures, an attributional LCA technique was used to compare scenarios **(Reeb et al., 2014)**. Additionally, the LCA aims to recommend viable solutions to reduce the environmental effect by identifying the system's hotspot(s).

In this study, the LCA adopts a gate-to-gate approach. It begins with the delivery of the EFB to the plant and terminates with the manufacture of final products prior to distribution. Fig. 3 depicts the system boundary of furfural and glucose co-production from EFB. In this LCA, environmental consequences associated with the acquisition of raw materials are excluded from this research. Hence, only on-site utility services such as heating and cooling and external electricity generation that aid in the operation of the plant are regarded as inside the boundary. These utility systems are assumed to provide only adequate energy to operate the unit within the boundaries of the inside battery limit (IBL).

The following assumptions were established for the LCA study:

i. The co-production of furfural and glucose from EFB is a continuous process, which eliminates the need for transportation between these process streams.
ii. The effect of infrastructure building and any associated procedures is ignored.
iii. Emissions from solid waste landfills, changes in land use, and transportation are not analyzed.
iv. This LCA does not address auxiliary activities such as wastewater treatment.
v. Due to the high adaptability of the final products, the consumer use stage and end of life phase, including ultimate disposal, are omitted.

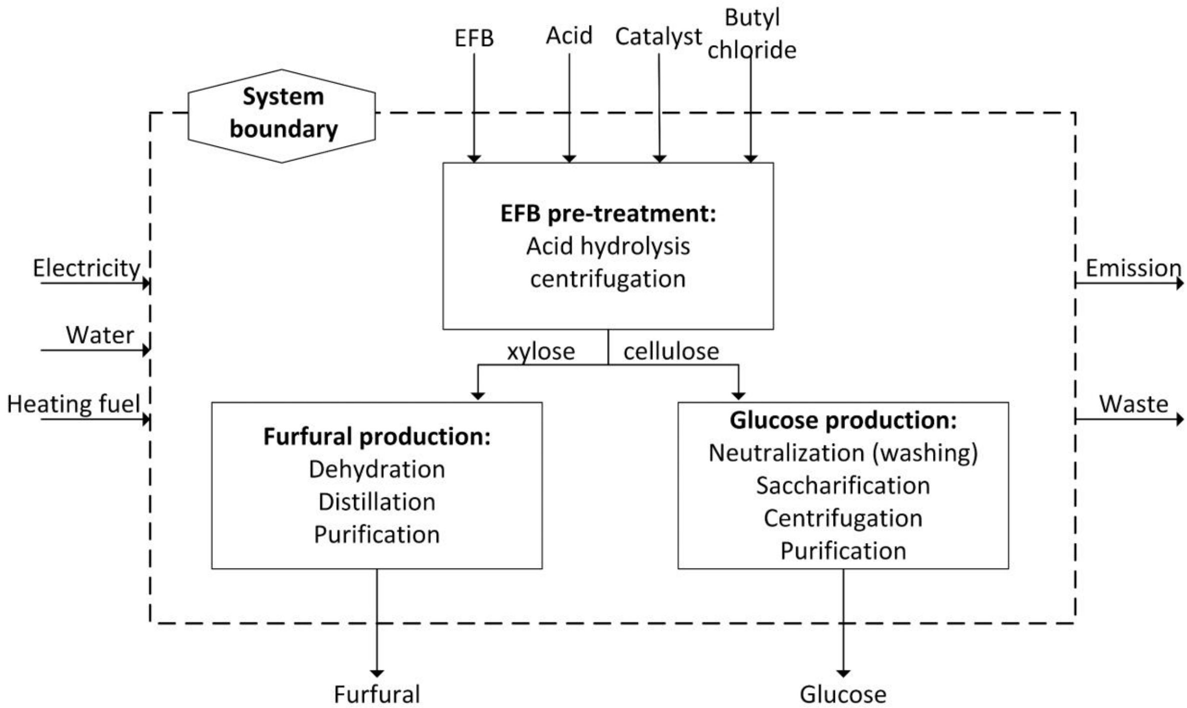

Fig. 3 *System boundary of furfural and glucose co-production from gate to gate*

2.3.2 Functional unit

The functional unit of this study processes 100 kg of dried EFB feedstock into furfural and glucose. The environmental impacts are calculated on the basis of 1 kg of product or 1 kWh of electricity. This indicates that the values obtained for material balance, environmental footprint, and their associated environmental loads are based on this production plant's expected capacity. The resulting data can then be used to optimize or scale the product.

2.3.3 Life cycle inventory

The primary objective of life cycle inventory analysis is to establish a relationship between the material flow and utility requirements of individual process units. Information on mass and energy balances **(see supplementary information, Table A.3)** acquired from process modeling are utilized to complete the life cycle inventory of furfural and glucose co-production systems. Table 2 summarizes the daily operation's input-output flow. The details of the environmental footprint connected with each utility system, including power, steam, hot water, and cooling water can be found in Table B.1 of supplementary information **(Section B)**. This design has four distinct types of heating utilities: high pressure steam at 35 bar, medium pressure steam at 10 bar, low pressure steam at 3 bar, and hot water provided at 80°C **(see supplementary information, Table C.1)**. Meanwhile, cooling water is delivered at a temperature of 30°C **(see supplementary information, Table C.1)**. Some assumptions are made throughout the life cycle inventory calculation process:

i. Electricity is provided by an external grid system. Due to the availability of more detailed data, the emissions from energy use are derived from Indonesia's electrical grid system **(Widiyanto et al., 2003)**. This is achievable since Malaysia and Indonesia use comparable fuel mixtures for power production **(Jayed et al., 2011)**. Detailed electricity consumption of each equipment is shown in supplementary information **(Section C2)**.

ii. For heat production, liquefied natural gas is employed as the combustion fuel **(Gilbert et al., 2018)**.

iii. An efficiency of 0.85 is assumed for the boiler and 0.925 for the steam distribution. Meanwhile, an efficiency of 0.60 is assumed for pumps **(Nieuwlaar et al., 2016)**.

iv. The environmental footprint of an industrial cooling tower is directly proportional to the process plant's desired specific cooling capacity **(Yu & Chan, 2009)**.

Table 2 *Overview of life cycle inventory data*

Process unit	Pre-treatment		Furfural synthesis		Furfural recovery		Glucose synthesis		Glucose recovery	
Stream	Inputs	Outputs	Inputs	Outputs	Inputs	Outputs	Inputs	Outputs	Inputs	Outputs
Feedstocks [a]										
EFB	111.11									
H_2O	6.03						8.86			
H_2SO_4	2.57									
Butyl chloride					0.14					
NaOH							0.08			
Products [a]										
Furfural						17.67				
Glucose										35.44
Waste [a]										
H_2O						20.95				6.48
H_2SO_4						1.78				
Glucose						4.17				
Acetic acid						1.84				
Impurities						5.37E-03				5.54E-03
Solid waste								37.55		
Liquid waste								1.88		
Total [a]	**119.71**	**0.00**	**0.00**	**0.00**	**0.14**	**46.42**	**8.94**	**39.43**	**0.00**	**41.93**

Utilities [b]					
Heating	61.02	37.30	332.47	8.37	461.61
Cooling	29.96		303.86	4.64	367.40
Electricity	16.84	7.79	0.02	9.83	0.03
Total [b]	**107.82**	**45.09**	**636.35**	**22.84**	**829.04**

[a] Unit is in kg.

[b] Unit is in kW.

2.3.4 Life cycle impact assessment method

The life cycle impact assessment (LCIA) framework is developed in accordance with the EN15804 standard characteristics method obtained from the European Life Cycle Database (ELCD) **(Mohammadi & South, 2017)**. The EN15804 midpoint approach comprises four impact categories, including global warming potential (GWP), acidification potential (ADP), eutrophication (EP), and human toxicity (HT). A detailed description of each environmental impact category is indicated in Table 3.

A characterization factor or equivalency factor is applied to the inventory streams in order to convert the impacts of emissions to the quantitative representation of their respective LCA categories. Additionally, normalization of the gathered data is performed in relation to global emissions.

Table 3 *Environmental impact category* ***(Mohammadi & South, 2017)***

Impact category	**Unit**	**Description**
GWP	kg CO_2 eq.	Index of the influence of greenhouse gas emissions on global warming.
ADP	kg SO_2 eq.	Index of a drop in pH as a prelude to acid rain.
EP	kg PO_4 eq.	Index of nutrient overload in terrestrial and aquatic ecosystems.
HT	kg 1,4-DB eq.	Index of potential for damage associated with each unit of chemical discharged into the environment.

2.3.5 Uncertainty analysis

An uncertainty analysis was performed for all emissions within the environmental impact categories to highlight the influence of possible data variation on LCA findings since data uncertainties are typical in the evaluation of novel process designs **(Sikdar, 2019)**. It aids researchers in estimating the similarity between projected and actual findings of LCA. In this case, the potential sources of uncertainty are the first to be identified and then followed by determining overall uncertainty by adding the numerous uncertainties inherent to the process.

3. Results and discussion

3.1 Overall LCA interpretation

There are different processing phases in the furfural and glucose co-production plant. For various manufacturing operating conditions, each phase contributes to environmental pollutants emissions at varying rates. Table 4, Figs. 4, 5, and 6 summarize the environmental impact of each unit process on four categories (GWP, ADP, EP and HT) based on characterization factor or equivalency factor **(see supplementary information, Table D.1)** whereas Table 5 displays the normalized impact scores of each process unit across those categories based on normalization factor **(see supplementary information, Table D.2)**. Normalization, as defined by the EN ISO 14044 standard, is the process of calculating the magnitude of category indicator results as compared to certain reference data **(ISO, 2006)**. The purpose of normalization is to better comprehend the relative magnitudes associated with each indicator result for the furfural and glucose products **(Kim et al., 2013)**. The normalized impact results indicate EP as the highest contribution to the environmental emissions in the whole co-production plant with approximately 6.12E-10 year per tonne EFB followed by GWP with 1.16E-10 year per tonne EFB and ADP with 2.28E-11 year per tonne EFB. On the other hand, the normalized impact score of HT is associated with 2.18E-17 year per tonne EFB, which is negligible in the proposed design.

***Table 4** Environmental impact contribution by each unit process with equivalency factor*

Impact Category	**GWP**	**ADP**	**EP**	**HT**
Unit/ tonne EFB	kg CO_2 eq.	kg SO_2 eq.	kg PO_4 eq.	kg 1,4-DB eq.
Acid hydrolysis	414.63	0.87	0.15	7.13E-06
Solid separation 1	36.45	0.18	0.02	2.43E-06
Dehydration	252.20	0.52	0.06	4.28E-06
Furfural purification	1707.24	2.22	0.52	3.23E-06
Neutralization	24.43	0.11	0.01	1.60E-06
Enzymatic hydrolysis	66.64	0.16	0.02	1.62E-06
Solid separation 2	33.45	0.16	0.02	2.19E-06
Glucose purification	2311.83	3.02	0.72	3.71E-06
Total	**4846.85**	**7.24**	**1.52**	**2.62E-05**

***Table 5** Normalized impact scores of each unit*

Impact Category	**GWP (year/tonne EFB)**	**ADP (year/tonne EFB)**	**EP (year/tonne EFB)**	**HT (year/tonne EFB)**

Acid hydrolysis	9.92E-12	2.72E-12	3.90E-11	5.95E-18
Solid separation 1	8.72E-13	5.54E-13	4.05E-12	2.02E-18
Dehydration	6.03E-12	1.65E-12	1.55E-11	3.57E-18
Furfural purification	4.08E-11	6.98E-12	1.38E-10	2.69E-18
Neutralization	5.84E-13	3.57E-13	3.06E-12	1.33E-18
Enzymatic hydrolysis	1.59E-12	5.16E-13	6.56E-12	1.35E-18
Solid separation 2	8.00E-13	4.89E-13	4.19E-12	1.82E-18
Glucose purification	5.53E-11	9.49E-12	4.02E-10	3.09E-18
Total (year/tonne EFB)	**1.16E-10**	**2.28E-11**	**6.12E-10**	**2.18E-17**

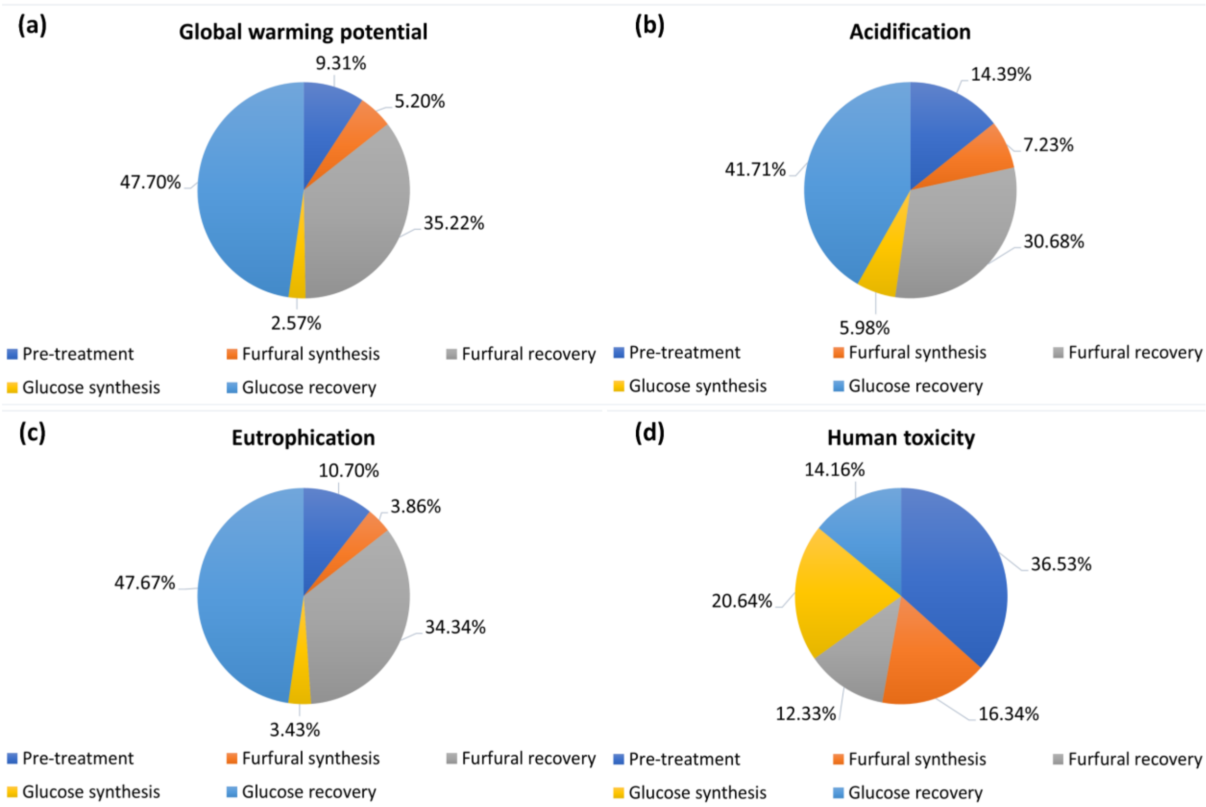

***Fig. 4** Contributions of different units to each impact category during co-production of furfural and glucose: (a) global warming potential, (b) acidification, (c) eutrophication and (d) human toxicity*

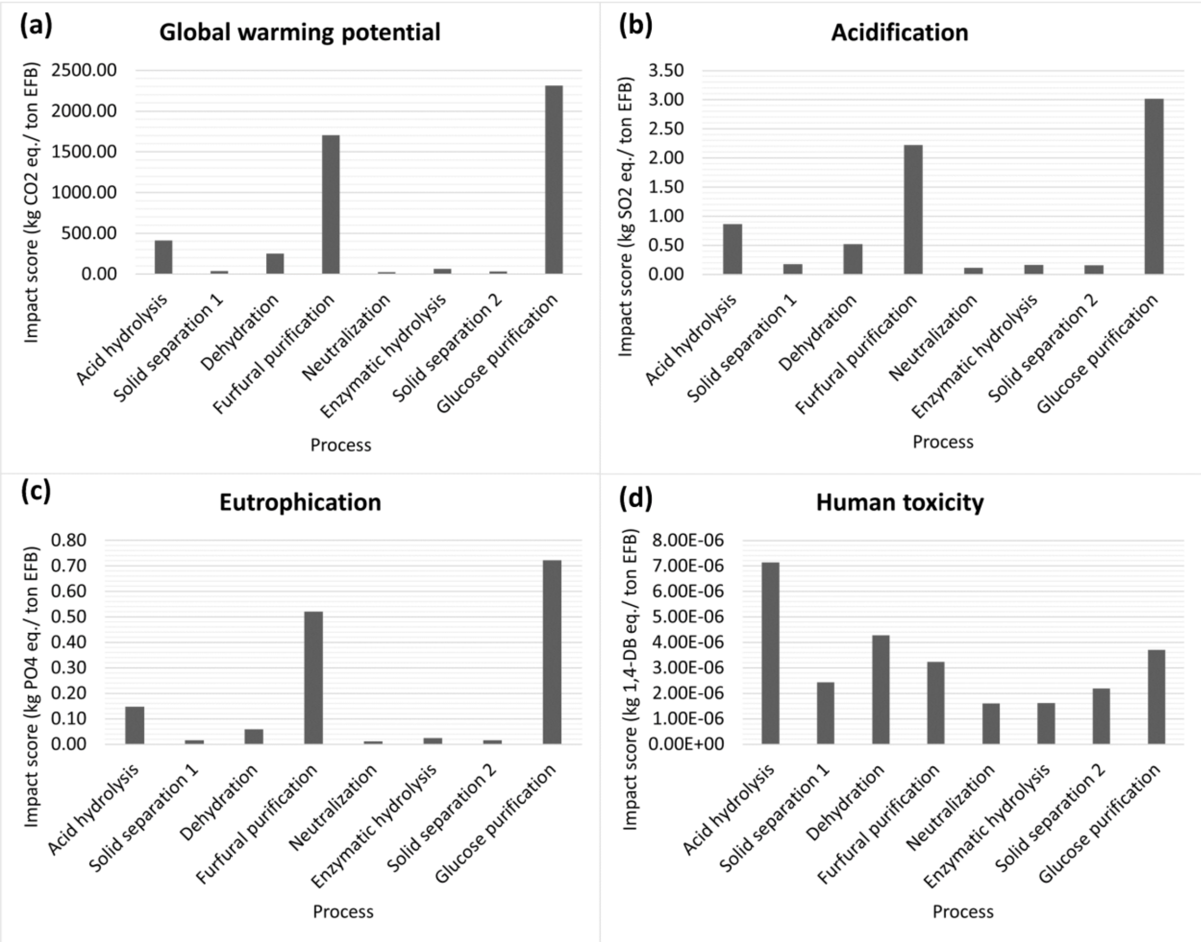

Fig. 5 *Impact score of different processes on each impact category during co-production of furfural and glucose production: (a) global warming potential, (b) acidification, (c) eutrophication and (d) human toxicity*

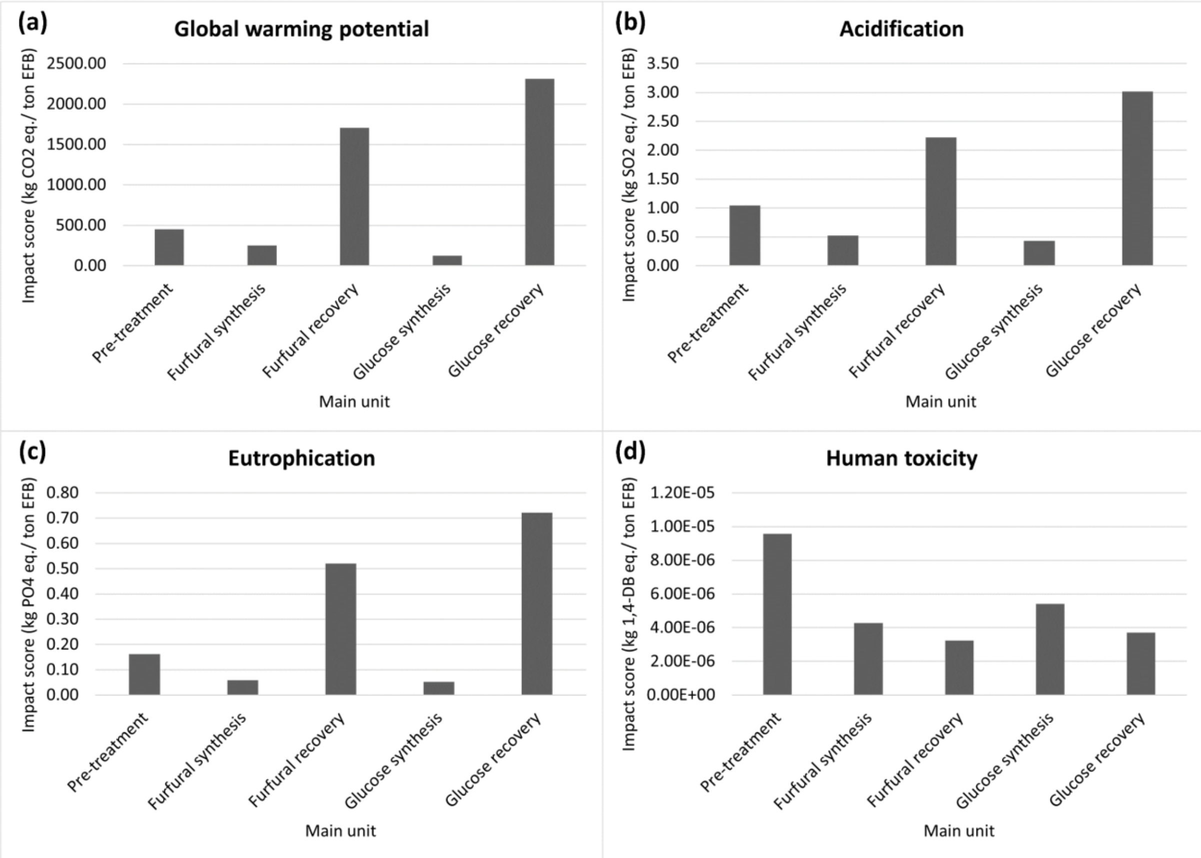

Fig. 6 *Impact score of different main units on each impact category during co-production of furfural and glucose production: (a) global warming potential, (b) acidification, (c) eutrophication and (d) human toxicity*

3.2 Global warming potential

According to the results shown in Table 4 and Fig. 4(a), the total GWP caused by the co-production of furfural and glucose was 4846.5 kg CO_2 eq., out of which 9.31%, 40.43% and 50.27% could be attributed to the EFB pre-treatment, furfural production (i.e., furfural synthesis and furfural recovery), and glucose production (i.e., glucose synthesis and glucose recovery) units, respectively. Glucose purification in the glucose recovery unit provided the biggest contribution to the GWP (2311.83 kg CO_2 eq.) in the proposed design, as depicted in Figs. 5(a) and 6(a). Furthermore, furfural purification in the furfural recovery unit gives the second greatest GWP (1707.24 kg CO_2 eq.). The contaminants were separated using a comparable distillation column in each of these process units. Remarkably, the steam and hot water utilized in the reboiler of the distillation columns are produced by the heat generated from the combustion of liquefied natural gas (LNG). The heat from this combustion is subsequently transported from the tubes to the water in the boiler to produce hot water and steam. With this regard, water boils at 100°C and then quickly evaporates. As a result, furfural and glucose recovery units have been identified as the hotspots of this proposed plant, requiring mitigation to reduce emissions.

Due to the fact that this co-production process necessitates the generation and consumption of enormous amounts of steam and hot water, a significant amount of LNG must be utilized. Obviously, LNG burning is related to the introduction of environmental contaminants that contribute to the GWP, including carbon dioxide (CO_2) which is the main GHG gaseous. To address these emissions, CO_2 may be utilized directly or turned into high-value compounds such as carbonated drinks, alcohols, dimethyl ether, light olefins, and aromatics through hydrogenation, photochemical, electrochemical, and biological conversions **(Kamkeng et al., 2021; Ye et al., 2019)**. As a result, it is advised that the EFB-based biorefinery be fitted with equipment capable of converting CO_2 into a useful product in order to increase the sustainability of the manufacturing plant in the future. Meanwhile, it should be emphasized that the liquid steam temperature after condensation remains quite high. Nevertheless, it is liquid and lacks sufficient pressure to be reused in this furfural and glucose co-production plant. Hence, it may be utilized as a viable source for the heating systems of nearby buildings, which typically use LNG to heat water.

On the other hand, the use of renewable carbon-neutral energy carriers such as hydrogen (H_2) is suggested to replace fossil fuel (LNG) in providing heat demand to the reboiler of the distillation column. H_2 is plentiful in nature and has become a promising tool for achieving decarbonization targets by generating heat and energy in a clean and efficient manner **(Al-Kuwari & Schönfisch, 2022)**. A region-specific study found that replacing diesel with LNG leads to a 16% rise in carbon footprint but replacing diesel with H_2 results in a significant decrease in carbon footprint by 47% **(Chang et al., 2019)**. In addition, **Wang and Wright (2021)** compared the environmental impacts of several types of alternative energy sources. They concluded that the employment of H_2 will only produce 9.66 g CO_2/ MJ, in which the carbon footprint can be significantly reduced by 63.86% if compared to LNG. GHG generation can be reduced when H_2 is used to replace LNG, thus enhancing the environmental sustainability of the EFB-based biorefinery. Future studies should pay greater attention to such an implementation in order to minimize the hotspot resulting from the reboiler in the distillation column.

3.3 Acidification potential

The EFB production and its processing into furfural and glucose in the EFB biorefinery led to ADP of 7.24 kg SO_2 eq./tonne EFB from the environmental impact categories. More specifically, in this environmental impact category, the contributions of EFB pre-treatment, furfural production and glucose production were deduced to be 14.39%, 37.91% and 47.70%, respectively. As illustrated in Figs. 4(b), 5(b), and 6(b), glucose and furfural recovery units contributed the most to ADP (approximately 42% and 31%, respectively). This is due to emissions from the high-heat-duty reboiler of the distillation column in the furfural and glucose purification processes. High pressure (HP) steam and hot water are provided to the reboiler to fulfill the heating demands. As a result, the principal compounds contributing to acidification, such as sulfur dioxide (SO_2), sulfur oxide (SO_x), and nitric oxide (NO_x), were released during HP steam and hot water generation. Notably, the acid hydrolysis process in the pre-treatment unit contributes the third highest acidification impact score (2.72 kg SO_2 eq. per tonne EFB as shown in Fig. 6(b). This might be caused by a series of reactions using H_2SO_4 as reactants to convert the hemicellulose of EFB to xylose. In parallel with this, acetic acid is produced as a by-product. Simultaneously, the major substances impacting acidification in the acid hydrolysis reaction were determined to be SO_x and NO_x.

Here, sludge management practices are necessary to reduce the pollutants to a specific threshold before contaminant disposal. Certain phosphorus recovery technologies, particularly those that use the digester supernatant, have the ability to reduce ADP associated with sewage sludge management **(Amann et al., 2018)**. Meanwhile, similar strategies for reducing GWP can be applied to reduce emissions of the ADP pollutants, including the usage of carbon capture, utilization, and storage technology to absorb and store the generated CO_2, reusing the steam for the heating systems of nearby buildings as well as switching fossil fuel (LNG) to renewable carbon-neutral alternatives (H_2).

3.4 Eutrophication potential

As shown in Table 4, the co-production of furfural and glucose from the EFB resulted in a total emission of 1.52 kg PO_4 eq., with the glucose production processes accounting for 51.11% of the total. According to Fig. 4(c), furfural production processes contribute the second highest EP, accounting for 47.67% of the released PO_4 equivalent, followed by pre-treatment units, accounting for 10.70% of the EP. As shown in Figs. 5(c) and 6(c), the top three highest EP values are contributed by glucose purification, furfural purification, and acid hydrolysis, which are identical to the findings of GWP and ADP. Similarly, the hot water and steam required by the reboiler of distillation columns are the main hotspots of EP. As discussed earlier in the ADP section, the formation of hot water and pressurized steam, as well as the series of reactions involved in acid hydrolysis generate side-products. Those products include nitrous oxide (N_2O) and NO_x which are the main contributors to EP. Therefore, similar solutions can be adopted to mitigate eutrophication issues in minimising ADP pollutant emissions.

3.5 Human toxicity

As shown in Table 4 and Fig. 4(d), the total human toxicity caused by the furfural and glucose co-production was calculated to be 2.62E-05 kg (1,4-DB eq.), with the EFB pre-treatment unit contributing 36.53%, followed by glucose the production units (34.80%), and the furfural production units (28.67%). The major components impacting the human toxicity category include nickel (Ni), cadmium (Cd), and lead (Pb). Those toxic components might harm human health if humans accidentally consume them, disturbing various body organ systems and resulting organs (e.g., kidneys, bone, lungs etc.) damage **(Sankhla et al., 2016)**. According to Figs. 5(d) and 6(d), acid hydrolysis has the highest HT impact score (7.13E-06 kg 1,4-DB eq.), resulting in the highest HT impact contribution in the EFB pre-treatment unit. Due to the series of reactions in the units, few toxic components are produced as by-products. However, HT is considered negligible in this proposed design if compared to other impact categories, accounting for 0.000003% of normalized impact scores. This is because there is a lack of information, so the HT category is only decided by electric utilities.

3.6 Uncertainty analysis

In fact, there are several unanticipated occurrences that might occur throughout an industrial procedure. In this study, the product purification process is one of the most crucial phases in the manufacturing procedure since it consumes a significant amount of energy **(Contreras-Zarazúa et al., 2021)**. Moreover, the mechanical, heating and cooling efficiency of equipment, such as pumps, heaters and coolers would decrease with time, thus requiring more energy after a given period. These concerns should be addressed when carrying out LCA, and they may be considered in an uncertainty analysis. Table 6 displays the results of the uncertainty analysis that was conducted based on the overall environmental performance of furfural and glucose co-synthesize processes. To account for variations in purification energy and the decline in mechanical, heating, and cooling efficiency over a certain period, a 20% increase in energy (i.e., electricity, heating, and cooling) consumption is assumed. When considering the process's uncertainties, the results show that only a slight increase (less than 5%) in environmental effects was determined in the GWP, AP, and EP categories. The findings also indicate a 15% increase in the HT category since most of the emission components considered in HT categories come from electricity usage. Although the HT category shows a significant increase in uncertainty case, its value (3.00E-05 kg 1,4-DB eq.) is still considered negligible. Overall, the findings of uncertainty analysis demonstrate that the effect of uncertainty factors is insignificant when undertaking LCA analysis, thus proving the robustness of this integrated plant.

***Table 6** Uncertainty analysis summary of LCA*

Impact categories	**GWP**	**AP**	**EP**	**HT**
Unit	**kg CO_2 eq.**	**kg SO_2 eq.**	**kg PO_4 eq.**	**kg 1,4-DB eq.**
Base case	4846.85	7.24	1.52	2.62E-05
Uncertainty case	4904.78	7.51	1.54	3.00E-05

Deviation (%)	1.20%	3.72%	1.40%	14.47%

4. Limitations

This research compares and evaluates the environmental implications of the integrated production of chemicals and food additives from palm oil EFB. In the end, this research is significant as it serves as an environmental sustainability indicator in the attempt to improve Malaysia's economic sector based on the EFB and achieve a cleaner bioeconomy. However, the gate-to-gate technique used in LCA becomes the primary constraint on the environmental study. The scope of this approach only considered the emissions within the manufacturing process and excluded the overall emissions of the palm oil industry from plantation to end user. On the other hand, this paper only focused on the analysis of the environmental impact and neglected other main pillars of sustainability, such as economic and social key elements.

In the future, the scope of LCA can be expanded by considering the emission factors from the plantation to the end user, thus implementing a cradle-to-grave approach. To decrease environmental effects and promote sustainability, the habits of recycling and reusing byproducts should be practiced. Further research is required to discover adaptive climate change mitigation methods and sustainable transformation plans for the palm oil EFB for a greener economy. For example, the study of the social life cycle can be performed to investigate how the palm oil EFB biorefinery would influence society, as well as the study of life cycle cost analysis can be carried out to investigate the economic feasibility of the integrated plant.

5. Conclusions

In this paper, a life cycle assessment (LCA) has been conducted to identify the environmental impacts of a proposed furfural and glucose co-production plant. Initially, the entire co-production process of furfural and glucose from palm oil empty fruit bunch (EFB) was simulated using Aspen Plus. The LCA inventory data was then collected from the mass and energy balances simulated by Aspen Plus. In a gate-to-gate LCA analysis, the total environmental footprint in terms of global warming potential (GWP), acidification (ADP), eutrophication (EP), and human toxicity (HT) were determined to be 4846.85 kg CO_2 equivalent per tonne EFB, 7.24 kg SO_2 equivalent per tonne EFB, 1.52 kg PO_4 equivalent per tonne EFB, and 2.62E-05 kg 1,4-DB equivalent per tonne EFB, respectively. Among the impact categories, EP has the highest potential to harm the environment, accounting for 81.53%, followed by GWP, accounting for 15.44%. The steam generating process emitted a considerable amount of EP and GHG pollutants (N_2O, NOx, CO_2, and CH_4). According to the normalized scores, the furfural and glucose recovery units have the greatest environmental effect when considering the GWP, ADP, and EP impact categories. On the contrary, the HT category is considered negligible. To address environmental emissions, several principal ways are suggested, including the utilization of CO_2, reusing steam to heat nearby buildings, shifting from LNG to renewable carbon-neutral energy such as H_2, as well as waste management prior to contaminant disposal. Furthermore, an uncertainty analysis on the LCA was performed to illustrate the influence of energy variation on the LCA. The findings indicated a 1–4% deviation in the GWP, AP, and EP categories.

Nonetheless, the research has certain limitations, primarily owing to the limited scope of the gate-to-gate method used in the environmental analysis. This technique solely examined emissions from the production process and was not based on the entire “cradle-to-grave” life cycle. Meanwhile, this study primarily analyzed environmental effects, disregarding economic and social sustainability pillars. Hence, future LCA may include plantation-to-end-user components by employing a cradle-to-grave strategy. Also, other sustainability pillars such as social and economic factors will be considered in the analysis by conducting cost-social life cycle analysis and life cycle cost analysis. In the future, additional research on the exploitation of other components of EFB (e.g., cellulose, lignin, and ash) for the production of commercial bioenergy and biochemicals should also be conducted to ensure the sustainability of the palm oil biorefinery industry.

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