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ENVIRONMENTAL IMPACTS OF RECYCLED NONMETALLIC FRACTION FROM WASTE PRINTED CIRCUIT BOARD

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ABSTRACT: Recently in Thailand, the recycling process of waste printed circuit board (WPCB) has retained a large volume of nonmetallic fraction (NMF), which has entered the industrial waste stream and awaits an appropriate treatment to be suggested. The aim of this paper was to assess environmental impacts of the recycled nonmetallic fraction from waste printed circuit board in Thailand, using the ReCiPe midpoint assessment method of life cycle assessment approach. For this purpose, one of the glass fiber reinforced plastic (GFRP) manufacturers in Thailand was selected to obtain data for NMF waste and the production of two new recycled NMF products. The environmental impacts of two new recycled NMF products compared with traditional GFRP product, and two recycled NMF products compared with conventional waste disposal methods by means of landfilling and incineration were considered. The result showed that the potential environmental impacts were in the damage categories of climate change, human toxicity, marine ecotoxicity, and fossil depletion. For overall comparison, the recycled NMF as a modified GFRP product (recycled product 1) showed the worst impacts to human toxicity, marine ecotoxicity, and fossil depletion categories compared with other methods because of the complex production technique and the chemical-based process. Moreover, the recycling of NMF as a new product (recycled product 2) is likely to be the most suitable waste management option in Thailand.

Keywords: Nonmetallic Fraction, Waste Printed Circuit Board, Recycling, Waste Management, Life Cycle Assessment

1. INTRODUCTION

E-waste, or Waste from Electrical and Electronic Equipment (WEEE), is an emerging and fast-growing waste stream with complex characteristics in both developed and developing countries. According to the global e-waste report in 2014, although the average highest per capita e-waste quantity (15.6 kg/cap.) was estimated in Europe, Asia is the largest e-waste generation source, around 16Mt [1]. In Thailand without related regulation in force, e-waste generation was estimated at 6.4 kg per capita in 2014 and has increased steadily around 10 to 20% every year [2], [3]. Therefore, the handling and treatment of these wastes have become a topic of worldwide concern.

Printed Circuit Board or PCB is a basic component in all electrical and electronic devices ranging from large to small items such as fridges, washing machines, computers, TVs, CD/DVD players, radios, mobile phones, and shavers. Although overall, the PCB proportion is only about 3% to 6% by WEEE total weight, the complex array of toxic substances present in PCBs are very specific and need to be treated carefully [4]. In general, PCB contains approximately 28 to 30% metals and 70 to 72% nonmetals [5], [6]. The typical metals in PCB consist of copper (20%), iron (8%), tin (4%), nickel (2%), lead (2%), zinc (1%), silver (0.2%), gold (0.1%), and palladium (0.005%) [7]. The value of the metallic fractions (MF) of PCB is a major economic driving force to recycle Waste Printed Circuit Board (WPCB). In Thailand, the commercial recycling process of the WPCB industry currently focuses only on the recovery of copper. After the recycling process of WPCB, a large volume of nonmetallic fraction (NMF) mainly consisting of resin and glass fiber, has entered the industrial waste stream and awaits appropriate treatment. This waste can be usually treated by conventional waste disposal methods, like incineration or secured landfilling. The incineration of NMF will cause the formation of highly toxic substances such as polybrominated dibenzodioxins and dibenzofurans (PBDD/Fs) while landfilling of the NMF will lead to secondary pollution caused by heavy metals and brominated flame retardants (BFRs) leaching to the groundwater [8], [9]. In addition, NMF disposal by incineration and landfilling can cause the loss of resource use because of the resin and glass fiber contained in NMF. In view of sustainable waste management and urban mining concepts, not only valuable metals such as copper, silver and gold in PCB can be recovered but also NMF should be exploited as a resource in other related industrial processes. In our previous studies [10], [11], NMF could be recycled as a filler in fiber-reinforced polymer to make products, e.g., artificial wall tile. Other studies also found that possible applications of NMF include construction materials, composite boards, sewer gates, heavy metal absorbers, activated carbon and sound absorbers [12]-[14].

The highlighted questions below have arisen and will be answered in this study.

1) What is the environmental impact(s) of these new fiber-reinforced plastic (FRP) products containing NMF compared with traditional Glass Fiber Reinforced Plastic (GFRP) products?

2) In terms of the environment, which method is the most appropriate waste management option for NMF in Thailand? Four different waste management methods including landfilling, incineration, recycling as a modified GFRP product, and recycling as a new product were considered in this study.

To answer these questions, the Life Cycle Assessment (LCA) method, a technique to assess the potential environmental impacts associated with a product, process, or service was applied in this study. The method could be undertaken by compiling an inventory of relevant energy and material inputs and environmental releases, evaluating the potential environmental impacts associated with identified inputs and releases and interpreting the results to help us make a decision. The four basic stages in conducting the LCA include goal and scope definition, inventory analysis, impact assessment and interpretation [15]. The method has been widely applied in many research studies, e.g., [16]-[18].

2. MATERIALS AND METHODS

2.1 Materials and Recycled Products

The waste material NMF was obtained from one of the WPCB recycling plants located in Samut Sakhon Province, Thailand. The physical and chemical characteristics of NMF from WPCB were thoroughly analyzed and can be found in our previous investigations [10], [11]. The NMF collected was then used as a resource (a secondary raw material) in the glass fiber reinforced plastic (GFRP) manufacturing process at the F.R.P. Industry Co., Ltd. In general, the compositions of fiber reinforced plastic (FRP) consist of resin mixed with a monomer, accelerator, hardener and filler. Because NMF material mainly consists of resin and glass fiber, it can be used to substitute for primary raw materials, i.e., resin and filler, of the FRP production process. The two types of furniture products (table top) listed below, containing NMF material, were finally selected as recycled products for this study.

1. Modified GFRP table top (or recycled product 1): using traditional production method by hand lay-up technique, together with NMF composite material to replace plywood (which is used to increase the thickness of the product), and to replace glass fiber.

2. New table top (or recycled product 2): a casting process transforming NMF waste to make a new composite product.

To make the NMF composite (we introduced this new composite to the GFRP factory) for both recycled products mentioned above, the type of chemicals used and ratio of chemical composition of each type of table top product in accordance with our Thai petty patent No. 8341 were used and summarized in Table 1. All details of raw materials including equipment used, manufacturing process, production techniques, processing time and properties tested are all found in Jareemit [19].

Table 1 Raw materials used for the 1x1 m^2 table top product with 1 cm thickness

Ingredients	Content (kg)		
	Traditional product	Modified product	New product
Polyester resin	2.90	10.81	8.56
Glass fiber	0.9	0.9	-
Methyl ethyl ketone peroxide	0.045	0.167	0.122
Plywood	12	-	-
NMF from WPCB	-	10.2	10.2
Styrene monomer	-	2.04	2.04
Acetone	1	1	1
Water	1	1	1
Total weight	17.845	26.117	22.922

2.2 Life Cycle Assessment (LCA)

As can be seen in Fig. 1, the system boundary of the study that defines what is included in the assessment starts by collecting of NMF from a waste generator in the Samut Sakhon area, transportation, waste treatment alternatives (recycling, incineration and landfilling), and manufacturing of FRP furniture products. The functional unit of the LCA study is based on 1x1 m^2 table top with 1 cm thickness. In this study, the waste treatment options detailed below are modeled so that we can compare their environmental impacts.

Option 1: NMF waste landfilling and traditional GFRP table top production. In this option, all NMF waste is transported to a hazardous waste landfill site located in Saraburi Province, about 140 km northeast of Samut Sakhon. The cement-based solidification/ stabilization is usually applied to immobilize toxic substances before depositing the waste in a secured landfill. The traditional GFRP table top with no NMF used as a resource is normally manufactured in Samut Sakhon.

Option 2: NMF waste incineration and traditional GFRP table top production. All NMF waste is treated at an incineration plant in Samut Prakan Province, located 65 km east of the waste generating plant. Similar to option 1, the traditional GFRP table top with no NMF used as a resource is normally manufactured in Samut Sakhon.

Option 3: NMF waste recycling as a modified GFRP table top (or recycled product 1). This option explores the potential environmental impacts of recycled product 1 as described above. The waste is used as a secondary material for the FRP production process at F.R.P. Industry Company, only 10 km away from the waste generator.

Option 4: NMF waste recycling as a new table top product (or recycled product 2). Similar to option 3, the NMF is used as a secondary material at the F.R.P. Industry Company, but to produce a new table top product.

The data used for life cycle inventory was primarily gathered from the F.R.P. Industry Co., Ltd. (e.g. raw materials in Table 1), previous researches[17]-[19], relevant reports, literature, and databases provided in SimaPro Version 7.3. The World ReCiPe Midpoint impact assessment method was chosen to estimate the environmental impacts in this study. The environmental impacts of NMF waste for all impact categories were assumed to be zero. In life cycle impact assessment, all emissions of the inventory were sorted into classes according to the effect on the environment. These emissions were then multiplied by the characterization factors of each substance within each impact category as presented in Eq. (1).

$$CI = \sum_s EL \times CF \quad (1)$$

Where subscript "s" mean substance; CI is category indicator; EL is emission load; and CF is characterization factor.

All collected data in relation to the four waste management models mentioned above was used as input data in SimaPro LCA software version 7.3 to calculate all environmental impact categories in this study (see more details of method in SimaPro Database Manual for the impact category indicators [20]).

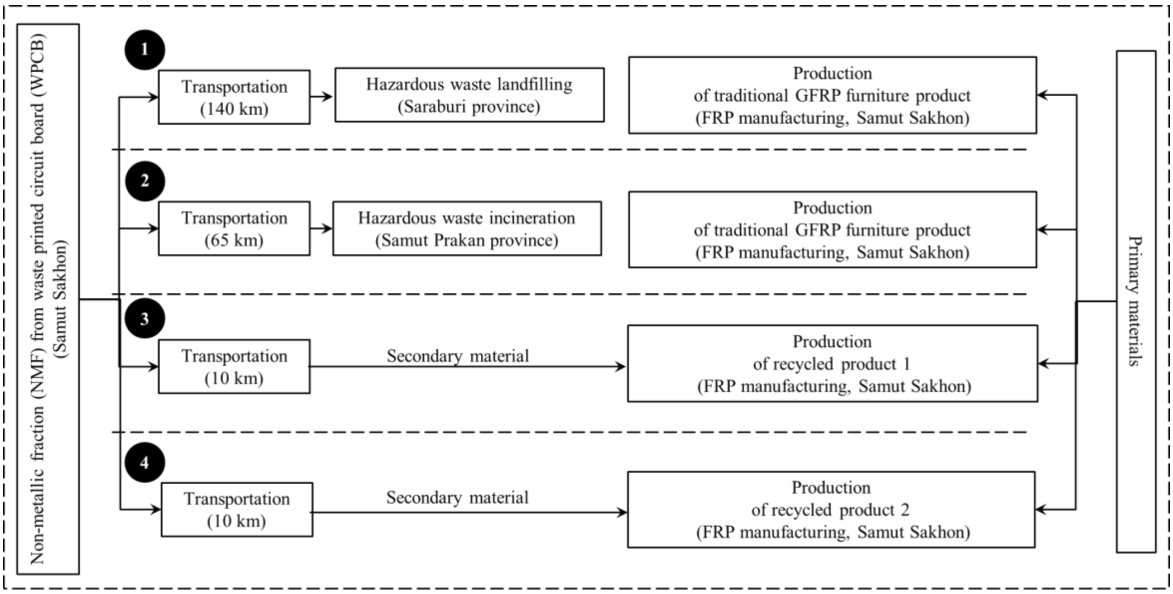

Fig. 1 System boundary of LCA study for NM from WPCB (option 1 – 4)

3. RESULTS AND DISCUSSION

In the case of NMF recycling, the weight percentage of raw materials used for the two products (recycled products 1 and 2) compared with traditional GFRP products are shown in Fig. 2. It can be seen that among those primary chemicals used to produce products, the highest amount of polyester resin is present in recycled product 1 (modified GFRP table top), followed by recycled product 2 (new table top product) and traditional product. The NMF from WPCB can be used to replace primary raw materials, like the plywood sheet, and glass fiber of the traditional GFRP product. However, the newly made NMF composite required another chemical (styrene monomer) to reduce the viscosity of the NMF mixture during the casting process [19]. Thus, the styrene monomer was additionally applied to make both recycled products about 8 to 9% as shown in Fig. 2 (calculated from data inventory of Table 1).

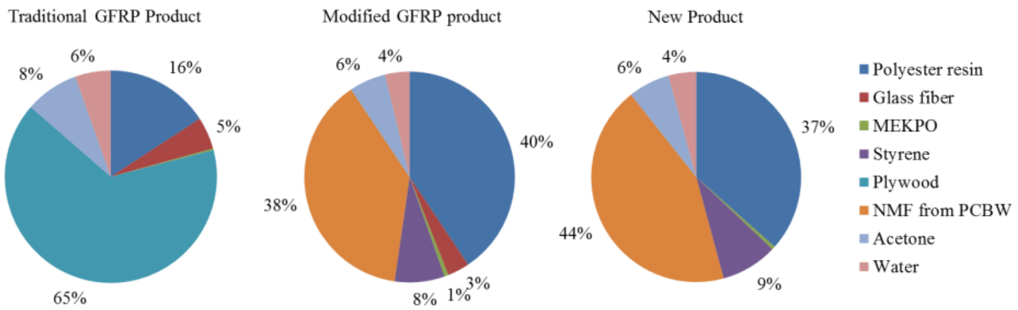

Fig. 2 Weight percentage of different raw materials used for traditional GFRP, modified GFRP and new product

From the calculation results of SimaPro program, Fig. 3 shows the environmental impacts of two new products containing NMF composite compared with the traditional GFRP product. They relate to raw materials used for a 1x1 m^2 table top with 1 cm thickness. Four damage categories, consisting of climate change, human toxicity, marine ecotoxicity and fossil depletion, are present for all three products. Only traditional GFRP product contributes agricultural land occupation impact because of the use of plywood sheet (see Fig.3). In the light of those four impact categories, except agricultural land occupation, overall the highest impact values resulted from the modified GFRP product (recycle product 1), followed by the new product (recycled product 2) and the traditional GFRP product. It became obvious that almost 100% of environmental impacts in all categories of the two recycled products resulted from polyester resin, a major raw material required in the production process (assuming zero impact for NMF waste). This is because these recycled NMF products depend highly on chemical use (see also Fig.2)

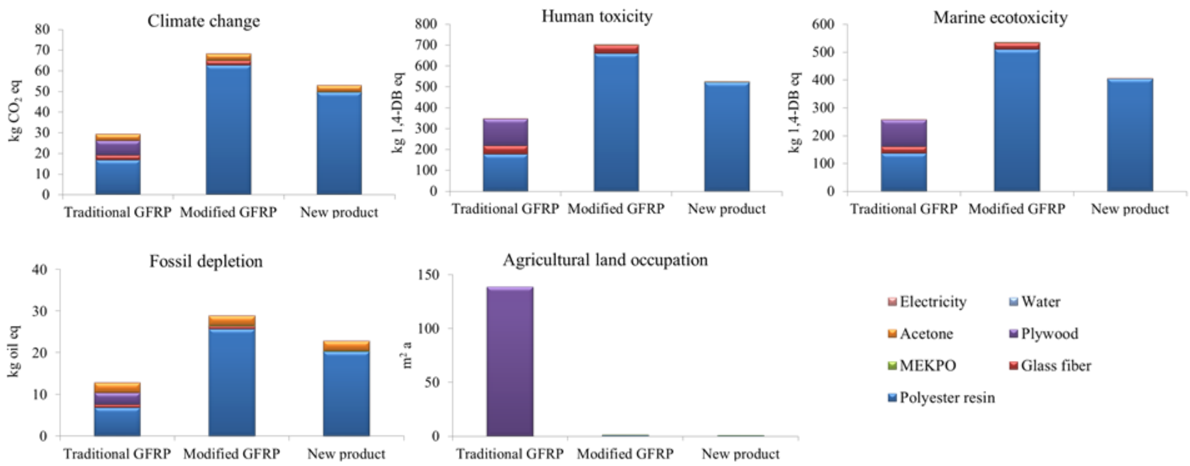

Fig. 3 Environmental impacts of traditional GFRP, modified GFRP and new product related to raw materials used for a 1x1 m^2 table top with 1 cm thickness

According to material selection guidelines for eco-compatible products [21], one recommendation here is to change most used chemicals to more environmentally friendly ones. In this case, based on the same production technique of GFRP manufacturing, two types of resin can be used in the process, namely, polyester resin and epoxy resin. When comparing the environmental impacts between polyester and epoxy resins, we found that epoxy resin has a much lower impact to human toxicity and marine ecotoxicity, around 80% while not differing much regarding climate change and fossil depletion impacts (see Fig. 4). However, after discussion with several manufacturers and suppliers in Thailand, polyester resin is still preferred over epoxy resin. Although epoxy resin has less toxicity, and can give a better property of products in terms of product strength, it costs more around twice compared with polyester resin. In addition, those manufacturers claimed that the properties of polyester resin were adequate for their customers' needs to produce GFRP products in terms of product strength and durability.

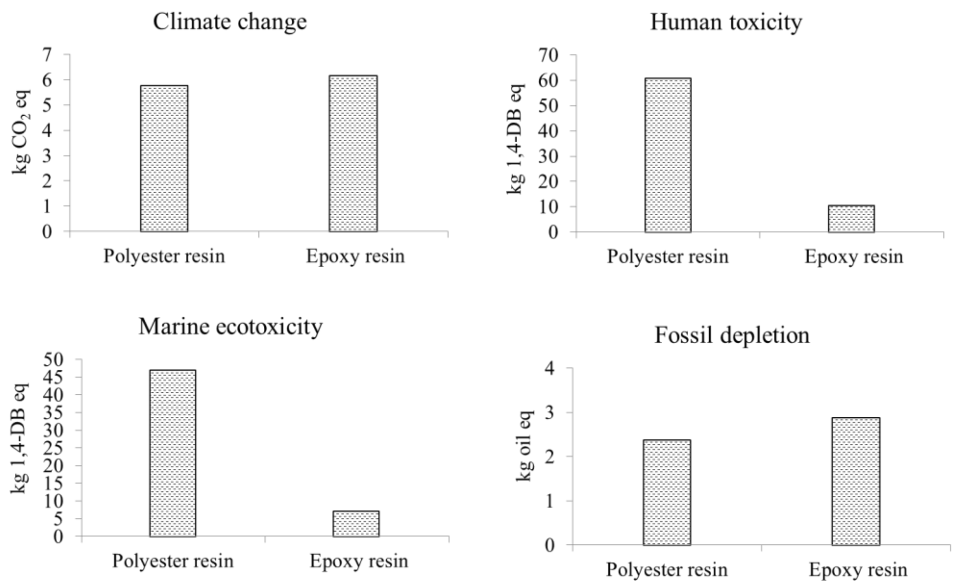

Fig. 4 Environmental impacts of 1 kilogram polyester resin compared with 1 kilogram epoxy resin

Finally, comparative environmental impacts of two recycled NMF products and conventional waste disposal methods by means of landfilling and incineration were conducted. As can be seen in Fig. 5, all options contribute to the five damage categories including climate change, human toxicity, marine ecotoxicity, fossil depletion and agricultural land occupation. Since plywood was not used as a raw material in the recycled products, no impact to the agricultural land occupation category was caused by the recycling options 3 and 4.

Looking at the climate change damage category, option 1 caused the worst impact when compared with other options. This could have resulted from the disposal process of landfilling, followed by the FRP production and the transportation between the waste generator and disposal site. In other words, landfilling is the most inappropriate method for this case in terms of climate change impact. Recycling option 3 shows the worst impact to human toxicity, marine ecotoxicity, and fossil depletion categories compared with other options (see Fig. 5). This is because recycled product 1 (option 3) required a more complicated production process by applying both traditional production method (hand lay-up technique) and casting NMF composite. Comparing between two recycling products (options 3 and 4), the new product option 4 had less impact on all damage categories.

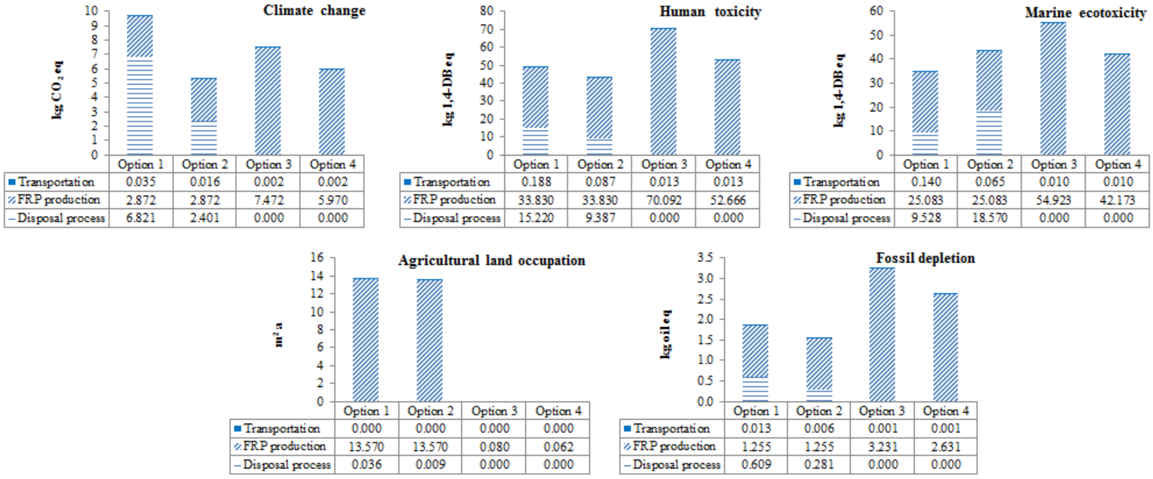

Fig.5 Environmental impacts of four waste management options for NMF from WPCB

4. CONCLUSION

After comparing our two recycled NMF products with the traditional GFRP product, it can be concluded that the highest impact values resulted from modified GFRP product (recycle product 1), followed by new product (recycled product 2) and traditional GFRP product. Although the recycling of NMF waste as new products shows higher environmental impacts than the traditional products, the traditional product contributes more damage categories than our recycled products. Among waste management options, it can be concluded that the potential environmental impacts were the damage categories of climate change, human toxicity, marine ecotoxicity and fossil depletion. For the overall comparison, because of a more complicated production technique and a chemical-based process, the recycled NMF as a modified GFRP product showed the worst impacts in human toxicity, marine ecotoxicity and fossil depletion categories compared with other methods. However, the manufacturers can help to reduce the toxicity of products by changing the raw material from polyester to epoxy resin. Thus, the recycling of NMF as a new product (recycled product 2) is likely to be the most suitable waste management option in Thailand.

5. ACKNOWLEDGEMENTS

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