Pertanika J. Sci. & Technol. 32 (S2): 37 - 48 (2024)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Environmental Assessment on Fabrication of Bio-composite Filament Fused Deposition Modeling Through Life Cycle Analysis

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ABSTRACT

The environmental effect of a manufacturing or service method is determined by the resource and energy inputs and outputs at each point of the product's life cycle. In Fused Deposition Modeling (FDM), generally, the material used for fabrication is plastic, and the raising of interest from different backgrounds of users could increase the issue of plastic pollution. Therefore, many scholars have proposed an initiative to employ bio-composite in FDM. In this study, an environmental assessment of global warming potential and fine particulate matter emission from the fabrication of bio-composite filament FDM was performed through its life cycle analysis using GaBi Software. Initially, data on resources and energy inputs and outputs were gathered. The functional unit in this study was the 1.0 kg wood/PLA composite filament extruded using a twin-screw extruder. All wastes were collected and recycled. The fabricated composite filaments were transported by container ship with a capacity of 5000 – 200 000 dwt gross weight for 100 km within Malaysia. Based on the results from the GaBi dashboard, the FDM process of bio-composite filament has contributed as much as 138.7 kg CO_2 eq on the global warming potential and $1.71e^{-4}$ kg N eq. on fine particulate matter by the electricity power generation in extrusion and printing processes. The main factor for this issue is the consumption of coal in electric power generation, which is considered a non-renewable resource. Therefore, it is recommended that natural fibers such as wood fiber be employed in the filament of

ARTICLE INFO

Article history:
Received: 16 August 2023
Accepted: 09 May 2024
Published: 14 June 2024

DOI: https://doi.org/10.47836/pjst.32.S2.03

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ISSN: 0128-7680
e-ISSN: 2231-8526

FDM to reduce the environmental impact. As shown in the study, the materials contribute less to the impact. Further study is suggested to compare the FDM technology with conventional technology using similar materials.

Keywords: Bio-composite, environmental assessment, fused deposition modeling (FDM), life cycle analysis (LCA)

INTRODUCTION

Recently, three-dimensional (3D) printing, also known as additive manufacturing technology, has gained popularity as a technology widely used in everything from production and prototyping art to education. The applications can be found in the construction, automotive, and packaging industries, where the materials are varied according to the applications. The filament used to make the finished printed part is an essential feedstock of fused deposition modeling (FDM). Generally, the materials used as a feedstock of 3D printing are from polymer groups, specifically thermoplastic polymers. The advantages of this type of material are that it is cheaper, easy to process, has a better environmental impact, and has good material properties. Consequently, researchers' rising interest in computing their feedstock can be found in many research articles in the current year (Table 1).

Table 1
In-house FDM filament process

Materials	Process	Author
Polylactic acid (PLA)	Single screw extrusion	Harshit K. Dave, 2022
Secondary recycled Acrylonitrile Butadiene Styrene (ABS)	Twin screw extrusion	Kapil Chawla, 2021
Poly-ether-ether-ketone (PEEK)	Single screw extrusion	Bharath Tej Challa, 2022
SiC/Al_2O_3/recycled Low-Density Polyethylene (LDPE)	-	Piyush Bedi, 2020
Ceramic Thermoplastic composite	Melt extrusion	Kosamiya, 2023
Polyvinylidene Fluoride (PVDF)/graphene (Gr)/Barium Titanate (BTO)	Twin screw extrusion	Farina, 2020
Graphene /Acrylonitrile Butadiene Styrene (ABS)	Twin screw extrusion/ chemical dissolution	Gurleen Singh Sandhu, 2020
Nylon 6/Aluminum/Aluminum Oxide	Single screw extrusion	Jasvir Singh, 2022
Birch/Polylactic acid (PLA)	Filament maker	Mahdi Rafiee, 2021
Oil Palm/ABS composite	Hot Press	Ahmad, 2021
Corn Husk/Post-Used Expanded Polystyrene	-	Ariel Leong, 2021
Rice straw/Polylactic-acid (PLA)	Twin screw extrusion	Wangwang Yu, 2021
Kenaf/Acrylonitrile Butadiene Styrene (ABS)	Twin screw extrusion	Mastura MT, 2022
Acacia Concinna/Polylactic acid (PLA)	Single screw extrusion	Muthu, 2022

Filament extrusion is a process used for 3D printing to produce the filament that serves as the printing feedstock of FDM. Creating a long and continuous solid filament entails melting and extruding thermoplastic polymer granules, such as acrylonitrile butadiene styrene (ABS) or polylactic acid (PLA), through a nozzle with a particular diameter size. The extrusion process in producing the filament is used to heat and push the polymer granules that are typically fed into a hopper, as shown in Figure 1. There is a concern about energy consumption, where the process from filament production to printing using a 3D printer requires a significant amount of energy. Energy consumption may contribute to greenhouse gas emissions and climate change (Khosravani & Reinicke, 2020).

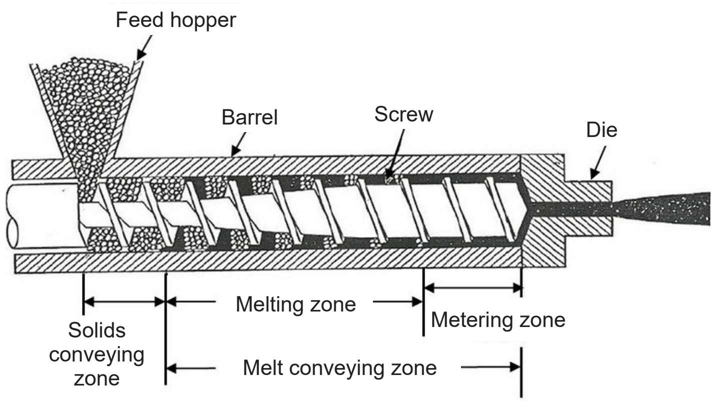

Figure 1. Schematic drawing of filament extrusion (Vlachopoulos & Polychronopoulos, 2019)

Typically, greenhouse gas emission is contributed by the manufacturing industry, where greenhouse gases (GHG) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are released into the atmosphere during various stages of the manufacturing process. These include the extraction of raw materials, the transportation of finished parts, and the disposal of waste products. Generally, GHG emissions are caused by burning fossil fuels such as coal, oil, and natural gas to generate energy for manufacturing processes. Consequently, the rise in energy consumption may increase the possibility of GHG emissions released into the atmosphere. A review study by Suárez and Domínguez (2020) focused on evaluating the environmental impact and sustainability of FDM technologies. They found that the largest environmental impact was from producing raw materials for FDM due to energy consumption and greenhouse gas emissions. Ulkir (2023), in his study, found the energy consumption of 3D printing associated with different types of materials, where recycled materials and bioplastics exhibited the most energy-efficient materials for 3D printing. These materials are recommended for sustainable 3D printing, which can reduce the environmental impact throughout its life cycle. Energy consumption in FDM is broken down into four phases: raw material preparation, filament deposition or printing process, post-processing, and waste disposal.

At the beginning of the process, energy is required for extrusion, where heat is used to melt the polymer and produce the long and continuous profile filament. Energy is also required for the FDM machine to heat the nozzle and printing platform, move the printing head, and supply power to the various motors and mechanisms. Additional energy may be required for the post-processing process, such as polishing. At the disposal phase, energy is consumed to process the waste and may be used to transport the waste to the disposal facility. However, the amount of energy consumed during the process varies, depending on factors such as the type of FDM machine, materials used, and specific printing parameters. A study by Hopkins et al. (2021) suggested semi-empirical equations that can accurately predict the energy use for each printing process. The volumetric-specific energy use was 24.8–85.7 kJ/cm^3.

Disposing of unneeded or failing FDM printed parts and support structures is the primary source of plastic waste pollution from FDM. Support structures are frequently used in FDM technology to support the printed object's position during printing. These support structures must be removed and disposed of after printing. As shown in Figure 2, errors or failed prints may produce discarded plastic parts during printing. It is suggested to recycle plastic waste. However, the recycling process could be difficult and may not always be possible. Anderson (2017) experienced using the recycled polylactic acid filament, and nozzle clogging occurred with decreased mechanical properties of the recycled filament compared with virgin filament. Pinho et al. (2020) supported this study and found some chain scission in the recycled polylactic acid filament. As a result, the semi-crystalline polymer experienced a 33% reduction in tensile stress and flexural strength. The polymer used in FDM is generally from non-renewable resources, such as petroleum, and once it is used, the leftover plastic spools may be discarded and end up in landfills.

Hence, plastic waste pollution from FDM can contribute to environmental issues without proper waste management and recycling processes. Several initiatives need to be taken to reduce pollution and improve the sustainable FDM process. Herianto et al. (2020) suggested an approach to recycle the filament of FDM using optimum parameters for the extrusion process. According to their findings, recycled polypropylene waste material can be effectively processed using extrusion to fabricate high-quality filament for FDM. This strategy could provide a sustainable and environmentally friendly solution for the manufacturing process of FDM.

Figure 2. Failed printed part

The growing interest in FDM technology has increased concerns about its environmental and human health impact. The emissions of hazardous particulate matter (PM) during the printing process are one of the key concerns. Particulate matter refers to microscopic particles that can be inhaled and cause respiratory issues, especially if they are fine enough to penetrate deep into the lungs. Studies have shown that 3D printing can generate significant matter, harming human health and the environment (Nyika et al., 2022). PM emissions can come from a variety of sources, such as the melting of the printing material, heating of the printing platform, and movement of the printer head. Yi et al. (2016) concluded that the impact of PM emissions is influenced by many factors, including the type of filament materials. They found that ABS generated bigger PM than PLA, possibly due to agglomeration. The geometric mean particle sizes, total particle number, and mass emissions varied significantly across the filament materials. The use of printer covers lowered PM emissions by a factor of 2. Lung deposition calculations revealed that PLA particle deposition in alveoli was three times that of ABS. Desktop 3D printers emit large quantities of ultrafine particles released into indoor spaces with insufficient ventilation (Khaki et al., 2021). Zhou et al. (2015) found that most of the particles emitted from the desktop 3D printers were less than 10 μm (PM10). The particle concentrations increased in parallel with the distance from the printer. Furthermore, the smaller the particle size, the higher the particle concentration, with particle sizes ranging from 0.25 to 0.28 μm. The maximum particle concentration for a single printer was roughly 2.5 x 104/L and 4x104/L for two printers. Therefore, it is important to conduct further research on the potential impact of FDM technology on the environment and health hazards so that mitigation strategies can be implemented to minimize any negative effects.

MATERIALS AND METHODS

The primary purpose of this research is to investigate the potential environmental implications of wood composite printed FDM. The study assesses the environmental implications of wood/PLA composite prepared in-house and used for FDM technology. Three stages of product development were included, starting from the composite extrusion, printing, and delivery.

Goal and Scope Definition

In order to achieve the goals above, the life cycle analysis (LCA) of FDM was performed using GaBi software and Environmental Footprint 2.0 and ReCiPe 2016 v1.1 Midpoint (H) methodology. The impact categories investigated were global warming potential (GWP) and particulate matter emission. A functional unit, namely, 1 kg wood/PLA composite, was used in the analysis to measure the environmental impact of the composite. Thus, 1 kg wood/PLA composite was determined as the functional unit. Land transportation for the delivery of the product was assumed within a 100 km distance.

The transportation of materials was the starting point for each system analysis. The primary electricity from the grid mix was considered to provide the requisite amount of electric power to the extruder and 3D printing machine. The characteristics of this study are summarized in Table 2. This study aims to evaluate the environmental impact of bio-composite filament in FDM technology.

Table 2
Inputs and outputs of the system

Amount	Unit	Unit Process	Reference
Inputs			
Polylactic Acid	1.05	kg	
Cooling water	4	kg	
Wood fiber	0.1	kg	
Electricity	6	MJ	MY: Electricity grid mix
Truck 7.5t-12t gross	100	km	GLO: Truck Euro 5
Outputs			
Plastic extrusion profile	1.05	kg	-
Plastic waste	0.05	kg	-
Wood fiber waste	0.05	kg	-

Life Cycle Inventory

Life cycle inventory (LCI), defined by ISO 14040, entails gathering data and computation techniques to quantify the flows, inputs, and outputs. LCI includes information such as energy, raw material inputs, products and wastes, and air, soil, and water emissions. The accuracy of data provided in LCI significantly impacts the reliability and comprehensiveness of an LCA.

Extrusion of Wood/PLA Composite Filament

Construction of the extrusion of a 1.05 kg wood/PLA composite filament system is presented in Figure 3. It includes the transportation of the PLA granules as raw materials and supplying electricity for the extruder machine within the system boundaries.

FDM of Wood/PLA Composite Filament

After the wood/PLA composite filament is fabricated through the extrusion process, the filament will be used for the FDM technology as a feedstock in the FDM machine. A regular desktop FDM machine was used in this study, and a part was expected to print within 8 hours using 1 kg of composite filament. The printed part was expected to be delivered to the customer within a 100 km distance. The system is presented in Figure 4.

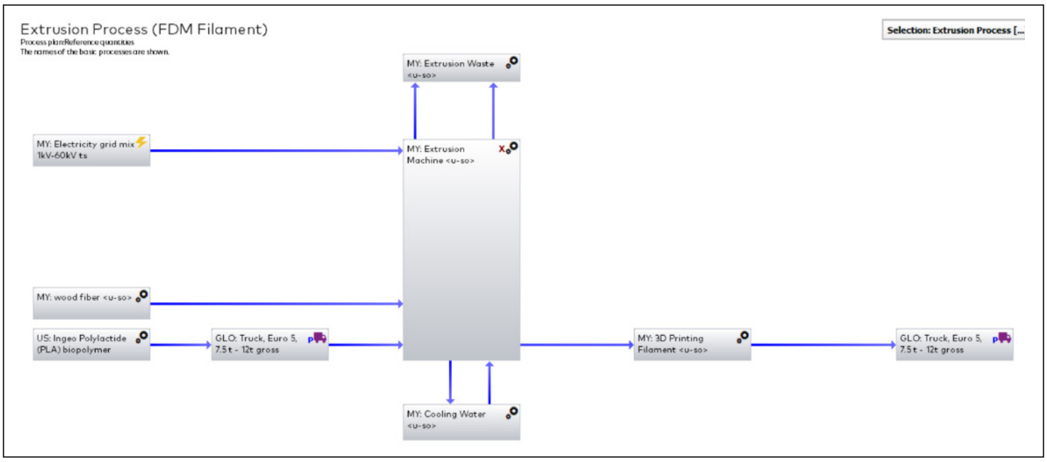

Figure 3. Extrusion process of FDM filament

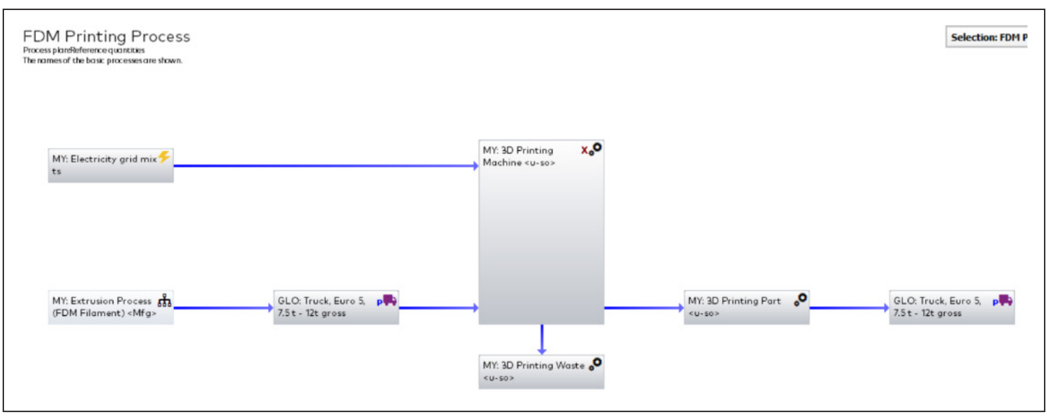

Figure 4. FDM printing system

RESULTS AND DISCUSSIONS

The impact assessment for this study was modeled and simulated using the LCA software, GaBi Professional v6.0 database, to measure the environmental burden and benefits.

Impact Assessment

Here, the results compared the total environmental impact of each wood/PLA composite FDM process for the evaluated impact categories contained in Environmental Footprint 2.0 and ReCiPe 2016 v1.1 Midpoint (H) methodology.

Global Warming Potential. From Figure 5, the total Global Warming Potential (GWP) value for an FDM printing of wood/PLA composite filament was 146 kg CO_2 eq. The values of the grid electricity mix from the FDM printing process that contributed to GWP

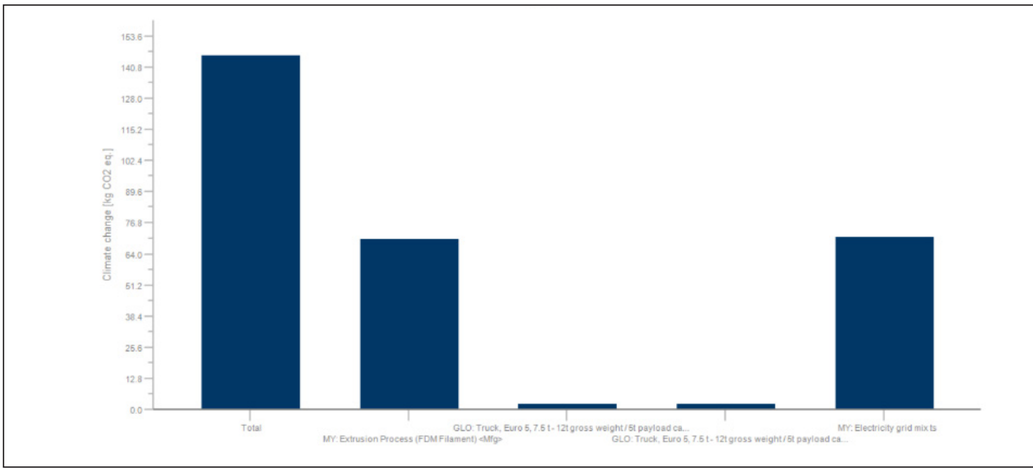

Figure 5. Total results for GWP

and from the extrusion process were 71.1 kg CO_2 eq and 67.6 kg CO_2 eq, respectively. Next, the value of PLA contributed to GWP was 0.708 kg CO_2 eq. The lowest contributor was transportation, with only 4.41 kg CO_2 eq.

Malaysian power generation is classified into five sources: oil, coal, natural gas, hydro, biomass, and others. Nearly 95 % of the electricity in Peninsular Malaysia is generated from coal (Rashid, 2021). Coal contains a large carbon content, and it releases greenhouse gases (GHG), mainly carbon dioxide, during the extraction, production, and combustion. When coal is used to generate energy in coal-fired power plants, a significant amount of CO_2 is released into the atmosphere. The combustion process involves the chemical reaction of carbon in coal with oxygen, which produces CO_2 as well as additional pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter. Regarding this, coal significantly contributes to GWP. Hence, it produces the highest amount of CO_2 per unit of energy generated. In Malaysia, natural gas that emits lower levels of CO_2 and other pollutants compared to coal-fired power plants is likely to be steadily replaced by coal in the future.

Based on the results of GWP, no significant value was obtained from wood fiber production. Only 0.708 kg of CO_2 eq was contributed to the production of PLA. PLA is a biodegradable polymer made from renewable resources and has a prominent role in the bio-polymer market due to its inherent qualities. Papong et al. (2014) concluded that although biopolymers like PLA have a smaller impact on GWP and fossil fuel consumption than synthetic polymers, they may have greater environmental consequences due to eutrophication, carcinogens, and ozone layer depletion. This phenomenon is due to increased agricultural production necessitating fertilizers, pesticides, and land use changes. It has been supported by the results of this study, as shown in Figure 6. Similar results were

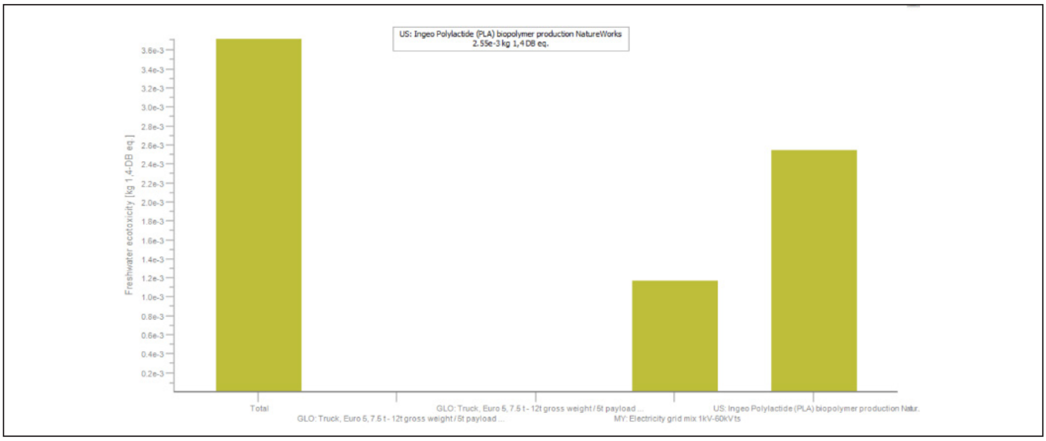

Figure 6. Results for freshwater ecotoxicity

obtained from the production of wood fibers. The demand for fertilizer and pesticides for agricultural production has contributed to the environmental impact discussed previously.

Particulate Matter Emissions. As seen in Figure 7, the biggest contributor to particulate matter emissions to produce bio-composite printed parts was during the extrusion of FDM filament, which stated as much as 2.02×10^{-4} kg N eq. The second largest contributor to PM emissions was the electricity grid mix, which recorded as much as 1.71×10^{-4} kg N eq. and the lowest contributor to PM emissions was PLA, which only contributed 3.93×10^{-5} kg N eq. The total fine PM emissions were determined to be 3.74×10^{-4} kg N eq.

Particulate matter emissions from PLA production probably consist of respirable particles harmful to the human body. The concentration and impact of particle emissions were influenced by the processing parameters that were set during the fabrication. Moreover,

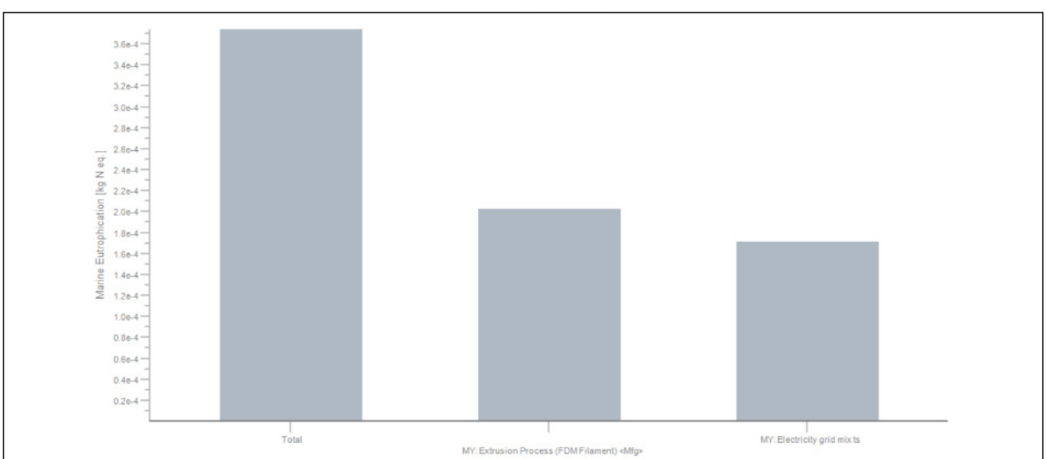

Figure 7. Results of particulate matter formation

the materials used for the processing would exhibit the concentration of the particle emissions and how dangerous they were. Chemical composition is a major concern in PM emissions, which will be released during fabrication, especially under certain high temperatures, such as more than 200 ^{o}C (Wojnowski et al., 2022). Some reports highlighted the hazardous emissions from Acrylonitrile Butadiene Styrene (ABS) that formed toxic fumes known as volatile organic carbon (VOC) (Farcas et al., 2020; Manoj et al., 2021; Stefaniak et al., 2017; Wojtyła et al., 2017). However, PLA may also emit VOCs that are harmful to young operators, especially children. A study by Zhang et al. (2017) showed that VOCs might condense throughout the printing process, resulting in bigger particles later in the print cycle. With the presence of wood fiber in the PLA composite, the PM emissions were reduced as the content of PLA was reduced. PM emissions are improved and will become less harmful if natural fiber, such as wood fiber, is employed in the feedstock of FDM.

CONCLUSION

Interest in FDM 3D printers, especially from researchers, has raised concerns about the environmental impact of the technology. Therefore, the study was conducted to evaluate the environmental impact of this technology using GaBi software. The investigation on the environmental impact of processing the bio-composite filament considered it environmentally friendly. It shows that the highest environmental impacts from this process are only contributed by electricity consumption. 138.7 kg CO_2 eq. and 1.71 x 10^{-4} kg N eq. were found for the global warming potential and fine particulate matter emissions, respectively. Both impacts were caused by the carbon content of coal, as electricity in Malaysia is mainly generated by coal. Moreover, fine particulate matter emissions were found from the production of PLA polymer as much as 0.393 x10^{-4} kg N eq. The recommendation to change power generation resources is not under the scope of the FDM user. Therefore, the employment of wood fiber in the composite PLA filament of FDM could be the solution to reduce emissions. Hence, the amount of PLA used for this process is reduced, and consequently, the fine particulate matter emissions will be reduced. Further study is suggested to be conducted to compare the significant impact of this technology with the conventional manufacturing process using the same bio-composites. Energy efficiency should be constructed to reduce toxic and greenhouse gas emissions.

ACKNOWLEDGEMENT

The Ministry of Higher Education (MOHE) of Malaysia funded the study through the Fundamental Research Grant Scheme (FRGS), No. FRGS/1/2020/TK0/UTEM/02/26. The authors thank Universiti Teknikal Malaysia Melaka for the support.

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