Life Cycle Assessment of Synthetic Polyolester Oil-Based Biolubricant Filled with Bacterial Cellulose Nanofiber

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First submission : 27th May 2022, Revised submission: 1st August 2022, Acceptance: 1st November 2022

Abstract

The challenge to increase lubrication consumption made of natural resources to support sustainable development has been eagerly researched lately. Lubricants with the addition of cellulose as additives can be a substitute for conventional lubricants. This study aims to identify significant impacts and determine alternative improvement scenarios with minimum potential implications in the experimental research of biolubricant products' life cycle. In this work, Life Cycle Assessment (LCA) with a cradle-to-gate system was carried out. The implementation scenario showed that palm oil fatty acid methyl ester (FAME) could reduce the GWP and Human Toxicity impact by ~21% and 51%, respectively, compared to synthetic oil.

Keywords: *Life cycle assessment (LCA); biolubricant; bacterial cellulose; lubricant, renewable energy*

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1. INTRODUCTION

Asia-Pacific, home to over 4.3 billion people (60% of the global population) has enormous lubricant consumption. In 2015, the lubricants demand in Asia-Pacific itself reached 53% of the global demand [1]. It is predicted that lubricant consumption will continue to increase due to the trend of consumption and the infrastructure budget that is always raised every year [2]. Moreover, the lubricant has high energy consumption and emissions. From a total of CO2 emissions globally in every aspect, lubricant production alone contributes about 4% [3]. Moreover, lubricant with green or biodegradable material is very limited [4].

Various research that studied lubricants with biodegradable material has been conducted, one of which is Bacterial Cellulose (BC). BC is biodegradable, inexpensive, and has a high thermal resistance. It is produced by the activity of acetobacter xylinum [5]. Recently, BC has been applied as a lubricant additive and provides a friction modifier and viscosity enhancer [6]. It can also be utilized as antimicrobial food packaging [7]. Although, there is always a drawback to every resource that is taken. Thus, the life cycle of this product is needed to be inspected. In this work, BC, which is mainly derived from coconut water, is used as the raw materials in LCA inventory

LCA is a powerful tool for comprehensively evaluating multiple environmental impacts across the product value chain. It allows for identifying the effect of production, and comparing technologies or products based on the same functional unit [8]. Every phase of the LCA is described in international standards (ISO 14040, ISO 14041). This step is iterative, where the level of detail and effort will depend on the research objectives [9]. **Figure 1** shows the steps for the LCA process. These steps are: (1) defining objectives and scope, (2) inventory analysis, (3) impact analysis/assessment, (4) interpretation (ISO 14040, 2006).

There are four main options for determining the system boundaries used based on the ISO 14044 standard in an LCA study: (1) Cradle to grave: includes materials and energy production chains all processes from raw material extraction through production, transportation, and use stages to the final product in its life cycle. (2) Cradle to gate: includes all processes from the extraction of raw materials through the production stage (a process in the factory), used to determine the environmental impact of a product's production [10]. (3) Gate to grave: covers the process from post-production to the end-life phase of its life cycle, used to determine the product's environmental impact after leaving the factory. (4) Gate to gate: covers the production stage process only and is used to determine the environmental impact of the production step or process.

LCA of polyolester oil with the addition of a bacterial cellulose powder-based biolubricant is presented in this study. From our previous experimental work, the performance of the prepared biolubricant was outstanding. However, the LCA of the product is important to be investigated. As far as the author was aware, the LCA of polyolester oil with the addition of bacterial cellulose powder has not yet been explored. This work discusses the LCA product of polyolester filled with bacterial cellulose powder. The sample preparation methodology was similar to nanofluid, using a sonicator to disperse the polyolester and bacterial cellulose powder [11]. To classify the reliability of the data obtained, a comparison is needed. However, the LCA of lubricant filled with cellulose powder and with oil base fluid has not yet been investigated. Barberio et al. investigated an LCA of alumina nanofluid, and the sample preparations are similar to our work. Thus, the literature is applied as a benchmark [12]

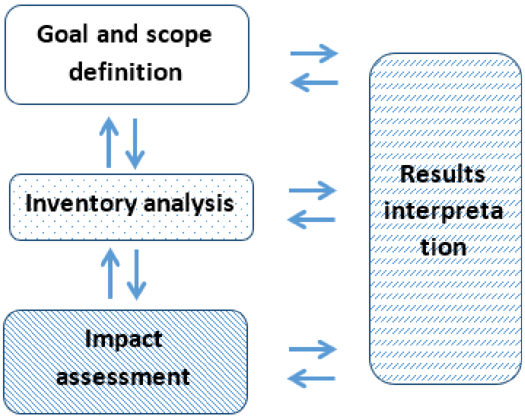

Figure 1. LCA methodology.

2. METHODS

The materials used to synthesize the biolubricant are similar to the previous work, a mixture of polyolester oil (POE with BC powder (Biolubricant-POE) [6]. LCA software, SimaPro 8, with CML method, was used to perform a cradle-to-gate LCA analysis. SimaPro incorporates different LCA databases and impact assessment methods [13]. The amount of electricity used to produce 1000 kg of lubricant was obtained from the literature [12]. The inventory data for producing these required materials were obtained from the USLCI and the Ecoinvent databases.

2.1 System Boundary

The system boundary (**Figure 2**) used in this LCA was cradle-to-gate. The cradle phase is started from the land acquisition phase for coconut cultivation, while the gate is after the Biolubricant-POE is synthesized. There were three main stages within the system: resource extraction, bacterial cellulose production, and biolubricant production.

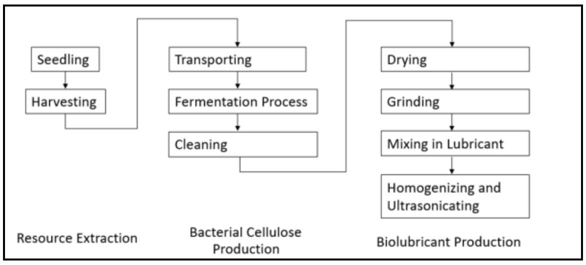

Figure 2. System boundary describing the stages involved in the cradle-to-gate LCA.

2.2 Assumptions

Several assumptions were made during input calculation and data analysis :

1. The bacterial cellulose is considered produced from coconut water only.
2. In this work, materials, transportation, electricity, and water consumption, were considered only for producing 1000 kg of lubricants.
3. The amount of energy consumption and transportation matter for the biolubricant synthesizing process is considered similar to our reference [12].

2.3 Inventory Data

Inventory analysis is carried out based on material input and output in the system. The input data consists of raw material requirements, energy/electricity, lubricant, and the means of transportation used. The calculation is based on the lubricant amount to be produced. BC production requires ethanol to maintain its quality [14]. The evaluation process was carried out by comparing the data with a previous work, which is an LCA study of alumina nanofluid. In this case, Biolubricant-POE has similar preparation method with the comparison data [12]. Table 1 shows an inventory of 1000 kg of alumina nanofluid products. Table 2 shows an inventory of 1000 kg of alumina nanofluid products. There are two main raw materials in preparing biolubricant, the base fluid (POE oil) and the additive (BC), which require electrical energy to process these two materials

Table 1. Primary input of alumina nanofluid production [12].

Input	Source	Amount	Unit
Al_2O_3 nanoparticle	[12]	90	kg
Distilled Water	Ecoinvent	900	kg
Ethanol	Ecoinvent	360	kg
Energy Consumption	Ecoinvent	36000	MJ

Table 2. Primary input of biolubricant production [6].

Input	Source	Amount	Unit
Coconut (BC Powder)	Ecoinvent	200	kg
POE Oil	Ecoinvent	900	kg
Ethanol	Ecoinvent	360	kg
Energy Consumption	Ecoinvent	36000	MJ

Table 3. Impact categories in the production of 1000 kg Alumina Nanofluid and Biolubricant-POE

Impact Category	Unit	Alumina Nanofluid [12]	Biolubricant-POE
Abiotic Depletion	kg Sb eq	0.0274	0.0392
Global Warming (100a)	kg CO_2 eq	7.34E+03	1.46E+04
Ozone layer depletion (ODP)	kg CFC-11 eq	0.000695	0.0013
Human Toxicity	kg 1.4 DB eq	294	1.49E+03
Photochemical Oxidiation	kg C_2H_4 eq	1.01	1.67
Fresh Water Aquatic Ecotox	kg 1,4 DB eq	10,5	4.49E+03
Acidification	kg SO_2 eq	9.19	15.5
Land Use	PDF*m^{2}yr	171	2.59E+02
Minerals Extraction	MJ Surplus	131	45.4
Fossil Fuels Taken	MJ Surplus	1.14E+04	2.35E+04

3. RESULTS AND DISCUSSION

3.1. Environment Impacts of Synthetic Lubricant

Table 3 shows the impact categories of biolubricant and nanofluid. It can be seen that the global warming potential (GWP) and Human Toxicity have high value in Biolubricant-POE. This is due to POE, which is categorized as a synthetic lubricant. The Fresh Water Aquatic Ecotix impact also has an enormous value. The inventories of POE production may contain hundreds of chemicals, of which many will potentially cause ecotoxic impacts on aquatic and terrestrial ecosystems, leading to damage to ecosystem quality [15]. In the end, the manufacturing process of synthetic lubricants is harmful to the environment [4][16]. Moreover, the land use impact also increases because the more coconut is produced, the more land is needed. If both products of alumina nanofluid and Biolubricant-POE are applied as machining coolant, Biolubricant-POE has a lower impact instead of alumina nanofluid due to less mineral extraction impact. It can be seen in **Figure 3** that the mineral extraction impact carried out by Al2O3 nanoparticles alone is very large. By replacing nanoparticles with BC as a lubricant additive, mineral extraction can be reduced to 80%. Moreover, in the lubricity performance, BC has an advantage over nanoparticles. Recent studies have clarified that BC could provide better friction coefficient reduction (up to 79%) compared to nanoparticles [6,17]. BC also has high thermal conductivity and resistance, which is suitable as a lubricant applied at a high working temperature [18].

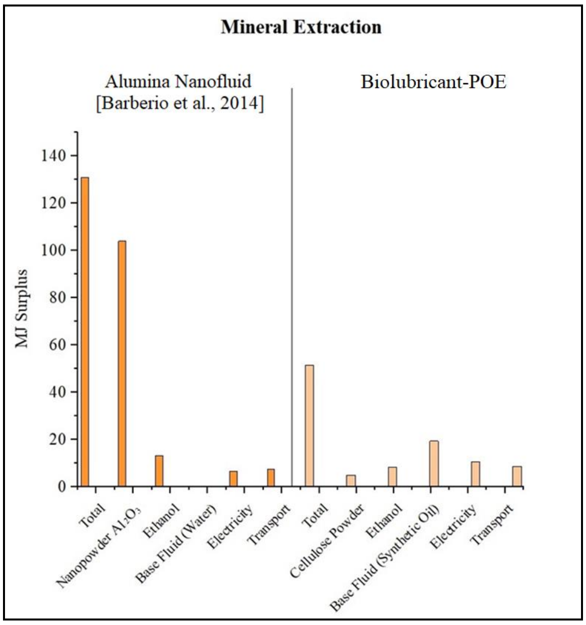

Figure 3. Mineral extraction resulting from producing biolubricant and alumina nanofluid

Furthermore, BC with nano-size particles could fill the scar and grooves in the rubbing surface. This will lower the surface roughness of the material and improve the lubricated material's lifetime [6]. However, the base fluid of the sample, POE, has an enormous value in the mineral extraction impact category. Therefore, POE is a critical value for this result. At the LCA interpretation stage, replacement of the base fluid with a better material can be carried out.

Table 4. Impact categories in the production of 1000 kg of Bioluricant-POE and Biolubricant-FAME

Impact Category	Unit	Bioluricant-POE	Biolubricant-FAME
Abiotic Depletion	kg Sb eq	**0.0392**	0.0803
Global Warming (100a)	kg CO_2 eq	1.46E+04	**1.16E+04**
Ozone layer depletion	kg CFC-11 eq	0.0013	**0.000973**
Human Toxicity	kg 1.4 DB eq	1.49E+03	**7.26E+02**
Photochemical Oxidiation	kg C_2H_4 eq	1.67	1.67
Fresh Water Ecotox	kg 1,4 DB eq	**4.49E+03**	6.74E+03
Acidification	kg SO_2 eq	15.5	**15.1**
Land Use	PDF*m^2yr	**2.59E+02**	7.37E+03
Minerals Taken	MJ Surplus	45.4	45.5
Fossil Fuels Taken	MJ Surplus	2.35E+04	**1.49E+04**

3.2 Interpretation

According to the impact category in Table 3, it was concluded that the critical point of Biolubricant-POE was the use of POE. This synthetic oil has a high impact on GWP and mineral extraction. Therefore, a base fluid with a better environmental impact category is needed. Palm Oil is suitable for this case because Indonesia is the leading palm oil producer that produces approximately 87% of the global palm oil [19]. Although to be applied as a lubricant, this palm oil needs to be processed further into fatty acid methyl ester (FAME). FAME are biodegradable and have high lubricity properties due to their functional groups that attract the metal surface better than mineral oil [20,21]. Thus, the interpretation scenario replaces the POE base fluid with FAME (Biolubricant-FAME). Table 4 compares the categorical impacts between Biolubricant-POE and without POE. **Figure 4** compares Biolubricant-POE and Biolubricant-FAME on global warming potential and human toxicity levels. It can be seen that Biolubricant-FAME as the base fluid has a better environmental impact than Biolubricant-POE, with a reduction in the global warming rate, ozonelayer depletion, human toxicity, and fossil fuels taken were 21, 25, 51, and 49% respectively for every 1000 kg oil manufacturing process.

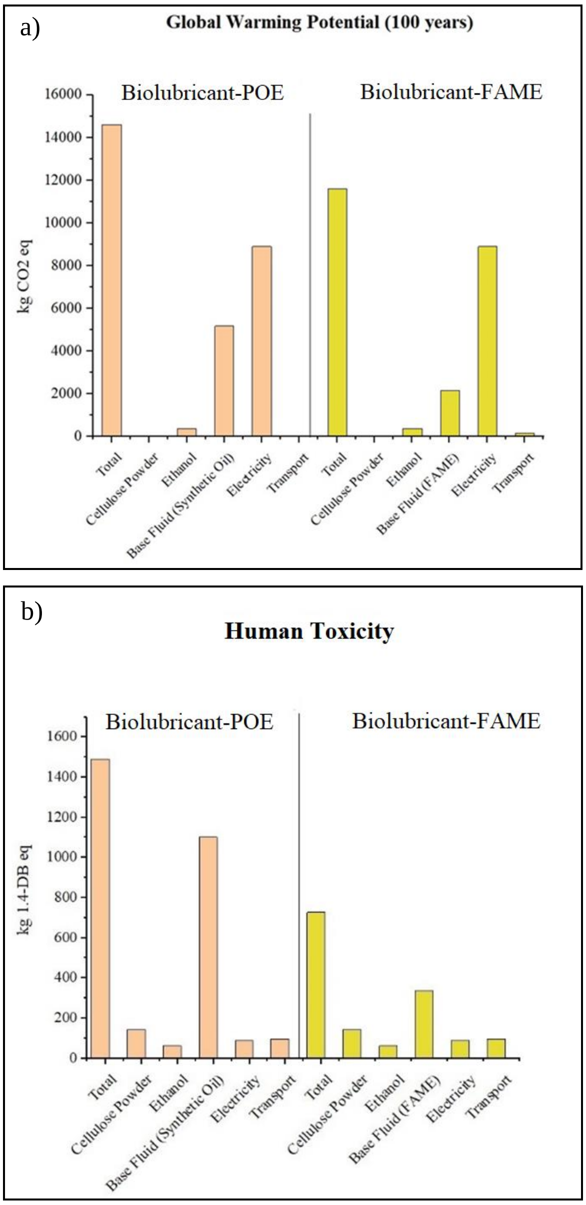

Figure 4. Global warming (100 years) (a.) human toxicity impact (b.) obtained from the production of Biolubricant-POE and Biolubricant-FAME.

4. CONCLUSIONS

The LCA analysis process for Biolubricant-POE production was successfully carried out. It can be seen that biolubricant with mineral or synthetic base fluid still has an enormous environmental impact. Therefore, to produce a minimum environmental impact, it is necessary to design a biolubricant with an environmentally friendly base fluid. The use of FAME as the base fluid for lubrication results in a very significant reduction in environmental impact. The GWP and human toxicity rates were decreased by 21% and 51%, respectively, compared to Biolubricant-POE. This proves that biolubricants with fully renewable materials can reduce the risk of environmental damage.

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