EVALUATION OF ENVIRONMENTAL IMPACTS FOR NON-METALLIC PART IN WASTE PRINTED CIRCUIT BOARDS (PCBs) USING COMBINED MATERIAL FLOW ANALYSIS (MFA) AND LIFE CYCLE ASSESSMENT (LCA)

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Program:	Petrochemical Technology
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ABSTRACT

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Warisara Rungsitikul: Evaluation of Environmental Impacts for Non-Metallic Part in Waste Printed Circuit Boards (PCBs) using Combined Material Flow Analysis (MFA) and Life Cycle Assessment (LCA)

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Keywords: Life cycle assessment/ Material flow analysis/ Waste printed circuit boards/ Recycling/ Environmental impacts/ E-waste

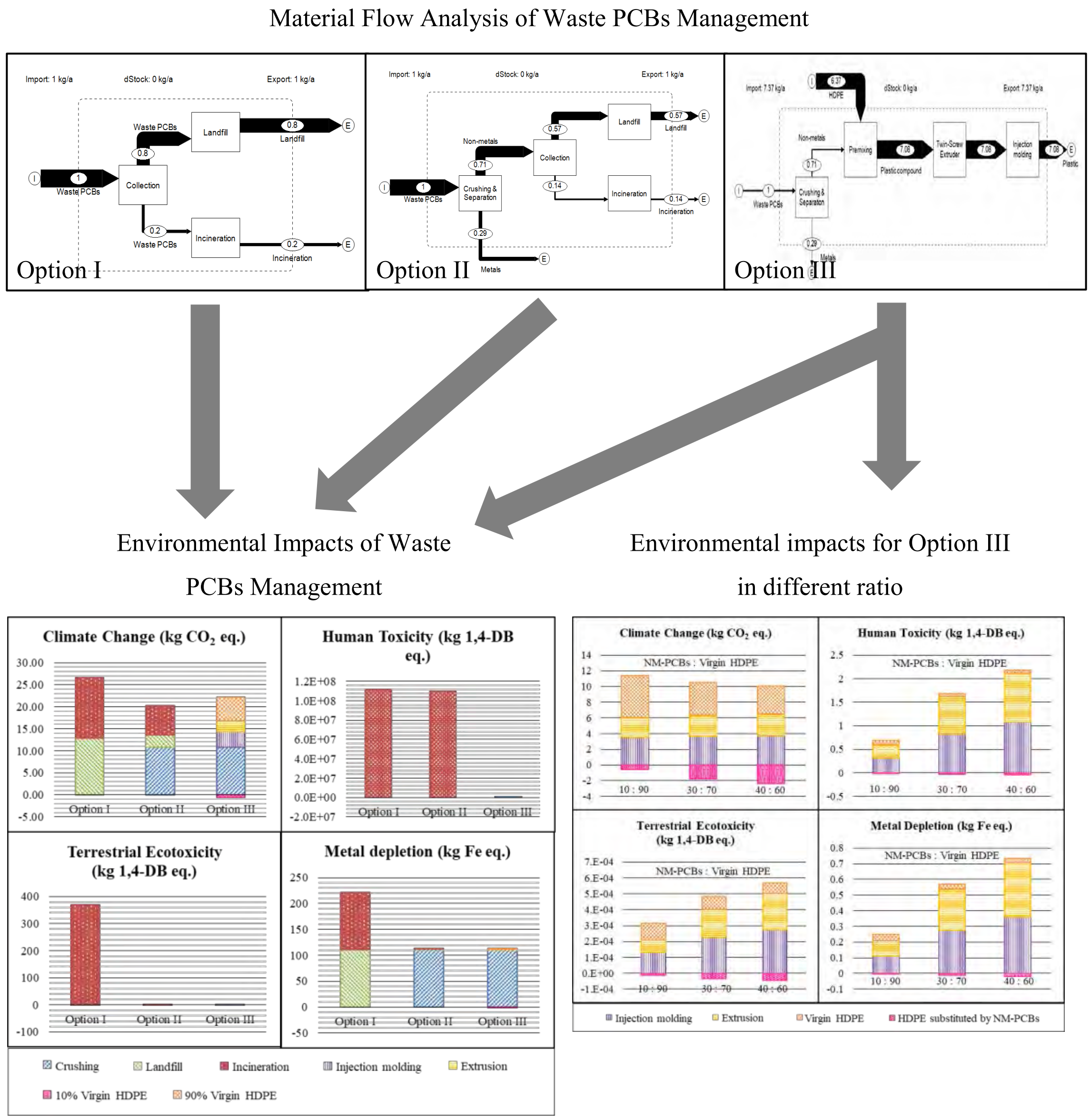
Printed circuit boards (PCBs) have become common components in most electric and electronic equipment. Because of their wide ranges of application, waste PCBs is becoming one of the most rapidly growing wastes. Recycling of waste PCBs is an important subject not only for the protection of the environment but also for the recovery of valuable metals. This study aimed to evaluate the waste PCBs management strategies using the combination of material flow analysis (MFA, STAN v.2.6.801) and life cycle assessment (LCA, SimaPro v.8.3.0.0) methods. The waste management scenario was considered for three different options; disposal of the waste PCBs (Option 1), separation as metallic and non-metallic parts before final disposal of the waste PCBs (Option 2) and recycling non-metallic parts of the waste PCBs (NM-PCBs) as a filler additive in HPDE compounded plastic (Option 3). From MFA results, PCBs can be separated into 71 wt.% of NM-PCBs and 29 wt.%. For climate change impact, the results demonstrated that the least impact value was the recycling the NM-PCBs (Option III) about 21.63 kg CO_2-eq which lower than disposal to landfill and incineration (Option I) about 26.59 kg CO_2-eq. The recycling of NM-PCBs as the substitute material for the production of recycling plastic supported a better environment in terms of climate change (kg CO_2-eq), human toxicity (kg 1,4-DB-eq.), terrestrial ecotoxicity (kg 1,4-DB-eq.) and metal depletion (kg Fe-eq). The ratio of NM-PCBs in virgin HDPE had a linear effect on the environmental impacts. Furthermore, the combination of MFA and LCA methods suitable for a powerful assessment of impact which supporting management of waste PCBs.

บทคัดย่อ

วริศรา รุ้งสิทธิกุล : การประเมินผลกระทบต่อสิ่งแวดล้อมของส่วนประกอบที่ไม่ใช่โลหะจากซากแผ่นวงจรอิเล็กทรอนิกส์ด้วยการวิเคราะห์การไหลของวัสดุและการประเมินวัฏจักรชีวิต (Evaluation of Environmental Impacts for Non-Metallic Part in Waste Printed Circuit Boards (PCBs) using Combined Material Flow Analysis (MFA) and Life Cycle Assessment (LCA)) อ. ที่ปรึกษา : ดร. อัมพิรา เจริญแสง และ ผศ. ดร. มานิตย์ นิธิธนากุล 79 หน้า

แผ่นวงจรอิเล็กทรอนิกส์ เป็นส่วนประกอบทั่วไปที่พบเจอในผลิตภัณฑ์เครื่องใช้ไฟฟ้าและอิเล็กทรอนิกส์ เนื่องจากแผ่นวงจรอิเล็กทรอนิกส์มีการใช้งานที่หลากหลายจึงทำให้เป็นหนึ่งในขยะที่มีปริมาณการเติบโตสูง ดังนั้นแผ่นวงจรอิเล็กทรอนิกส์ควรมีการจัดการอย่างถูกต้อง โดยการรีไซเคิลซากแผ่นวงจรอิเล็กทรอนิกส์ถือเป็นทางเลือกหนึ่ง ซึ่งไม่เพียงแต่จะเป็นการปกป้องสิ่งแวดล้อมแต่ยังสามารถนำโลหะกลับมาใช้ประโยชน์ใหม่ โดยการศึกษานี้มีวัตถุประสงค์เพื่อประเมินกลยุทธ์การจัดการซากแผ่นวงจรอิเล็กทรอนิกส์ด้วยการวิเคราะห์การไหลของวัสดุ (Material Flow Analysis: MFA, STAN v.2.6.801) และการประเมินวัฏจักรชีวิต (Life Cycle Assessment: LCA, SimaPro v.8.3.0.0) เป็นเครื่องมือในการประเมินผลกระทบต่อสิ่งแวดล้อม กระบวนการจัดการของเสีย คือ การกำจัดซากแผ่นวงจรอิเล็กทรอนิกส์ (วิธีที่ 1) การแยกซากแผ่นวงจรอิเล็กทรอนิกส์เป็นส่วนประกอบที่เป็นโลหะและส่วนประกอบที่ไม่ใช่โลหก่อนนำไปกำจัด (วิธีที่ 2) การรีไซเคิลส่วนประกอบที่ไม่ใช่โลหะของซากแผ่นวงจรอิเล็กทรอนิกส์โดยใช้เป็นสารเติมแต่งในกระบวนการผลิตพลาสติกด้วยพอลิเอทิลีนความหนาแน่นสูง (วิธีที่ 3) จากการวิเคราะห์การไหลของวัสดุแผ่นวงจรอิเล็กทรอนิกส์สามารถแยกออกมาเป็นส่วนประกอบที่ไม่ใช่โลหะ 71% และส่วนประกอบที่เป็นโลหะ 29% โดยน้ำหนัก สำหรับผลกระทบต่อการเปลี่ยนแปลงภูมิอากาศ การรีไซเคิลส่วนประกอบที่ไม่ใช่โลหะของซากแผ่นวงจรอิเล็กทรอนิกส์ (วิธีที่ 3) ให้ผลกระทบที่น้อยที่สุด มีค่าเป็น 21.63 kg CO_2-eq ซึ่งน้อยกว่าการนำไปกำจัดด้วยการฝังกลบและการเผา (วิธีที่ 1) ซึ่งมีค่าเป็น 26.59 kg CO_2-eq การรีไซเคิลส่วนประกอบที่ไม่ใช่โลหะของซากแผ่นวงจรอิเล็กทรอนิกส์ที่ใช้ทดแทนพอลิเอทิลีนความหนาแน่นสูงในการผลิตพลาสติกจะช่วยสนับสนุนสิ่งแวดล้อมให้ดีขึ้น โดยอัตราส่วนของส่วนประกอบที่ไม่ใช่โลหะต่อพอลิเอทิลีนความหนาแน่นสูงมีผลกระทบเชิงเส้นต่อสิ่งแวดล้อม นอกจากนี้วิธีการวิเคราะห์การไหลของวัสดุและการประเมินวัฏจักรชีวิตมีความเหมาะสมต่อการประเมินผลกระทบที่มีต่อสิ่งแวดล้อมซึ่งสนับสนุนต่อการจัดการซากแผ่นวงจรอิเล็กทรอนิกส์

GRAPHICAL ABSTRACT



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CHAPTER I
INTRODUCTION

1.1 Introduction

Electronic waste (E-waste) is a term of electronic products which have become un-used, non-working or outmoded. In Thailand, E-waste is becoming one of the fastest-growing waste and has been disposed to incineration or landfill which has been increased the environmental impact. Recycling of electronic products for reuse of metals and nonmetals is one of the ways to manage e-waste which reduce the impacts on the environment, the use of natural sources and solving the global warming problem. It is important to be a source of renewable sources and to ensure the future of raw materials in industrial.

E-waste is generated from several discarded electronics such as computers, televisions, mobile phones, microwave and refrigerators. They mostly contain a common component, known as printed circuit boards (PCBs). These PCBs are composed of both precious metals (e.g., Cu, Fe, Au, Ag, Pt, Pd) and non-metals (e.g., thermosetting resins, glass fibers, brominated flame retardants) which are proportionately weighted about 3-5% of electrical appliances. PCBs contain about 20-30% metallic and 70% of non-metallic (Huang *et al.*, 2009). Waste PCBs can be considered as an urban mineral resource for the recovery of various metals. As a result, the recycling of PCB is a requirement of the domestic and international recycling industry.

The recycling of e-waste plastics can be more complicated compared to plastics from other sources due to the presence of brominated flame retardants (BFRs) (Sahajwalla & Gaikwad, 2018). BFRs are added to a wide variety of products to make them less flammable. They are commonly used in plastics, textiles, electrical and electronic equipment. They require safe handling and recycling because have high toxic that can affect both human and environment (Ma *et al.*, 2016).

Recycling PCBs begins with the separation of precious metals which the amount of these metals depends on the type of electrical appliances. In Thailand, PCBs is separated by manual separation for disassembling the IC pieces and various plastics

(Lee *et al*.,2012). PCBs go through the mechanical process, which crushes into a smaller size or use as a shaking table that operates based on the difference in density between metals and a circuit board or non-metals. The primary product acquired are metals such as copper and non-metal parts.

Non-metallic part of the waste PCBs refers to a residue produced by separating the copper and other precious metal materials from the waste PCBs through physical and chemical methods (Song *et al*.,2016). As the non-metallic part containing few quantities of heavy metals, the landfill may cause potential threats to the environment and security for the leachate that would penetrate to groundwater (Song *et al*.,2016). For incineration, non-metallic material contains a large number of low calorific value composites, such as glass fibers and other inorganic constituents. it may produce large amounts of dioxins and other carcinogens, causing severe environmental contamination (Song *et al*., 2016). Therefore, the recycling of waste PCBs should be attention to protect the environment and increase the value of materials. In this study, the non-metallic part of waste PCBs was utilized as an additive for compounded plastic made by crushing and mixing with virgin high-density polyethylene (HDPE) to form compounded plastic by injection molding.

The purpose of this study is to evaluate the waste flow and environmental impacts for the non-metallic part of waste PCBs by the combination of material flow analysis (MFA) and life cycle assessment (LCA) methods to use as a tool. The scenarios were considered including disposal of the waste PCBs to incineration and landfill (Option I), separation as metallic and non-metallic parts before disposal of the waste PCBs (Option II) and recycling non-metallic parts of waste PCBs as filler in HDPE (Option III). The amount of waste PCBs was analyzed at both goods and substances (Cu, Fe) and identified according to their properties and treatment options. This study compares the appropriate routes among three options based on the environmental impacts such as climate change, human toxicity, terrestrial ecotoxicity, and metal depletion. The results of this study show the waste flow and their impacts on the environment for the three waste PCBs management scenarios.

1.2 Objectives

- To study the material flow analysis (MFA) and life cycle assessment (LCA) of the waste PCBs for the non-metallic parts using STAN (v.2.6.801) and SimaPro (v.8.3.0.0) software, respectively.
- To study the physical recycling the non-metallic of waste PCBs as a filler for the compounded plastic.
- To apply MFA at both goods and substances level to estimate the amount of the non-metallic component of the waste PCBs.
- To analyze environmental impacts including climate change, human toxicity, terrestrial ecotoxicity and metal depletion of the waste PCBs at each scenario.
- To compare the waste treatment options that would be an appropriate scenario for waste treatment of PCBs.

CHAPTER II

LITERATURE REVIEW

The disposal of PCBs process generated many of wastes which have both metal and plastic parts. The mismanagement of these wastes can cause adverse effects to the environment, human and animals due to the plenty of toxic materials in PCBs such as heavy metal and BFRs. The recycling of waste PCBs is an important subject not only for the protection of the environment but also for the recovery of valuable materials. The most widely used tools to manage the wastes are material flow analysis (MFA) and life cycle assessment (LCA). MFA is an analytical tool of systematic assessment of flows and materials within a complex system which used to manage the waste route of each scenario. Furthermore, the environmental impacts were evaluated using LCA method.

2.1 Printed Circuit Boards (PCBs)

The printed circuit boards (PCBs) are essential parts of electric and electronic equipment which provides the basic platform to connect different electronic components, including resistors, relays capacitors, diodes, microchips, and other integrated circuits, in a rigid manner. PCBs are used in motherboards, random access memory (RAM), and network interface cards. Similarly, other uses include other consumer electronics, such as TVs, digital cameras, and MP3 players. On the other hand, PCBs are also used in high-end commercial electronic equipment, such as aerospace, electronic defense products, healthcare equipment, and communication routers (Awasthi *et al*., 2017).

PCBs waste can contain up to 60 elements (Szałatkiewicz, 2014), some of which are valuable and some hazardous. This variety of elements can be classified into three groups: metals, inorganic, and organic. 30 wt.% of the PCB are metal elements. The rest are 37 wt.% of inorganic filler and 31 wt.% of organic substances as shown in Table 2.1.

Table 2.1 Composition of PCBs from discarded personal computer (Szałatkiewicz, 2013)

Material	Element	Concentration (mass %)	Total (mass %)
Organic Epoxy resin	C	18.1	31.8
	H	1.8	
	N	0.32	
	O	6.03	
	Br	5.07	
	Sb	0.45	
Inorganic Glass fiber	SiO_2	24.7	37.6
	Al_2O_3	9.35	
	CaO	3.36	
	MgO	0.081	
	BaO	0.0022	
	NaO	0.09	
	SrO	0.035	
Metal Circuit Solder	Cu	14.6	30.1
	Sn	5.62	
	Pb	2.96	
Lead Frame	Fe	4.79	
	Ni	1.65	
	Cr	0.356	
	Mo	0.016	
Contacts	Ag	0.045	
	Au	0.0205	
	Pd	0.022	

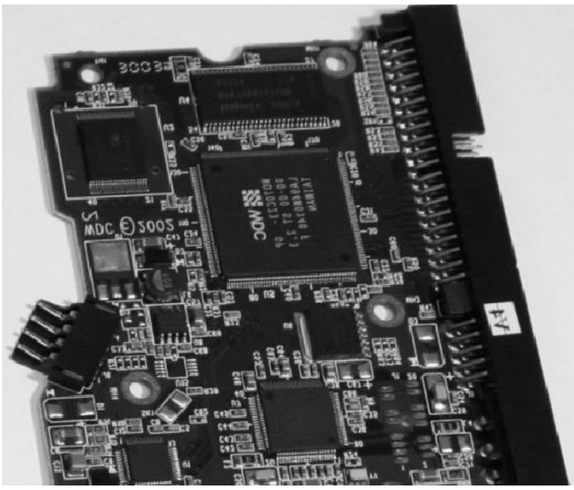


Figure 2.1 Example of an electronic printed circuit board (from a hard disk drive) (Szałatkiewicz, 2014).

There are two main approaches for PCBs treatment and metal recovery: mechanical processing and chemical processing. The mechanical approach in Figure 2.2 which includes: dry crushing, pulverizing followed by high voltage electrostatic separation to get a mixture of metal powder (silver, aluminium, gold, copper, lead, zinc and tin).

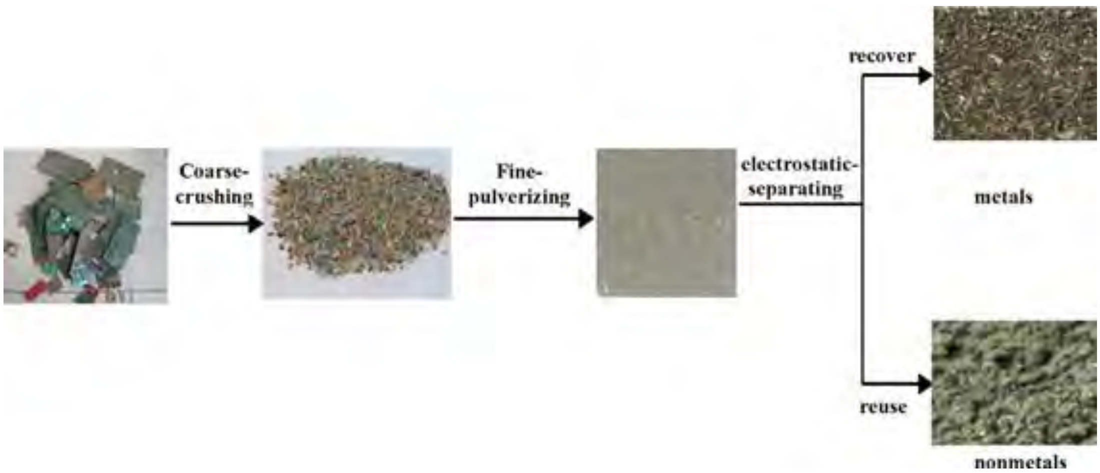


Figure 2.2 Separation of a printed circuit board (Huang *et al*., 2009).

Waste printed circuit boards (WPCBs) is a topic that has been widely discussed about the recycling process, including pre-treatment and metal recovery. PCBs are separated from WEEE in pre-processing steps, with the application of two main technologies: the manual dismantling of devices or mechanical treatment and chemical treatment (Awasthi *et al*., 2017). The inappropriate dismantling process is not a promising recycling method for the WPCBs; however, its recycling efficiency is low efficiency and causes negative impacts on the environment and human health. Another way of processing waste of printed circuited boards is the chemical treatment which has been well established in terms of scientific research on a laboratory scale. However, this work seeks an environmentally friendly process through heating with a water-soluble ionic liquid (IL) to separate electronic components and tin solder from WPCBs of computers (Awasthi *et al*., 2017). Guo and co-workers (2015) investigated that, the efficient alkali fusion leaching is a separation process to recover metals in crushed metal enrichment, which originated from WPCBs.

2.1.1 Resource Utilization of Non-Metallic Materials

There are also about 70 wt.% non-metallic materials after separation (Guo *et al*., 2009). The non-metallic materials of PCBs (NM-PCBs) mainly consist of thermoset resins and glass fibers. Thermoset resins cannot be remelted or reformed because of their network structure (Guo *et al*., 2009). Incineration is not the best method for treating non-metallic materials because of inorganic fillers such as glass fiber which significantly reduces fuel efficiency. Disposal in a landfill is the method for treating non-metallic materials of PCBs, but it may cause secondary pollution and resource-wasting. In order to take full advantage of non-metallic materials of waste PCBs, non-metallic materials were used to produce modified phenolic molding compound (PMC) and non-metallic plate (NMP), achieving complete recovery of reusable resources (Huang *et al*., 2009). Non-metallic materials were used to replace wood flour in the production of modified PMC as shown in Figure 2.3. This process can protect timber resources and reduce the cost of PMC. The filling of non-metallic materials in PMC improved the impact strength and heat deflection temperature

(HDT), reduce flexural strength and ranch fluidity. Ranch fluidity reduces dramatically with the increase of the content of non-metallic materials (Huang *et al*., 2009).

Figure 2.3 The specimens of PMC (Huang *et al.,* 2009).

2.1.2 Physical Recycling of Non-Metallic Fractions from Waste PCBs

Non-metallic materials of PCBs (NM-PCBs) consist of plastics include resin, filler and addition agents (Guo *et al*., 2009). Plastics classified into thermoplastic and thermoset. In general, the fillers for polymers have two functions; one is to reduce the cost of the products, and the other one is to enhance the performance of the products. Sometimes, the properties of filler are crucial to the performance of the polymer products. Therefore, how to take advantage of filler for polymer products is a significant topic. The thermosetting resins, glass fiber, ceramics, and residual metals contained in the NM-PCBs as fillers for thermosetting resin and thermoplastic resin composites considering physical recycling methods.

Concrete is a versatile and most popular construction material. The NM-PCBs can use with some effectiveness as a partial replacement of inorganic aggregates in concrete applications to enhance the engineering properties of concrete such as strength, durability, shrinkage and permeability (Guo *et al*., 2009).

Viscoelasticity is the property of materials that exhibit both viscous and elastic characteristics when undergoing deformation. Viscoelasticity is the result of the diffusion of atoms or molecules inside of an amorphous material. Viscoelasticity materials include amorphous polymers, semicrystalline polymers, asphalt materials, etc. The glass fibers and resins contained in the NM-PCBs can enhance viscoelastic materials by composition effect to improve the temperature susceptibility (Guo *et al.*, 2009).

The advantages of physical recycling methods are relatively simple, convenient, and environmentally sound, low equipment invests, and low energy cost and highly potential of products (Guo *et al.*, 2009).

Nithitanakul and co-workers (2017) from Excellence on Hazardous Substance Management (HSM) developed the project under the utilization of the recycling of waste PCBs. The method was conducted by mixed the NM-PCBs as a filler with virgin HDPE and recycled HDPE at different ratio (10:90, 20:80, 30:70, and 40:60) to produce compounded plastic resin. The mixture of NM-PCBs and HDPE was transferred into an extrusion and injection molding process to form the compounded plastic resin. After that, the product was tested the mechanical properties including melt flow index (MFI), tensile testing, flexural testing, impact testing and morphology. From the experiment of compounded the NM-PCBs with virgin HDPE/recycled HDPE, the additive of NM-PCBs caused some properties to change. For example, the additive of NM-PCBs had an effect on an increase of tensile testing and bending testing but the reduction in the flexibility of the product make the test sample fragile. Furthermore, 20% of adding NM-PCBs represented the maximum of elongation. Therefore, the application of NM-PCBs for forming into the product can mix up to 20% which elongation of this product was better than the virgin HDPE product. For the virgin HDPE and recycled HDPE, these results showed that the test of recycled HDPE corresponded to the virgin HDPE. The recycled HDPE can be substituted the virgin HDPE. The selection of HDPE and the proportion of NM-PCBs depended on the product or workpiece that needed to be mold.

NM-PCBs were analyzed by X-ray fluorescence spectrometry analysis (XRF) to determine the element concentration (Nithitanakul *et al.*, 2017). Table 2.2 shows the composition of NM-PCBs.

Table 2.2 The composition of NM-PCBs by XRF technology (Nithitanakul et al., 2017)

Element	Concentration (mass %)	Element	Concentration (mass %)
Silica	19.18	Sulfur	0.39
Calcium	15.80	Titanium	0.32
Aluminium	10.00	Iron	0.24
Bromine	6.75	Strontium	0.15
Barium	2.15	Chlorine	0.13
Phosphorus	1.51	Sodium	0.10
Copper	1.28	Potassium	0.059
Magnesium	0.82	Zinc	0.0055

2.1.3 Chemical Recycling of Non-Metallic Fractions from Waste PCBs

Chemical recycling is to decompose the waste polymers into their monomers or some useful chemicals by means of chemical reactions. The chemical recycling of NM-PCBs is the process which is the separation of the NM-PCBs and M-PCBs and the upgrading of the products. There are four ways to recycle the NM-PCBs by chemical method, which are pyrolysis, gasification, supercritical fluid depolymerization and hydrogenolytic degradation (Guo *et al*., 2009). Pyrolysis process has been widely researched as a method of recycling synthetic polymers because it leads to the formation of gases, oils, and chars which can be used as chemical feedstocks or fuel. For gasification process, NM-PCBs containing brominated flame retardants can be achieved to prevent the generation of brominated dioxins and to prevent the regeneration of brominated dioxins. A super critical fluid is any substance at a temperature and pressure above its thermodynamic critical point. It converts the polymers contained in the NM-PCBs into monomers, but there are several challenges, such as choosing proper supercritical fluids and additives, cost of energy and equipment investment controlling. Furthermore, hydrogenolytic degradation is an innovative recycling technique for feedstock recycling of thermosetting resins, although there is little reported study on recycling the NM-PCBs by hydrogenolytic degradation in available documents (Guo *et al*., 2009).

The main purpose of chemical recycling methods is to convert the polymers contained in NM-PCBs to chemical feedstocks or fuels. Compared with physical recycling methods, chemical recycling methods have the advantages of converting BFRs to monomers and taking out the heavy metals left (Guo *et al*., 2009). Therefore, the trend of the chemical recycling for NM-PCBs is to make the best of advantages over physical recycling to compensate for the higher cost of chemical recycling methods.

2.2 Material Flow Analysis (MFA)

Material flow analysis (MFA) is a tool to systematically analyze the flows and stocks of materials within a system defined in space and time (Cencic, 2016). It is concerned with gathering, harmonizing, and analyzing data about physical flows and stocks from different sources with varying qualities to gain an understanding of the stocks and flows of materials in the investigated system. In MFA the term “substance” is defined, like in chemistry, as a single type of stuff consisting of uniform units. If the units are atoms, the substance is called “element,” such as carbon or iron; if they are molecules, it is called “chemical compound,” such as carbon dioxide or iron chloride. A substance is designated “conservative” when it is not destroyed or transformed in a process or by any event during its life cycle. The term “good” describes merchandise and wares. It is mostly used as a plural, “goods,” and describes an economic entity of stuff with economic value. There are only a few goods that have no economic value, e.g., rainwater, or a negative value, e.g., waste. Goods are made up of one or several substances. The economic turnover of goods is usually reported in all kinds of statistics, and their production figures are mostly known, as they are of economic relevance. Such information is a prerequisite for establishing material budgets. “Material” serves as an umbrella term for both substances and goods (Finkbeiner, 2016).

MFA consists of several steps that have slightly changed since the employment of MFA software facilitating the application of error propagation and data reconciliation. (Laner *et al.*, 2016)

A process is defined as transport, transformation, or storage of materials. The transport process can be a natural process, or it can be man-made. A stock is defined as a material reservoir and is allocated to a process comprising the mass of materials that are stored within the process. It can stay constant (steady state), or it can increase (accumulation of materials) or decrease (depletion of materials). Processes are linked by the flow of materials. Flows entering or leaving the system are called import or export and flows entering or leaving a process are called inputs and outputs (Finkbeiner, 2016).

The system is the actual object of any MFA investigation. A system is defined by a group of MFA elements (processes, flows, etc.), the interaction between them, and the boundaries between these and other elements in space and time. An open system interacts with its surroundings. It has either material or energy imports and exports or both, while a closed system is conceived as a system in complete isolation, preventing material and energy flows across the system boundary. Everything within the system is part of the investigation. Everything outside the system should not be considered. Therefore, the golden rule is to keep the system as small and simple as possible, still conveying a reliable and valid result (Finkbeiner, 2016).

2.2.1 Selection of System Boundaries

The spatial system boundary is usually determined by the scope of the study. It coincides often with a politically defined region, the premises of a company, or a hydrologically defined region such as the catchment area of a river. The temporal system boundary is most often a year because many data are reported in this time resolution, and the yearly basis helps to outweigh momentary unsteadiness of flows. If smaller objects such as technology or factory are studied, shorter system boundaries from hours to days might be adequate (Finkbeiner, 2016).

2.2.2 Selection of Flows and Material

The number of processes necessary to describe the system depends on the objective of the study and the complexity of the system. Generally, processes can be divided into subprocesses, so that handy systems of the maximally 10-15 process can be realized. The selection of processes is a result of the course of understanding the system. The flow of goods is determined by the inputs and outputs of the processes (Finkbeiner, 2016).

Tran and co-workers (2018) studied the material flow analysis (MFA) for management of waste televisions (TVs) from households in urban areas of Vietnam. They applied MFA at both goods and substance level to support e-waste management in Vietnam. TVs were selected as the study object because they are the most common and affordable home appliance in Vietnam. This analysis of MFA is applied in a three-step analysis. First, TV life cycle is qualitatively investigated to identify all related processes and flows. Second, MFA is used to analyze the life cycle of TV supply, consumption and discarding to estimate the number of obsolete TVs from households in the urban area. Third, MFA is used to quantitatively analyze the flows of obsolete TVs and their materials in the waste management system. The substance flows were determined based on the flows of (waste) TVs and the substance concentration in TVs. The analysis was conducted for six main substances, that is glass, plastic, Cu, Fe and steel, Al and precious metals (Au, Ag, Pd).

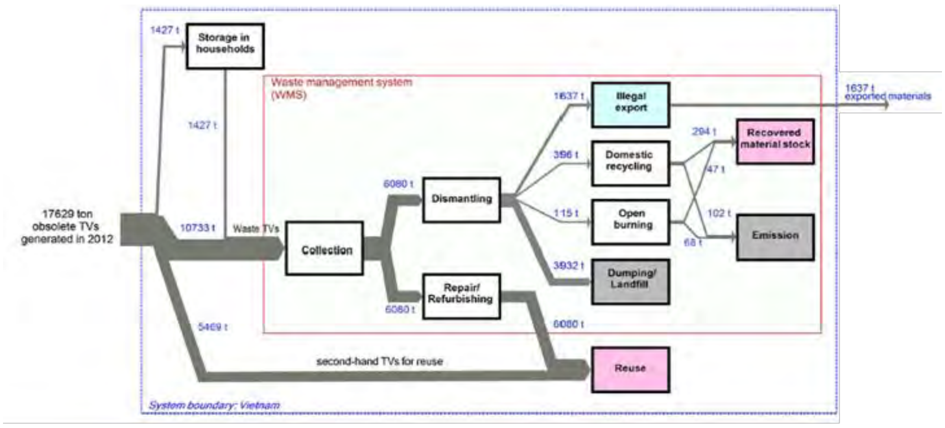


Figure 2.4 MFA for obsolete TVs generated from households in urban areas in Vietnam in 2012.

From Figure 2.4, it was estimated that the amount of obsolete TVs generated in 2012 was 634 (±32) thousand TVs, equivalent to 17,629 (±889) t TVs. The flows of obsolete TVs in the current e-waste management system showed that about 66% of them finally returned to the market via direct reuse or after repair/refurbishing. Among the rest, about 3% was sent to domestic recycling or open burning for material recovery, 9% was illegally exported for material recovery and 22% finally ended up in open dumping sites. The MFA of the six main substances (i.e., copper, aluminum, ferrous and steel, precious metals, plastics and glass) showed that about 76% of the base metals contained in obsolete TVs was reused in second-hand TVs or domestically recycled. This study can be considered as a demonstration example of MFA application in supporting e-waste management in Vietnam. The results showed that MFA is a simple, but efficient management tool, which can provide transparent and systematic analysis.

2.3 Life Cycle Assessment (LCA)

The life cycle assessment (LCA) is a process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment to assess the impact of those energy and materials used and releases to the environment and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing, extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal (Khasreen *et al*., 2009).

The standardized LCA process based on ISO 14040 and consists of four distinct analytical steps: defining the goal and scope, creating the life-cycle inventory, assessing the impact and finally interpreting the results (Khasreen *et al*., 2009).

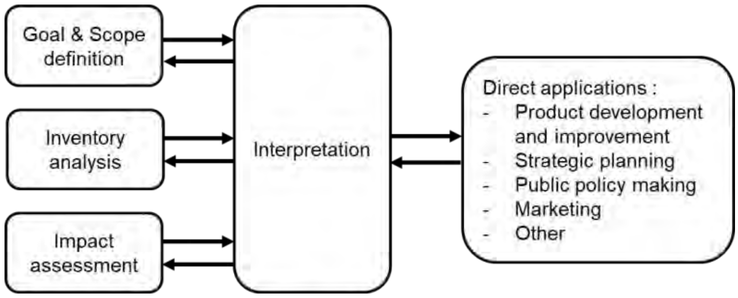


Figure 2.5 Illustration of life cycle assessment procedure (Hoogervorst *et al*., 2004).

2.3.1 Goal definition and Scoping

The goal and scope definition phase is the first step in the LCA study. In this phase, the purpose of the study is described. This description includes the intended application and audience, and the reasons for carrying out the study. Furthermore, the scope of the study is described. This includes a description of the limitations of the study, the functions of the systems investigated, the functional unit, the systems investigated, the system boundaries, the allocation approaches, the data requirements, data quality requirements, the key assumptions, the impact assessment method, the interpretation method, and the type of reporting (Hoogervorst *et al*, 2004).

2.3.2 Inventory Analysis

In the Life Cycle Inventory (LCI) analysis, data are collected and interpreted, calculations are made, and the inventory results are calculated and presented. The analysis results in a flow model of the technical system (Hoogervorst *et al*, 2004).

Emissions, energy requirements and material flows are calculated for each process. These data will then be adapted and weighted to the functional unit, which is defined in the goal and scope so that the whole life cycle of the product can be considered (Hoogervorst *et al*, 2004).

2.3.3 Impact Assessment

In the Life Cycle Impact Assessment (LCIA), the product or production system is examined from an environmental perspective using category indicators. The LCIA also provides information for the interpretation phase (Hoogervorst *et al*, 2004).

For comparative assertions, there are four mandatory elements of LCIA

- selection of impact categories, category indicators and models
- assignment of the LCIA results (classification)
- calculation of category indicator results (characterization)
- data quality analysis.

2.3.4 Interpretation

The final phase of LCA is interpretation. The purpose of this is to analyze results, reach conclusions, explain limitations and provide recommendations based on the findings of the preceding phases of the LCA or LCI study and to report the results of the life-cycle interpretation in a transparent manner. Life-cycle interpretation is also intended to provide a readily understandable, complete and consistent presentation of the results of an LCA or an LCI study, in accordance with the goal and scope definition of the study (Khasreen *et al*., 2009).

The life cycle analysis also presents three variants, depending on the phases of the life cycle that are studied; cradle to grave; cradle to gate and cradle to cradle. An analysis cradle to grave includes the entire life cycle of a product, from the extraction of raw materials ("cradle") to the deposition phase ("grave"), passing through the use phase. In an analysis cradle to gate, it is only considered a part of the life cycle of the product, the one that goes from the extraction ("cradle") to the factory gate, i.e. encompasses prior to their transportation to the final consumer. The use phase and the deposition of a product are generally omitted. The analysis cradle to cradle is a variant of the analysis cradle to grave, in which the last stage of the life cycle of a product is a recycling process.

Hou and co-workers (2018) studied the life cycle assessment (LCA) of end-of-life treatments for plastic film waste. They used LCA to assess the environmental impacts of various plastic film waste treatment system. Mixed waste is collected by trucks and sent to either a landfill site, incineration for energy recovery, or a material recovery facility (MRF) for recycling. For recyclable waste is either collected by trucks or dropped off by a consumer to specific collection sites and then transported to MRF for recycling. They considered four different waste treatment scenarios: landfill disposal of plastic films in the mixed waste, incineration of plastic films in mixed waste, recycling of plastic films in mixed waste and recycling of plastic films in recyclable waste. The results demonstrate a considerable advantage of recycling over landfill disposal or incineration. The main environmental benefit is from the recycling of plastics that can substitute for the production of plastics from virgin materials.

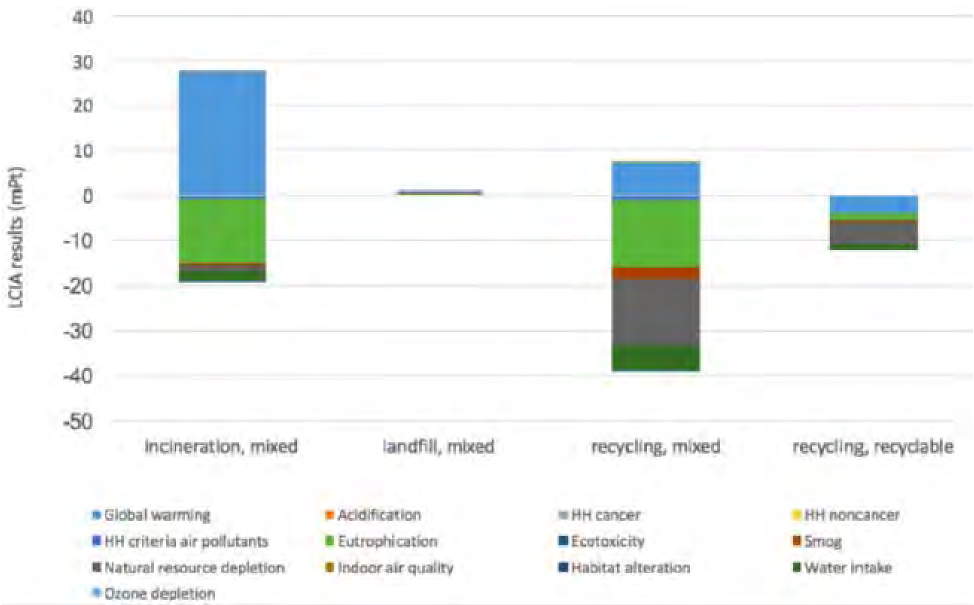


Figure 2.6 Environmental impacts of different plastic film end-of-life treatment scenarios.

For the combination of MFA and LCA, Sevigne-Itoiz and co-workers (2015) studied the contribution of plastic waste recovery to greenhouse gas (GHG) savings in Spain. They concentrated on the quantification of greenhouse gas (GHG) emissions of post-consumer plastic waste recovery (material or energy) by considering the influence of the plastic waste quality, the recycled plastic application and the markets of recovered plastic. The aim was to quantify the environmental consequences of different alternatives in order to evaluate opportunities and limitations to decrease GHG emissions. The methodologies of material flow analysis (MFA) for a time period of thirteen years and consequential life cycle assessment (CLCA) had been integrated. The results showed that to improve resource efficiency and avoid more GHG emissions, the options for plastic waste management were dependent on the quality of the recovered plastic. The results also showed that there was an increasing trend of exporting plastic waste for recycling, mainly to China, that reduces the GHG benefits from recycling, suggesting that a new focus should be introduced to take into account the split between local recycling and exporting.

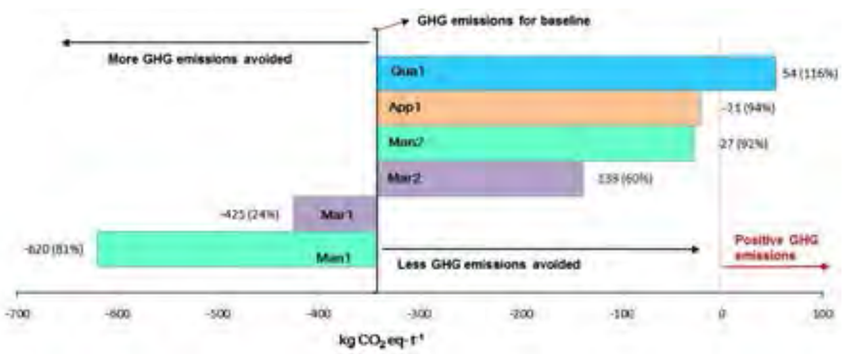


Figure 2.7 GHG emissions for all alternative scenarios (kg CO_2 eq. t^{-1}).

CHAPTER III

EXPERIMENTAL

3.1 Scope of Research

The scope of this research aimed to investigate the environmental impacts from three different options with the scenarios on the utilize of non-metallic part PCBs waste (NM-PCBs). The details are as following;

1. The data of waste PCBs composition including metallic and non-metallic parts were obtained from primary and secondary data sources.
2. The treatment process of the non-metallic part in waste PCBs was used as a filler for producing compounded plastic resin by the injection molding process.
3. The elements of waste PCBs for MFA which is conducted in this study included the substance level comprising of Cu and Fe.
4. The waste PCBs treatment is classified into three scenarios.
    a. The waste PCBs was disposed of by incineration and landfill.
    b. Separation of the waste PCBs was divided into metallic and non-metallic parts before disposed of by incineration and landfilling process.
    c. Recycling of non-metallic PCBs waste (NM-PCBs) was designed as a filler for plastic resin production.
5. The material flow analysis for the waste PCBs management was calculated by STAN (v.2.6.801).
    a. The amount of waste PCBs was defined as 1 kg.
    b. The metal component was separated from the waste PCBs by crushing process for recycling.
    c. The disposal of for the non-metallic of waste PCBs was assumed to be 80% landfilling and 20% incineration (Sattel, 2016).
    d. The raw materials to produce plastic resin was 90% of HDPE virgin and 10% of non-metallic of waste PCBs (base on the appropriate result obtained from the previous pilot study of recycling of waste printed

circuit boards development project (non-metallic part) (Center of Excellence on Hazardous Substance Management, 2017).

6. The environmental impacts for the waste PCBs management were evaluated by SimaPro v.8.3.0.0
    a. The function unit was set to be 1 kg of the waste PCBs.
    b. The four significant impacts were selected to study, including climate change (kg CO_2-eq), human toxicity (kg 1,4-DB-eq.), terrestrial ecotoxicity (kg 1,4-DB-eq.) and metal depletion (kg Fe-eq).
    c. The results were analyzed by the European, ReCiPe midpoint method with Hierarchist version (developed by RIVM, CML, Pre Consultants, Radboud University Nijmegen and CE DelftC, 2016).

3.2 Equipment

Software:

1. SimaPro (v.8.3.0.0)
2. STAN (v.2.6.801)
3. Microsoft Office 2017 (Excel)

3.3 Methodology

3.3.1 Define the Goal and Scope to Calculate the Material Flow Analysis (MFA) of the Waste PCBs Using STAN (v.2.6.801)

a. Set the scope and system boundaries of the waste PCBs process.
b. Collect the input and output data including the composition of the waste PCBs, the disposal and recycle of the waste PCBs process, and other data that involves with objective and system boundary.
c. Calculate and compare the mass balance of waste flow at both goods and substances for each scenario using STAN program.

3.3.2 Study the Environmental and Human Health Impacts with the Life Cycle Assessment (LCA) Procedures Using SimaPro (v.8.3.0.0)

a. Identify the input and output data including the materials, the emissions, the amount of each material, the disposal and recycle method at each scenario.
b. Input the information and the data of each scenario in SimaPro program.
c. Consider the impact categories including climate change, human toxicity, terrestrial ecotoxicity and metal depletion.
d. Calculate and compare the environmental impacts, including climate change, human toxicity, terrestrial ecotoxicity and metal depletion using ReCiPe midpoint method.

3.3.3 Evaluate and Compare the Effect of the Waste PCBs Management

a. Collect and evaluate the results from the combination of MFA and LCA at each scenario.
b. Compare the environmental and human health impacts of each scenario to find the best scenario which appropriates for managing waste PCBs.

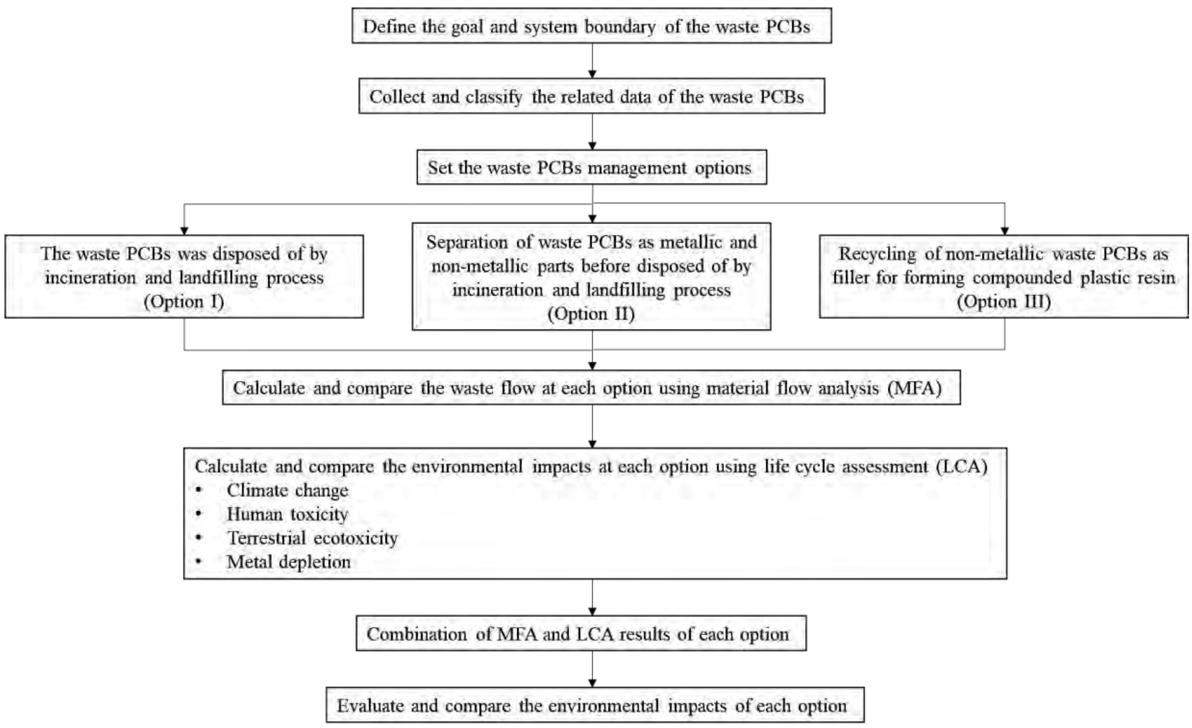


Figure 3.1 The experimental procedures diagram.

CHAPTER IV

RESULTS AND DISCUSSION

The combination of MFA and LCA method offers a powerful assessment tool for evaluating the environmental impacts of the waste PCBs management. The waste flow boundary was scoped from the input PCBs waste to its recycle product and final disposal scenario. The component data of the waste PCBs was gathered from the previous literature (Szalatkiewicz, 2013). The waste flow of PCBs was developed through MFA using STAN (v.2.6.801). The MFA of PCBs waste was conducted with Cu and Fe as a substance flow. The results from the MFA was applied for evaluating the environmental impacts from each scenario using SimaPro (v.8.3.0.0) program (LCA software). The ReCiPe with the midpoint method was selected because it does not include potential impacts from future extractions (Goedkoop *et al*., 2013). The PCBs waste management scenarios were considered including the disposal of PCBs (Option I), separation of waste PCBs before disposal (Option II) and recycling of the non-metallic PCBs to produce compounded plastic resin (Option III). The results of MFA and LCA analysis from each scenario were compared and discussed to find the appropriate waste PCBs management.

4.1 Waste Classification

According to United Nations University (Baldé *et at*., 2017), they estimated the global waste electrical and electronic equipment (WEEE) production which was about 41.8 million metric tons (Mt) in 2014 (Awasthi *et al*., 2017). Among WEEE, the production of waste PCBs stands out as the most difficult component to treat and most valuable part to recycle. It only counts for 3% by weight of the total amount of WEEE (Szałatkiewicz, 2014). The waste PCBs composition can be classified based on the literature as shown in Table 2.1. The component of waste PCBs mostly composed of 30% metals, 32% organic, and 38% inorganic (Szalatkiewicz, 2013). For MFA study, The amount of waste PCBs was assumed to be 1 kg to simple understanding and calculation. From Table 4.1, 1 kg of waste PCBs has 0.32 kg of epoxy resin, 0.38 kg of glass fiber. Among the rest, 0.30 kg is the heavy metals, which contains 0.15 kg of Cu and 0.048 kg of Fe. Both substances were used to calculate the fraction of each metal in the specific which is known as a substance flow analysis (SFA) in each scenario.

Table 4.1 The component of the waste PCBs based on 1 kg (Szalatkiewicz, 2013)

Component		Mass (kg)
Epoxy Resin		0.32
Glass Fiber		0.38
Heavy metal	Copper	0.15
	Tin	0.056
	Lead	0.030
	Ferrite	0.048
	Nickel	0.017
	Chromium	0.0036
	Molybdenum	0.00016
	Silver	0.00045
	Gold	0.00021
	Palladium	0.00022
Total		1.00

According to the study of recycling of waste printed circuit boards development project (non-metallic part) (Nithitanakul *et al*., 2017). The PCBs were separated into a metallic part (M-PCBs) and non-metallic part (NM-PCBs). The composition of the NM-PCBs after the separation process is shown in Table 2.2. The hazardous and/or reusable components are selectively disassembled from the waste PCBs such as inductors, resistors, capacitors and IC chips. After that, the waste PCBs were crushed and sized to smaller pieces. The M-PCBs and NM-PCBs were separated using magnetic separation. The recycling of NM-PCBs can be summarized based on physical and chemical methods. In this study, NM-PCBs was recycled as a physical method by adding the plastic compound production process due to the suitability of technology and equipment in Thailand (Nithitanakul *et al.*, 2017).

4.2 Material Flow Analysis (MFA)

The MFA for waste PCBs management was calculated for each option. The waste flow was divided into three options starting from the waste PCBs generation to its end-of-life. It was analyzed for both goods and substances using STAN (v.2.6.801). The considered substances were Cu and Fe because they are dominant species and precious metals PCBs. The recycling of these components is more useful than that of the discarding. These metals can be recycled and used as secondary raw materials in the ferrous industry.

4.2.1 The Disposal of Waste PCBs to Incineration and Landfill (Option I)

For the MFA of waste PCBs (Figure 4.1), the amount of waste was considered to be 1 kg. It was assumed that no stock in each process. After being collected, nearly 80 wt.% (Sattel, 2016) of the waste PCBs was assumed to be disposed of by landfill, which contain some heavy metals (Cu, Fe and Hg). The metals ready to leach away into the ground and damage to the ecosystem (Sattel, 2016). Then, the wastes transported to incineration was about 0.2 kg. The incineration of waste PCBs can cause the release of heavy metals such as Cu, Fe, Hg and Pb to the atmosphere through the air emissions. This is an important exposure route that these heavy metals exposed to humans and environments.

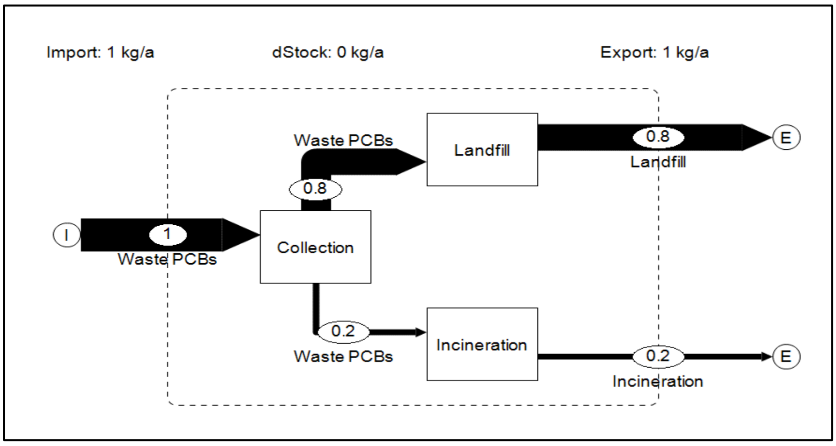


Figure 4.1 Material flow analysis of the waste PCBs disposal based on 1 kg of waste PCBs (kg).

The considered substances in this study were Cu and Fe as shown in Figure 4.2. At 1 kg of PCBs, the amounts of Cu and Fe were equal to 0.15 and 0.05 kg, respectively. According to the scenario that the landfill was accounted for 80% of the waste disposal, the amount of Cu was calculated to be 0.12 kg and 0.04 kg for Fe. Thereby, about 0.03 kg of Cu and 0.01 kg of Fe were burned in the incineration process.

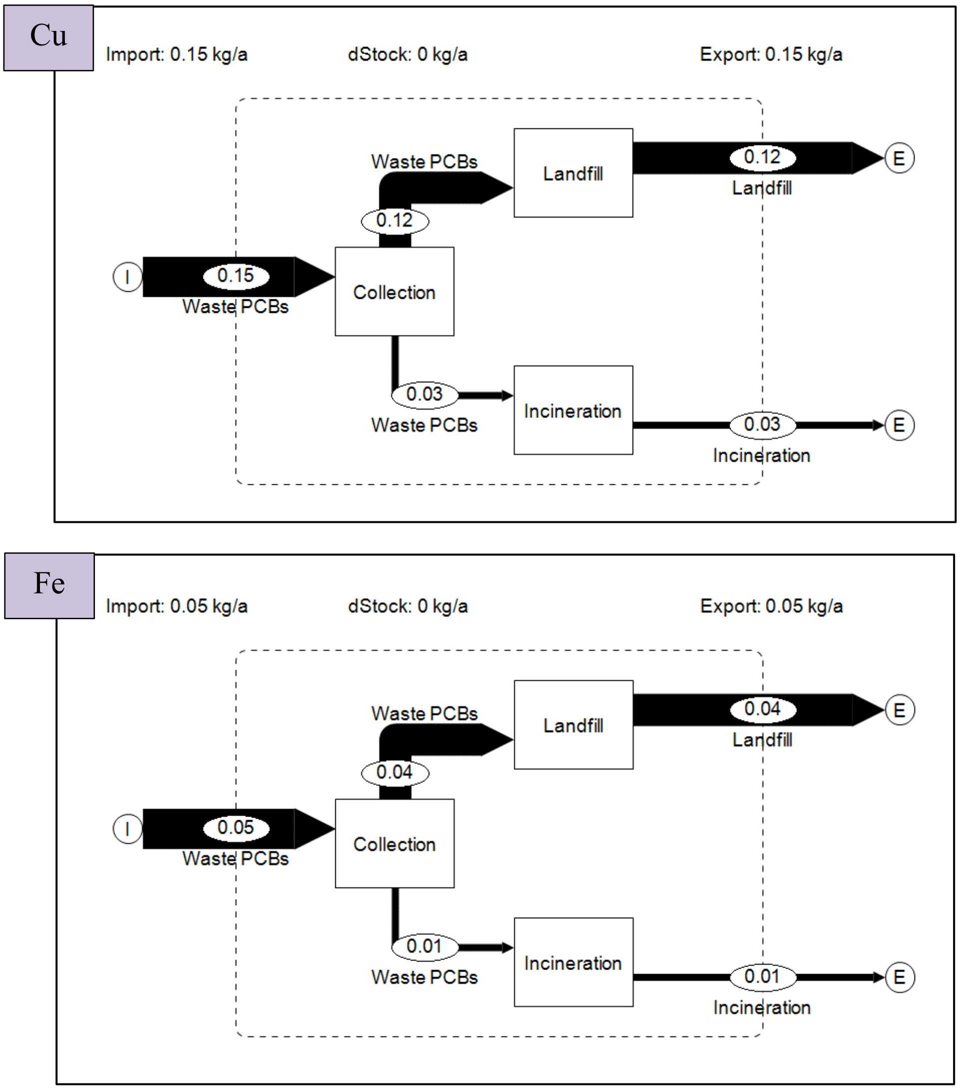


Figure 4.2 Substance flow analysis of the waste PCBs disposal based on 1 kg of waste PCBs (kg), Cu and Fe, respectively.

As a result, Option I was assumed as a worst-case scenario. This option represents the waste treatment without any recycling method. This can lead to adverse problems for the environments because it contains the major component hazardous.

Therefore, waste PCBs should be managed properly before discarded. The separation of waste PCBs into a metallic part and non-metallic part is an alternative to increase the utilization of the valuable product. At present, a manual disassembly is the most practical option to remove the different components of the waste PCBs. Mechanical and chemical processes are the methods used to treat the waste PCBs by means of particle sizes and then, separate continuously into a metallic part and non-metallic part.

4.2.2 Separation of Waste PCBs Before Disposed to Incineration and Landfill (Option II)

According to the MFA of the waste PCBs, it was derived to be 1 kg. The current PCBs management is shown in Figure 4.3. Beginning with, the waste PCBs was crushed and separated into two parts, 0.29 kg of the metals and 0.71 kg of the non-metals. All metals which can be separated, were recycled and utilized as a secondary raw material. On the other hand, the non-metallic part which is composed of epoxy resins and glass fiber was treated by combustion and landfill (Guo *et al*, 2009). The disposal methods were defined based on it is a common method that recently used for the waste disposal (Guo *et al*, 2009) by landfill and incineration, which are about 0.57 kg and 0.14 kg, respectively.

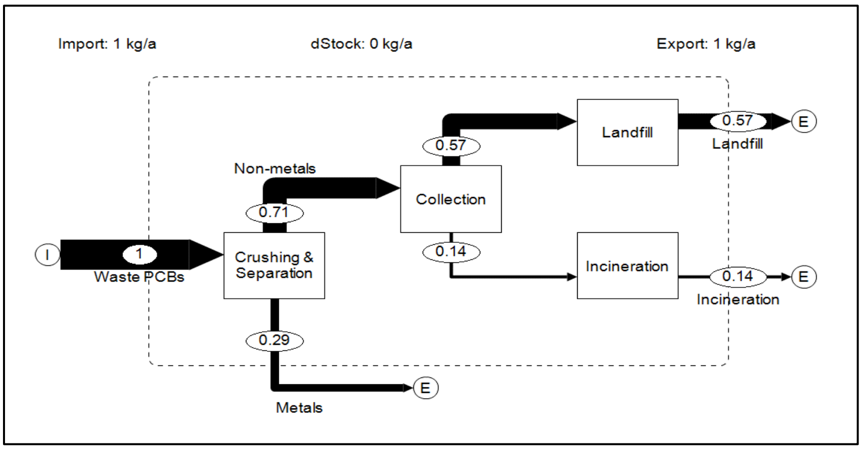
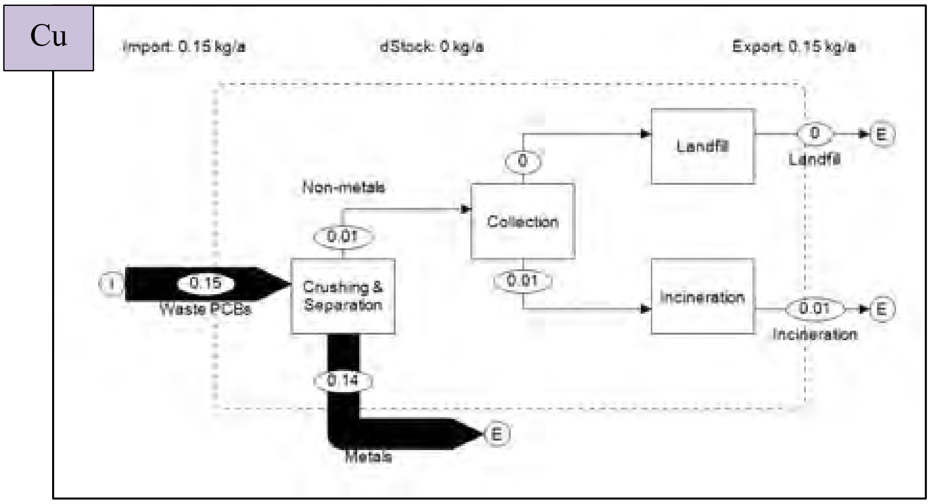


Figure 4.3 Material flow analysis of separation of waste PCBs into M-PCBs and NM-PCBs before discarded based on 1 kg of waste PCBs (kg).

The non-metallic part of waste PCBs (NM-PCBs) is generally contaminated with some of the other heavy metals. For the substance flow analysis (SFA), Cu and Fe fraction in the MFA of PCBs waste as shown in Figure 4.4. The composition of Cu contaminated in the NM-PCBs was accounted to be about 1.28 wt.% and 0.24 wt.% of Fe. About 0.15 kg of Cu and 0.05 kg of Fe in the waste PCBs that were crushed and separated into M-PCBs and NM-PCBs by magnetic separation. Cu (0.14 kg) and Fe (0.05 kg) that can be separated from waste PCBs, will be recycled and recovered. Among the rest, about 0.01 kg of Cu and 0.0017 kg of Fe in NM-PCBs were sent to dispose of by landfill and incineration.



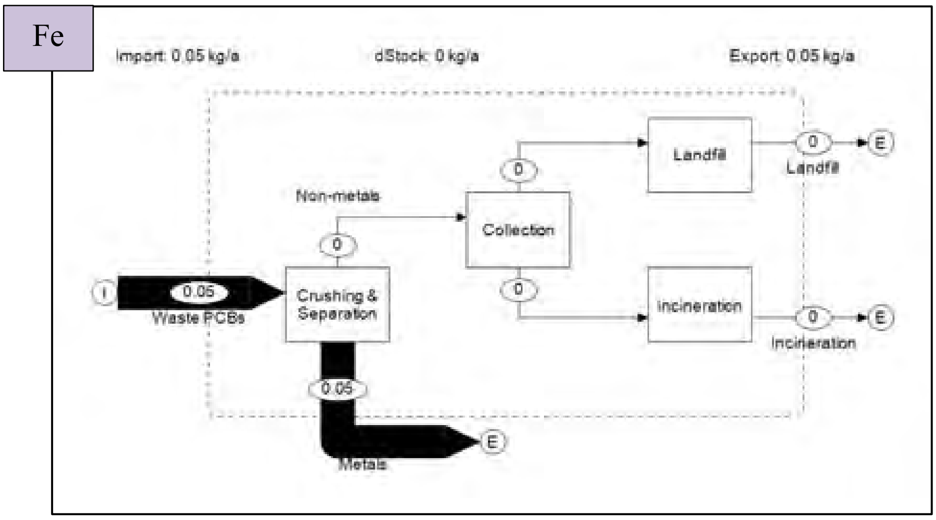


Figure 4.4 Substance flow analysis of separation of waste PCBs into M-PCBs and NM-PCBs before discarded based on 1 kg of waste PCBs (kg), Cu and Fe, respectively.

The treatment of the NM-PCBs by landfill, and incineration can cause environmental impacts such as climate change, water and land pollution. The waste cannot be degraded for a long time after being buried which will destroy the ecological balance and cause soil deterioration due to the inorganic metallic and heavy metals (Guanghan *et al.*, 2016). Incineration is another method to handle the non-metallic part of the waste PCBs. This method can also cause a serious environmental problem concerning mainly by air emissions. Under the high temperature and aerobic environment conditions, the inorganic metal of the non-metallic materials of waste PCBs, such as lead (Pb) and arsenic (As), will release into the atmosphere and harm to the atmospheric environment (Guanghan *et al.*, 2016). For appropriate waste utilization, the non-metallic part should be recycled to reduce the adverse effects on the environments and also increase the value of the materials.

4.2.3 Recycling of Non-metallic Waste PCBs as Filler for Forming Plastic (Option III)

From the developed project under the utilization of the waste PCBs (non-metallic part) by (Nithitanakul *et al.*, 2017). This study used virgin HDPE because of the same quality control through the research. Recycled HDPE can be hard to control the quality due to the different sources of this waste. The non-metallic PCBs waste was utilized as a filler for premixing with virgin HDPE at 10:90 ratio by tumble mixer for 10 minutes. After that, the mixture was mixed again by a twin-screw extruder and temperatures at which used to melt the plastic is between 180-220°C. With this process, both materials were completely merged. Then, the mixture of HDPE and composite materials were molded by the injection molding machine. The MFA and SFA of this process are shown in Figure 4.5 and 4.6. The non-metallic in PCBs from the crushing process was 0.71 kg and the virgin HDPE used in mixing was 6.37 kg. So, the amount of plastic produced was 7.08 kg.

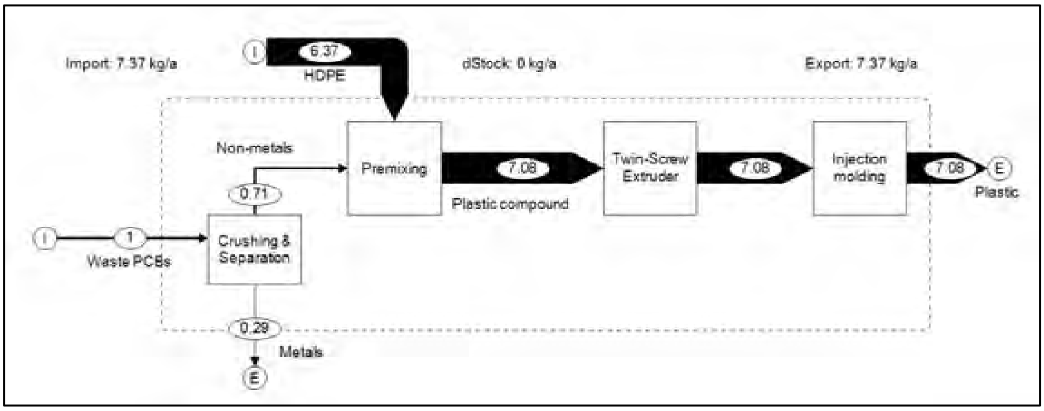


Figure 4.5 Material flow analysis of recycling the non-metallic in PCBs for forming compounded plastic resin based on 1 kg of waste PCBs (kg).

The number of substances in the non-metallic part was gathered as listed in Table 2.2. In virgin HDPE resins, there are no Cu and Fe components. Thus, the mass flow of the recycling process will only contain the Cu and Fe from the non-metallic of PCBs, equivalent to 0.01 kg of Cu and 0.0017 kg of Fe. The 7.08 kg of the plastics were contaminated with Cu and Fe for 0.01 and 0.0017 kg, respectively.

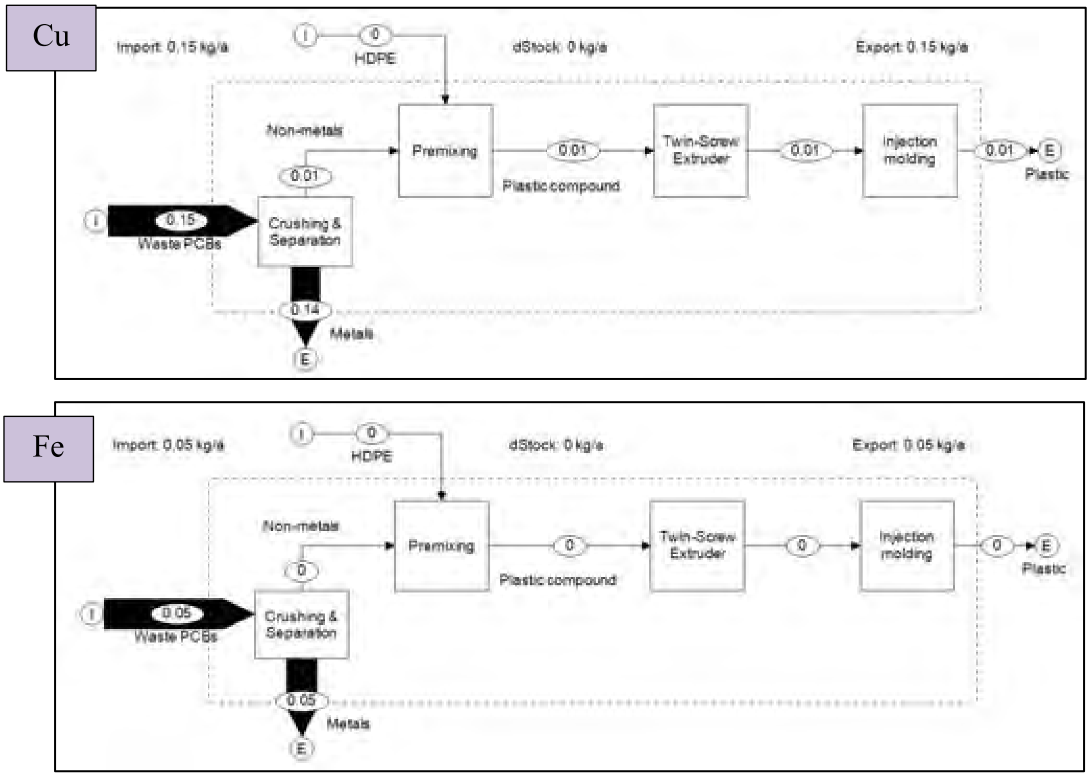


Figure 4.6 Substance flow analysis of recycling the non-metallic in PCBs for forming compounded plastic resin based on 1 kg of waste PCBs (kg), Cu and Fe, respectively.

4.3 Life Cycle Inventory Analysis (LCIA)

The input and output data which used in SimaPro software to calculate the environmental impact was compiled into three sections depending on each option, disposal of waste PCBs to incineration and landfill, separation of waste PCBs before disposed of by incineration and landfill, and recycling of non-metallic waste PCBs as a filler for plastic resin. The functional unit was set to be 1 kg of the waste PCBs.

4.3.1 Inventory Data for the Disposal of Waste PCBs to Incineration and Landfill (Option I)

The inventory data for landfill and incineration option is shown in Tables 4.2 and 4.3, respectively.

Table 4.2 Inventory data for landfill of plastic waste in Option I based on 1 kg of waste PCBs

Landfill	Unit	Amount
Output: Emission to air[a]		
Methane	Kg	0.0575
Carbon dioxide	Kg	0.174
Carbon monoxide	Kg	3.12×10^{-5}
NM-VOC	Kg	0.00275
Nitrogen	Kg	3.28×10^{-5}
Dinitrogen monoxide	Kg	0
Hydrogen chloride	Kg	0.0204
Sulfur dioxide	Kg	0.0164
Output: Emission to soil[a]		
Deltamethrin	Kg	4.61×10^{-8}
Input: Material[b]		
Epoxy resin	Kg	0.26
Glass fiber	Kg	0.30
Copper	Kg	0.12
Tin	Kg	0.0452
Lead	Kg	0.0238
Ferrite	Kg	0.0385

Table 4.2 Inventory data for landfill of plastic waste in Option I based on 1 kg of waste PCBs (continued)

Landfill	Unit	Amount
Input: Material[b]		
Nickel	Kg	0.0133
Chromium	Kg	0.00286
Molybdenum	Kg	0.000129
Silver	Kg	0.000362
Gold	Kg	0.000165
Palladium	Kg	0.000177
Waste to treatment[b]		
Waste plastic, mixture, sanitary landfill	Kg	0.80

[a] Obtained from Behrooznia *et al*. (2018).

[b] Obtain from Nithitanakul *et al.* (2017).

Table 4.3 Inventory data for incineration of plastic waste in Option I based on 1 kg of waste PCBs

Incineration	Unit	Amount
Input: Energy[a]		
Diesel fuel	GJ	3.22×10^{-6}
Output: Emission to air[a]		
Carbon dioxide	Kg	0.00024
Sulfur dioxide	Kg	7.76×10^{-8}
Methane	Kg	9.92×10^{-9}
Benzene	Kg	5.6×10^{-10}
Cadmium	Kg	7.7×10^{-13}
Chromium	Kg	3.82×10^{-12}
Copper	Kg	1.31×10^{-10}
Dinitrogen monoxide	Kg	9.2×10^{-9}
Nickel	Kg	5.38×10^{-12}
Zinc	Kg	7.7×10^{-11}
Benzo (a) pyrene	Kg	2.3×10^{-12}
Ammonia	Kg	1.536×10^{-9}
Selenium	Kg	7.7×10^{-13}
PAH	Kg	2.52×10^{-10}
NM-VOC	Kg	2.2×10^{-7}

Table 4.3 Inventory data for incineration of plastic waste in Option I based on 1 kg of waste PCBs (continued)

Incineration	Unit	Amount
Output: Emission to air[a]		
Nitrogen oxides	Kg	3.42×10^{-6}
Carbon monoxide	Kg	4.80×10^{-7}
Particulates, < 2.5 µm	Kg	3.40×10^{-7}
Mercury	Kg	0.72
Dioxin	Kg	72000
Furan	Kg	72000
Input: Material[b]		
Epoxy resin	Kg	0.064
Glass fiber	Kg	0.0756
Copper	Kg	0.0294
Tin	Kg	0.0113
Lead	Kg	0.0060
Ferrite	Kg	0.0096
Nickel	Kg	0.003317
Chromium	Kg	0.000716
Molybdenum	Kg	3.22×10^{-5}
Silver	Kg	9.05×10^{-5}
Gold	Kg	4.12×10^{-5}
Palladium	Kg	4.42×10^{-5}
Waste to treatment[b]		
Waste plastic, consumer electronics, incineration	Kg	0.20

[a] Obtained from Behrooznia *et al*. (2018).

[b] Obtain from Nithitanakul *et al.* (2017).

4.3.2 Inventory Data for Separation of Waste PCBs before Disposed to Incineration and Landfill (Option II)

The inventory data for crushing, landfill and incineration process is shown in Figures 4.4, 4.5 and 4.6, respectively.

Table 4.4 Inventory data for crushing of waste PCBs in Option II based on 1 kg of waste PCBs

Crushing	Unit	Amount
Input: Energy[a]		
Electricity	kWh	0.08
Output: Emission to air[a]		
Particulates	Kg	0.0529
Nitrogen oxides	Kg	9.70×10^{-5}
Ammonia	Kg	2.04×10^{-6}
Hydrogen chloride	Kg	3.92×10^{-5}
Sulfuric acid	Kg	2.04×10^{-6}
Input: Material[b]		
Epoxy resin	Kg	0.3197
Glass fiber	Kg	0.3780
Copper	Kg	0.1468
Tin	Kg	0.0565
Lead	Kg	0.0298
Ferrite	Kg	0.0482
Nickel	Kg	0.0166
Chromium	Kg	0.00358
Molybdenum	Kg	0.00016
Silver	Kg	0.00045
Gold	Kg	0.000206
Palladium	Kg	0.00022
Waste to treatment		
Waste electric and electronic equipment, shredding	Kg	1.00

[a] Obtained from Hong *et al*. (2015).

[b] Obtain from Nithitanakul *et al.* (2017).

Table 4.5 Inventory data for landfill of plastic waste in Option II based on 1 kg of waste PCBs

Landfill	Unit	Amount
Input: Material[a]		
Epoxy resin	Kg	0.2557
Glass fiber	Kg	0.3024
Copper	Kg	0.007162
Ferrite	Kg	0.001318
Waste to treatment		
Waste plastic, mixture, sanitary landfill	Kg	0.567

[a] Obtain from Nithitanakul *et al.* (2017).

Table 4.6 Inventory data for incineration of plastic waste in Option II based on 1 kg of waste PCBs

Incineration	Unit	Amount
Input: Energy[a]		
Electricity	MJ	0.0014
Output: Emission to air[a]		
Carbon dioxide	Kg	0.1346
Carbon monoxide	Kg	1.42×10^{-9}
Sulfur dioxide	Kg	2.01×10^{-8}
Hydrogen chloride	Kg	2.17×10^{-8}
Particulate	Kg	0.00035
Mercury	Kg	0.00
Dioxin	Kg	50992.70
Furan	Kg	50992.70
Input: Material[b]		
Epoxy resin	Kg	0.0639
Glass fiber	Kg	0.0756
Copper	Kg	0.00179
Ferrite	Kg	0.000330
Waste to treatment		
Waste plastic, consumer electronics, incineration	Kg	0.142

[a] Obtained from Khoo (2019).

[b] Obtain from Nithitanakul *et al.* (2017).

4.3.3 Inventory Data for Recycling of Non-Metallic Waste PCBs as Filler for Producing Compounded Plastic Resin (Option III)

The data-set for this option was classified in two parts: firstly, the treatment process included waste separation by crushing (Table 4.4) of the PCBs waste. Secondly, the recycling of NM-PCBs by utilizing as a filler of which it was mixed with virgin HDPE resins to produce the compounded plastic resin. This process included injection molding (Table 4.7), and extrusion (Table 4.8). For the production of the virgin, the process was divided into injection molding (Table 4.9) and extrusion (Table 4.10).

Table 4.7 Inventory data for injection molding of the compounded plastic resin in Option III based on 1 kg of waste PCBs

Injection molding	Unit	Amount
Material[a]		
Epoxy resin	Kg	0.3197
Glass fiber	Kg	0.3780
Copper	Kg	0.00895
Ferrite	Kg	0.00165
Polyethylene, high density, granulate	Kg	6.37
Injection molding processing	Kg	7.08

[a] Obtain from Nithitanakul *et al.* (2017).

Table 4.8 Inventory data for extrusion of compounded plastic resin in Option III based on 1 kg of waste PCBs

Extrusion	Unit	Amount
Material[a]		
Epoxy resin	Kg	0.3197
Glass fiber	Kg	0.3780
Copper	Kg	0.00895
Ferrite	Kg	0.00165
Polyethylene, high density, granulate	Kg	6.37
Extrusion, co-extrusion of plastic sheets	Kg	7.08

[a] Obtain from Nithitanakul *et al.* (2017).

Table 4.9 Inventory data for injection molding to produce virgin HDPE in Option III based on 1 kg of waste PCBs

Injection molding	Unit	Amount
Material[a]		
Polyethylene, high density, granulate	Kg	7.08
Injection molding processing	Kg	7.08

[a] Obtain from Nithitanakul *et al.* (2017).

Table 4.10 Inventory data for extrusion to produce virgin HDPE in Option III based on 1 kg of waste PCBs

Extrusion	Unit	Amount
Material[a]		
Polyethylene, high density, granulate	Kg	7.08
Extrusion, co-extrusion of plastic sheets	Kg	7.08

[a] Obtain from Nithitanakul *et al.* (2017).

4.4 Life Cycle Assessment (LCA)

The MFA results from Section 4.2 and inventory analysis from Section 4.3 were used for the environmental impact evaluation. The three scenarios developed are the disposal of PCBs (Option I), separation of waste PCBs before disposing of by (Option II) and recycling of the non-metallic PCBs to produce compounded plastic resin (Option III). Each option was conducted based on the common waste management process that significantly contributes to the environmental impacts which give a different effect on the environment and the alternative option for utilizing NM-PCBs for recycling purpose. The scenarios analysis is intended to help to guide which option is suitable for waste PCBs management. The waste was considered starting from the waste generator to its final disposal or treatment.

The method adapted for evaluating the environmental impacts was analyzed by SimaPro software with ReCiPe midpoint method (Hierarchist version). The ReCiPe method was selected because this method is commonly used. It has various of impact assessment and modern than other methods e.g., CML-IA, Eco-indicator 99, USEtox or TRACI (Goedkoop *et al.*, 2013). The environmental impact in the ReCiPe has 18 impact categories. The details of environmental impacts are explained in Appendix A. An impact values of all category were shown in Appendix C. The potential impact categories were selected from the factor that directly affects to human and environment. In this study, the four impacts were selected, including climate change, human toxicity, terrestrial ecotoxicity and metal depletion. The results for all environmental impact categories were displayed in Table 4.10. Furthermore, climate change (kg CO_2-eq), human toxicity (kg 1,4-DB-eq), terrestrial ecotoxicity (kg 1,4-DB-eq) and metal depletion (kg Fe-eq) results were shown in Figure 4.7, 4.10, 4.13 and 4.16 respectively.

4.4.1 Environmental Impacts of the Waste PCBs Management

Table 4.11 presents the overall LCA assessment results with the use of the ReCiPe method. Option I had the highest of all potential environmental impacts. This could be the waste PCBs has a high level of heavy metals such as Cu, Au, Sn and Pd thus contaminated with the incineration and landfill process which caused serious damage to the environment. After separation of the waste PCBs into M-PCBs and NM-PCBs (Option II), the environmental impacts are decreased because the contained heavy metals are leached out. The lowest environmental impact for each option was obtained by Option III, of which the waste PCBs was separated, and the NM-PCBs was utilized as an additive in plastic compound production. This method can reduce a large amount of human toxicity because of less burning waste.

Table 4.11 Environmental impacts of waste PCBs management

Impact category	Unit	Option I	Option II	Option III
Climate change	kg CO2 eq	26.59	20.29	21.63
Ozone depletion	kg CFC-11 eq	1.36×10^{-5}	6.94×10^{-6}	7.08×10^{-6}
Terrestrial acidification	kg SO2 eq	0.39	0.23	0.22
Freshwater eutrophication	kg P eq	0.108	0.056	0.055
Marine eutrophication	kg N eq	0.011	0.0066	0.0061
Human toxicity	kg 1,4-DB eq	1.12×10^{8}	1.10×10^{8}	22.15
Photochemical oxidant formation	kg NMVOC	0.180	0.119	0.130
Particulate matter formation	kg PM10 eq	0.1539	0.0964	0.0955
Terrestrial ecotoxicity	kg 1,4-DB eq	368.96	1.756	0.0059
Freshwater ecotoxicity	kg 1,4-DB eq	12.73	0.865	0.034
Marine ecotoxicity	kg 1,4-DB eq	2137	2.048	0.232
Ionising radiation	kBq U235 eq	0.782	0.491	0.586
Agricultural land occupation	m2a	0.820	0.523	0.882

Table 4.11 Environmental impacts of waste PCBs management (continued)

Impact category	Unit	Option I	Option II	Option III
Urban land occupation	m2a	1.654	0.875	0.869
Natural land transformation	m2	0.016	0.0084	0.0086
Water depletion	m3	0.271	0.220	0.217
Metal depletion	kg Fe eq	221.74	112.79	111.37
Fossil depletion	kg oil eq	6.86	5.22	10.10

4.4.2 Climate Change Impact

The comparison of the environmental impact result for three selected options regarding climate change is displayed in Figure 4.7. The highest impact was 26.59 kg CO_2-eq emitted from Option I. Option II had the lowest impact (20.29 kg CO_2-eq) and the second was Option III (21.63 kg CO_2-eq). Option I had the highest impact which is caused by incineration (52 wt.%) and landfilling (48 wt.%) (see Figure 4.8). Because the heavy metals (Cu and Fe) in waste PCBs and GHG are the major release pollution during burning, the incineration and landfill processes produced a considerable amount of GHGs releases which contribute to climate change (Khoo, 2019). While Option II mainly released the emission from the crushing process. After the separation of the waste PCBs, the separated metals can be recycled, which did not include in the calculated emissions. The emissions from the incineration and landfill decreased because of some metals remained in the NM-PCBs. Furthermore, the low climate change was generated by Option III due to the utilization of waste PCBs. The emissions were considered by the process as shown in Figure 4.9, of which the filler was used to produce the plastic compound resins. So, this process included injection molding, extrusion of NM-PCBs and the process from producing the virgin HDPE. The waste separation was done by only crushing process which generates GHGs about 10.81 kg CO_2-eq. In addition, about 10% of virgin HDPE production was substituted by the NM-PCBs. This helps to reduce the GHG emissions by 3% as shown in Figure 4.8 (0.59 kg CO_2-eq.). Thereby, the total GHG was reduced the waste treatment and utilization, which equal to 21.63 kg CO_2-eq.

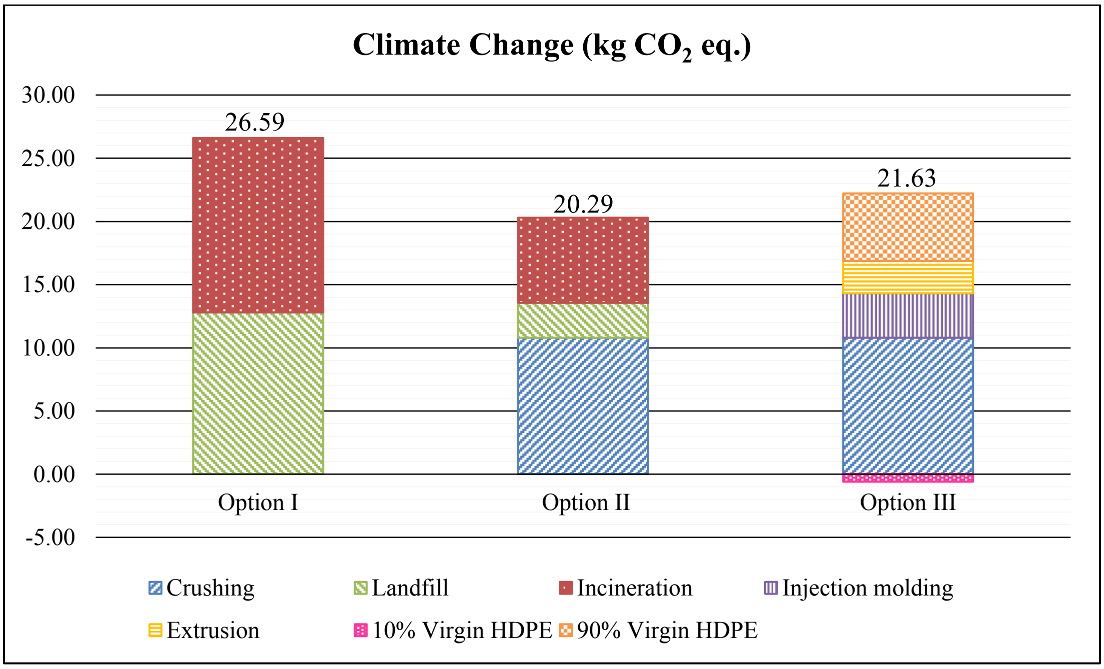


Figure 4.7 Climate change impact (kg CO_2-eq) of waste PCBs management.

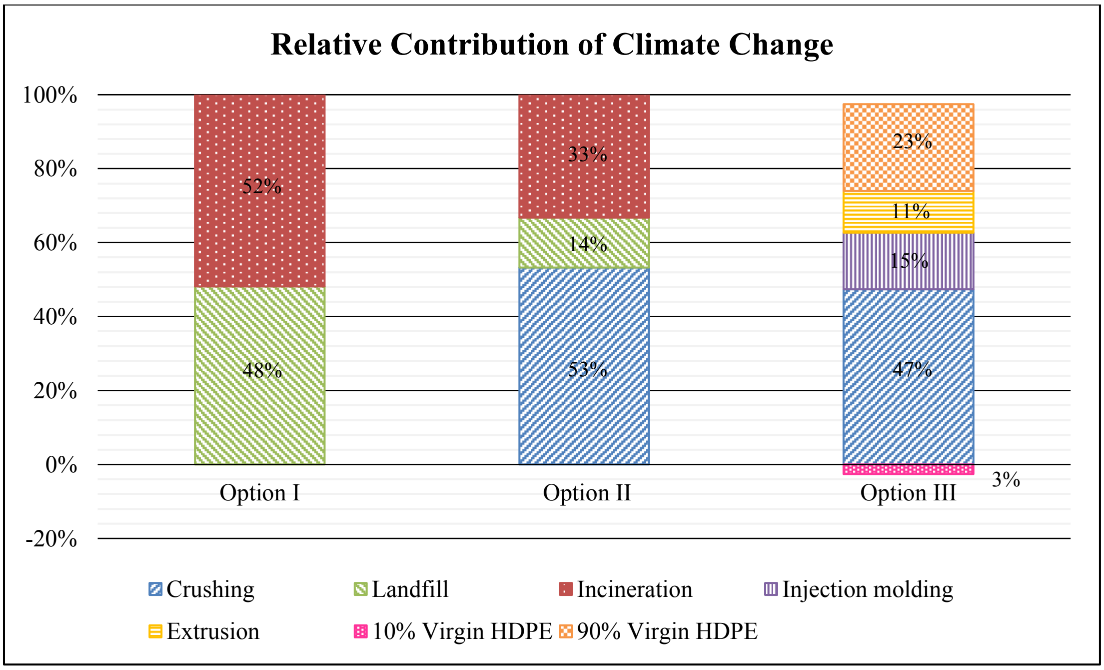


Figure 4.8 Relative contribution of climate change impact for waste PCBs management.

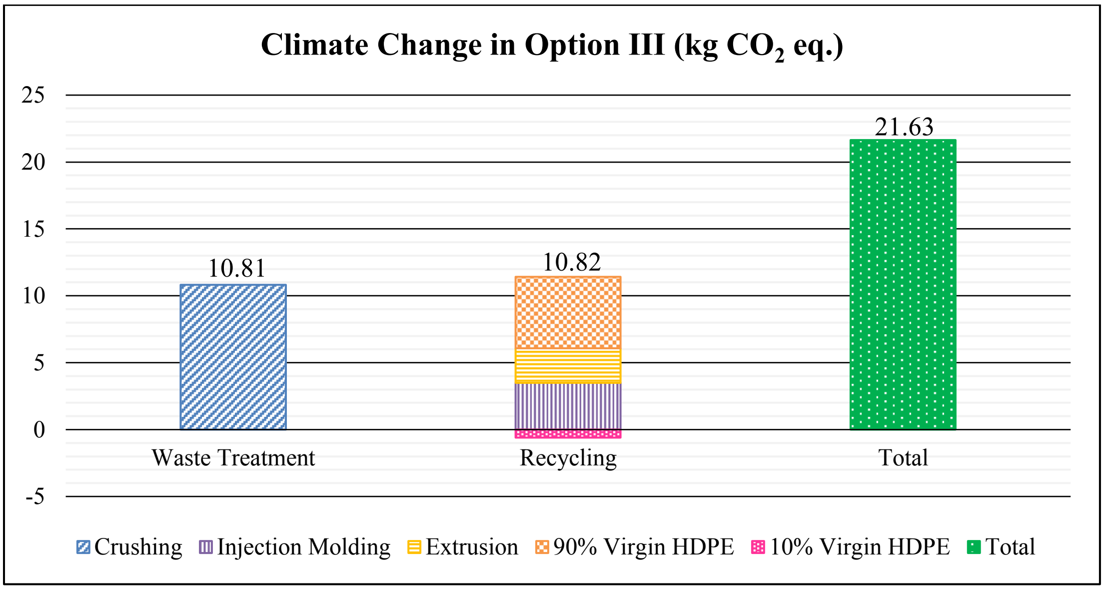


Figure 4.9 Climate change impact (kg CO_2-eq) in Option III.

4.4.3 Human Toxicity Impact

From Figure 4.10, the human toxicity impact of the waste PCBs treatment options was about 1.12×10^8, 1.10×10^8, and 22.15 kg 1,4-DB-eq generated by Option I, II, and III, respectively. Option I and II had a dramatically high impact on toxic release because of the incineration process (see in Figure 4.11). The human toxicity impact is caused by the emissions during burning in the incineration process for both Option (I, II). Polycyclic aromatic hydrocarbon (PAH) and Hg that released during the burning are toxic to the human (Aryan *et al*., 2019). Because of the separation of metals in Option II, the waste contains the lower heavy metals. Therefore, the value of human toxicity impact in Option II is lower than Option I. In contrast, Option III had the lowest human toxicity impact category. As can be seen in Figure 4.12, the human toxicity impact of Option III was caused by the using of energy in the crushing treatment process (Hong *et al*., 2015) that equal to 21.47 kg 1,4 DB-eq. The waste utilization and recycling process are a friendly option to the environment due to the fact that it reduces the potential emissions such as dioxins, PAHs, and Hg which can cause a serious effect to this impact (Aryan *et al*., 2019). Hence, Option III emitted less any of these emissions (0.68 kg 1,4-DB eq).

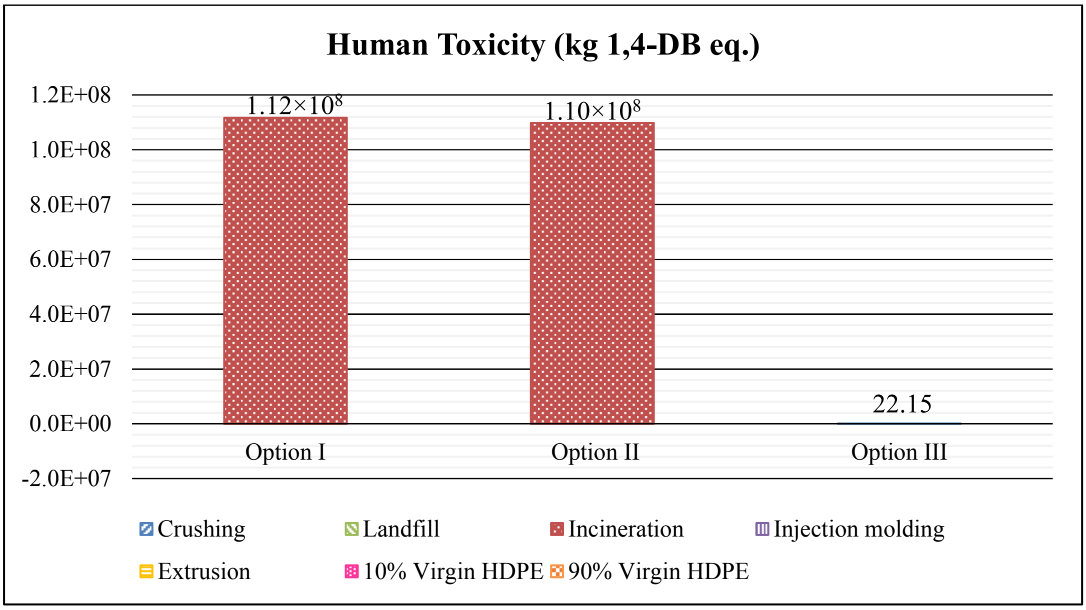


Figure 4.10 Human toxicity impact (kg 1,4-DB-eq) of waste PCBs management.

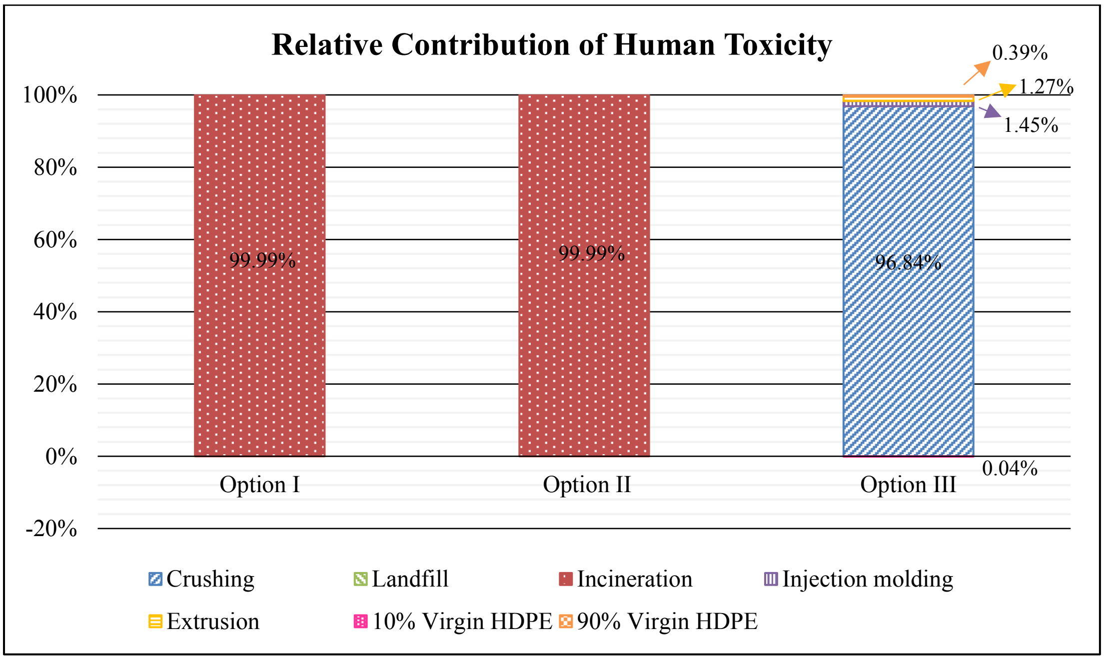


Figure 4.11 Relative contribution of human toxicity impact for waste PCBs management.

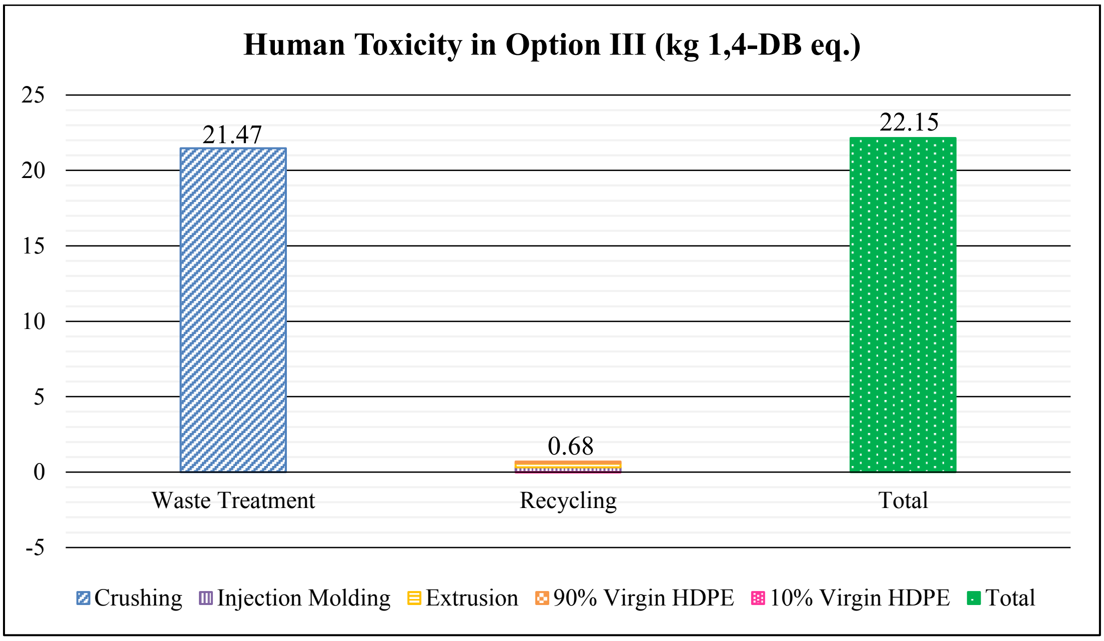


Figure 4.12 Human toxicity impact (kg 1,4-DB-eq) in Option III.

4.4.4 Terrestrial Ecotoxicity Impact

The impact of terrestrial ecotoxicity is known in Figure 4.13. The results were found to be 368.96, 1.76, and 0.0059 kg 1,4-DB-eq by Option I, II and III, respectively. Option I had the highest terrestrial ecotoxicity impact which is generated mainly from the incineration process. The impact was caused by various heavy metals such as Hg, Cu and Au and PAH emissions which are toxic to the environment due to the burning of the waste PCBs (Aryan *et al.*, 2019). In Option II, after the waste separation, the heavy metals were removed from the NM-PCBs part so that the impacts of terrestrial ecotoxicity from incineration process could be greatly reduced. Moreover, Option III generated lower impact because the waste PCBs is used as a substitute material for the virgin HDPE production. Notwithstanding, the crushing process obviously contributed to the terrestrial ecotoxicity impact as displayed in Figure 4.15. As a result, the impact that is expected to be released during the production of the plastic compound is lower.

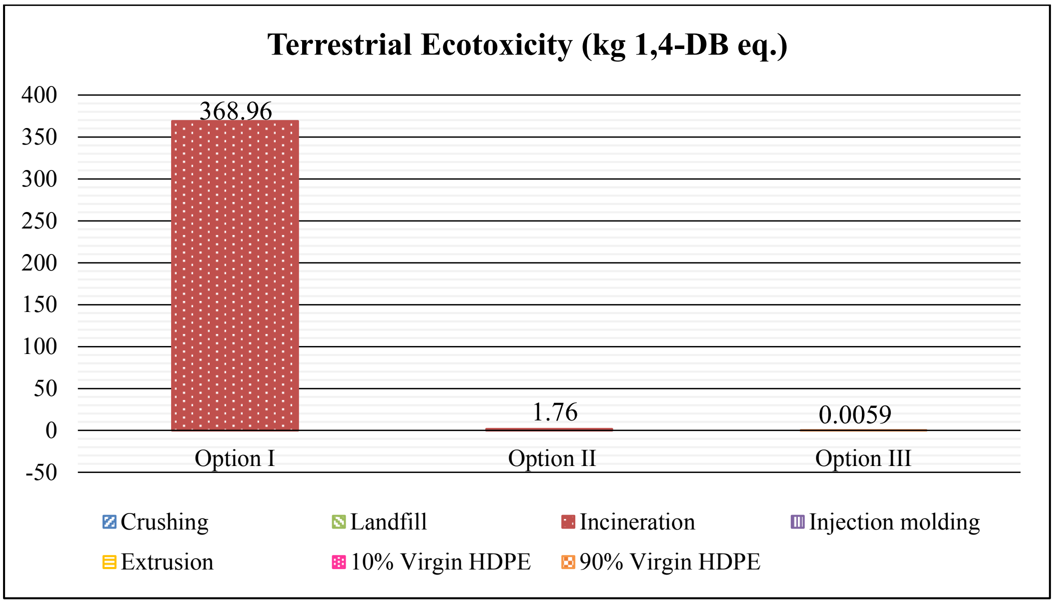


Figure 4.13 Terrestrial ecotoxicity impacts (kg 1,4-DB-eq) of waste PCBs management.

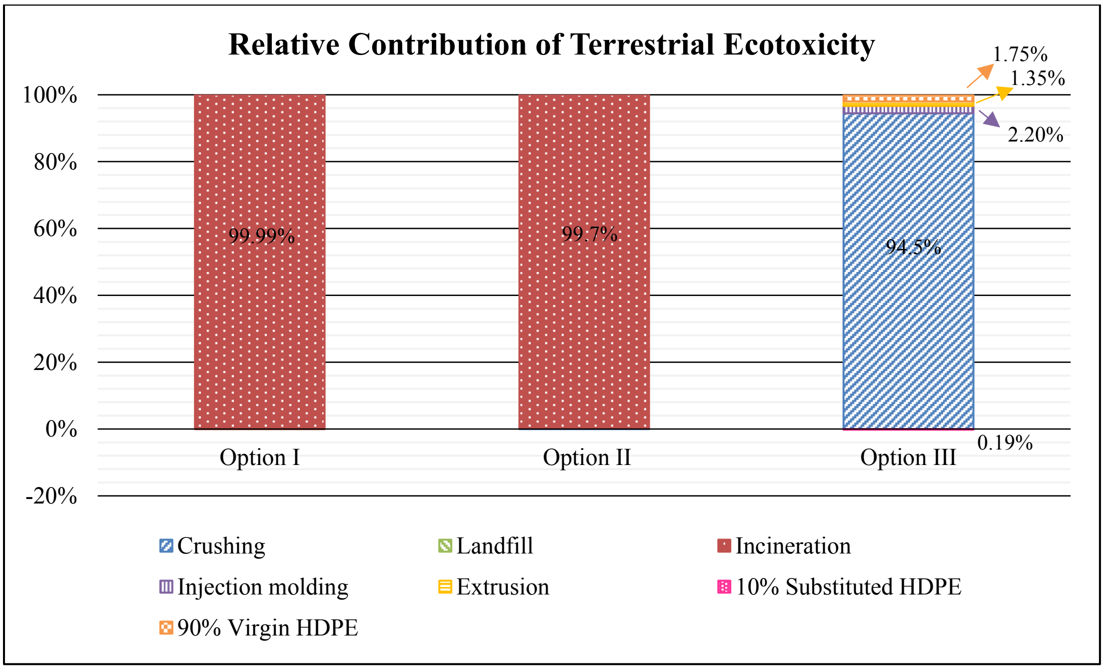


Figure 4.14 Relative contribution of terrestrial ecotoxicity impact for waste PCBs management.

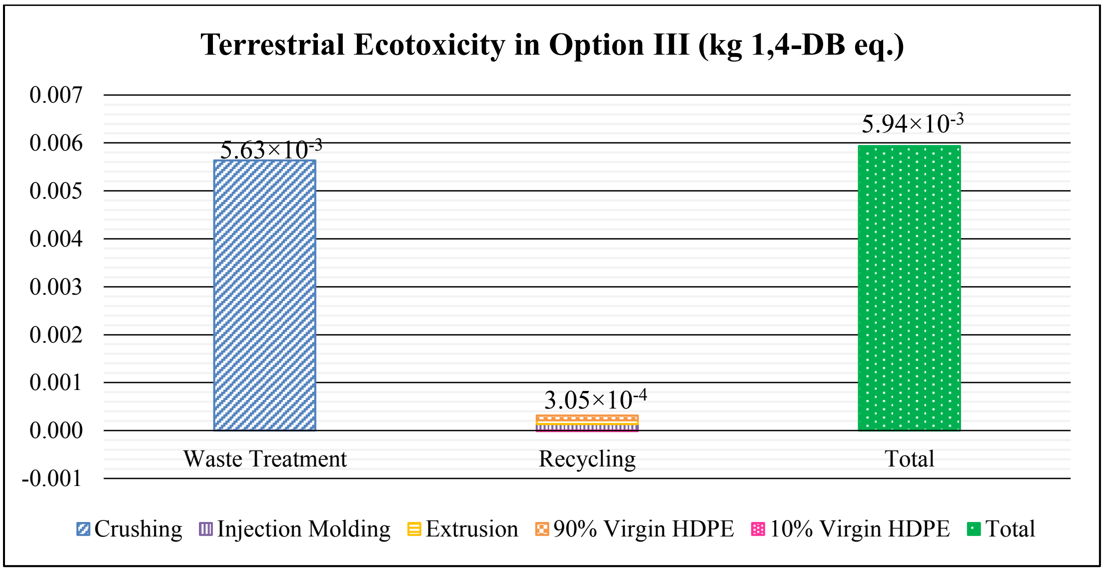


Figure 4.15 Terrestrial ecotoxicity impact (kg 1,4-DB-eq) in Option III.

4.4.5 Metal Depletion Impact

Metal depletion impact from the waste PCBs treatment in each option was found to be 221.74, 112.79, and 111.37 kg Fe-eq as shown in Figure 4.16. Option I had the highest metal depletion generated from the incineration and landfill due to the fact that the heavy metals contaminated in waste PCBs are released during the processes (Aryan *et al.*, 2019). This option did not include the waste separation between M-PCBs and NM-PCBs. For Option II and III, the waste PCBs had been separation the metals part which directly causes the decreasing of metal depletion. Therefore, the impacts which are emitted from Option II and III generated from the crushing process. This because of the fact that the waste PCBs is still contaminated with heavy metals such as Cu and Fe (Norgate & Haque, 2010) which corresponds to the result shown in Figure 4.18. Option III (Recycling process) was contaminated with a few metals and not utilized (Aryan *et al.*, 2019). As a result, the metals depletion in this process is the lowest.

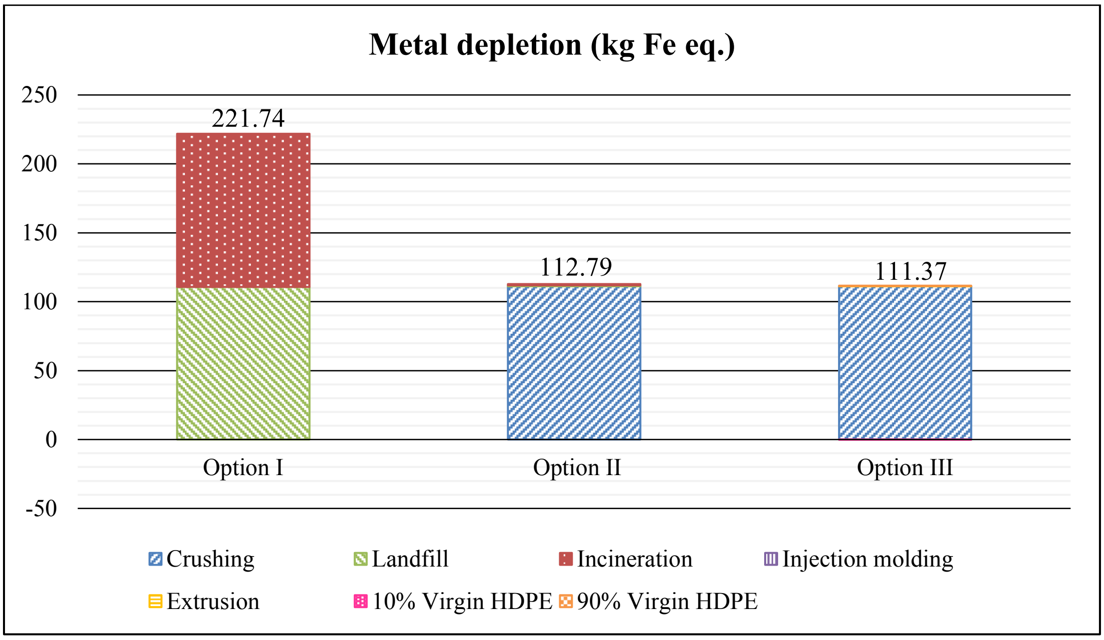


Figure 4.16 Metal depletion impact (kg Fe-eq) of waste PCBs management.

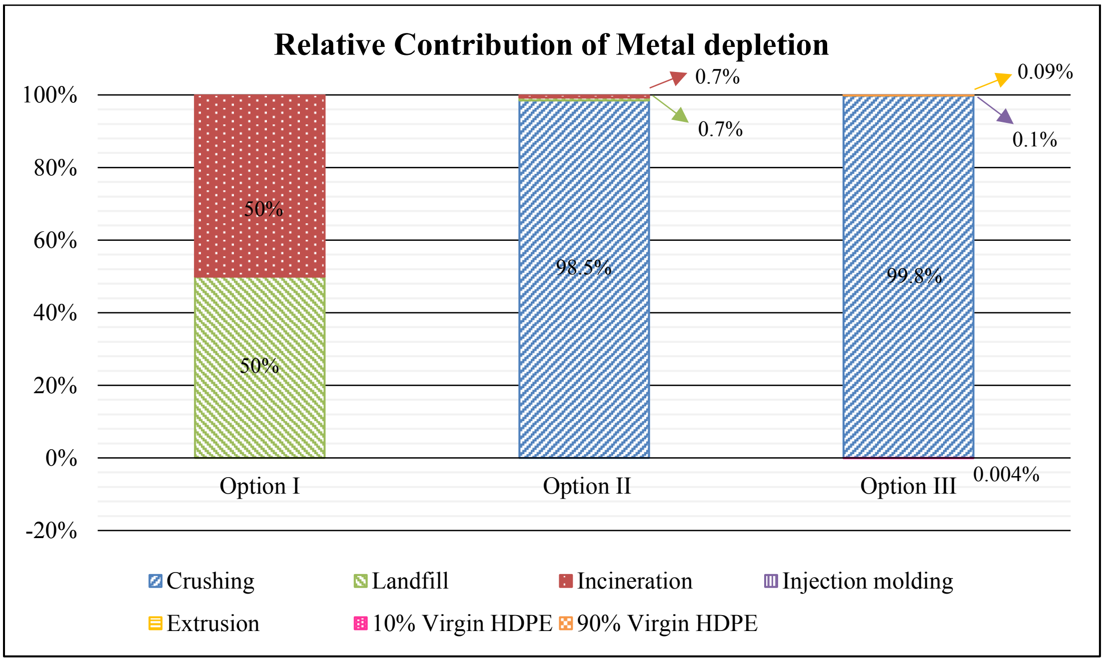


Figure 4.17 Relative contribution of metal depletion impacts for waste PCBs management.

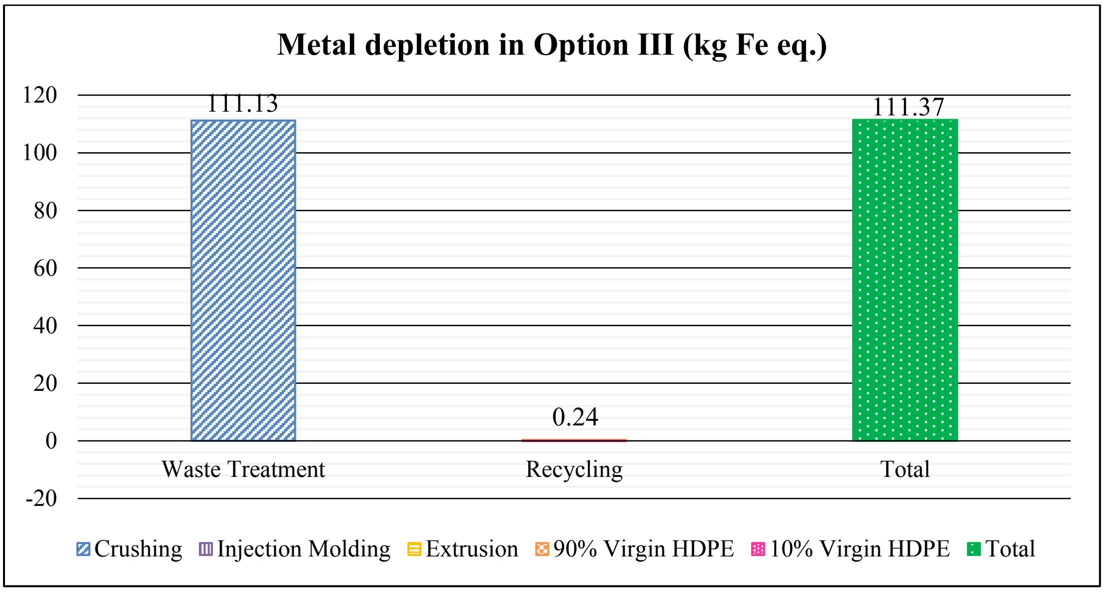


Figure 4.18 Metal depletion impacts (kg Fe-eq) in Option III.

4.5 Combined Material Flow Analysis (MFA) and Life Cycle Assessment (LCA)

MFA was used to analyze the flow of materials into, through and out of a specific system which does not allow for the calculation of the environmental impacts (Lopes Silva *et al*., 2015). Therefore, the combined analysis with LCA to evaluate the environmental impacts is an appropriate alternative to achieve the objectives. The results of the mass flow analysis from MFA were combined in the flow chart which presents the environmental impact results from the LCA of the three options. The results of four environmental impact categories including climate change (CC, kg CO_2-eq), human toxicity (HT, kg 1,4-DB-eq), terrestrial ecotoxicity (TE, kg 1,4-DB-eq) and metal depletion (MD, kg Fe-eq) are shown in Figures 4.19 to 4.21. In Section 4.1, the amount of waste PCBs was assumed to be 1 kg of the feed to process regarding in the MFA study.

The treatment of waste PCBs in Option I was divided into landfill and incineration as shown in Fig 4.19. The amount of waste was disposed of by landfill over than incineration. However, human toxicity and terrestrial ecotoxicity impacts were generated from incineration over than landfill because the burning of waste PCBs releases the toxic gas damage to human and environment (Aryan *et al.*, 2019). The climate change impact of both treatments (Option I and II) nearly equals despite less of the amount of waste in incineration due to the heavy metals and dioxins. The result shows that incineration is an important process that contributes to the amount of GHGs released (Khoo, 2019). For the metal depletion impact, the results for both treatments were similar to the climate change impact. Therefore, the incineration process is a major considered process that can cause damages to the environment and human.

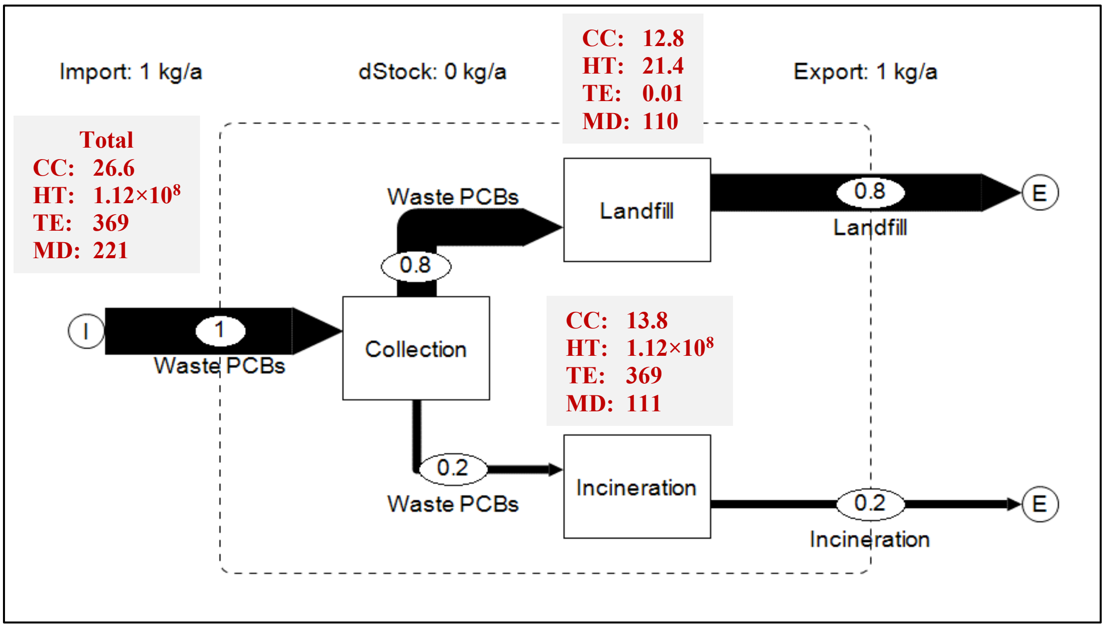


Figure 4.19 Combined MFA and LCA in disposal waste PCBs management (Option I); CC: Climate change (kg CO_2-eq), HT: Human toxicity (kg 1,4-Db-eq), TE: Terrestrial ecotoxicity (kg 1,4-DB-eq), MD: Metal depletion (kg Fe-eq).

In Option II, crushing, landfill and incineration were accounted for the treatment process in this option and shown in Figure 4.20. It has the separation of waste PCBs into the metallic part (M-PCBs) and non-metallic part (NM-PCBs). The NM-PCBs was separated about 0.71 kg and then disposed of by landfill and incineration. The waste PCBs was crushed which generates a large amount of metal depletion and climate change impacts when compared with the other treatment options. The metal depletion impact was caused by crushing process because the waste PCBs material contained many toxic metals, whereas after the separation process, the NM-PCBs sent to incineration and landfill were contaminated with a smaller amount of metals. So, the metal depletion impact caused by incineration and landfill had much extremely lesser than that of the crushing process. The crushing process did not affect to the human toxicity and terrestrial ecotoxicity. Although the incineration generated a large amount of human toxicity impact, its impact was much lesser than that of the crushing and landfill.

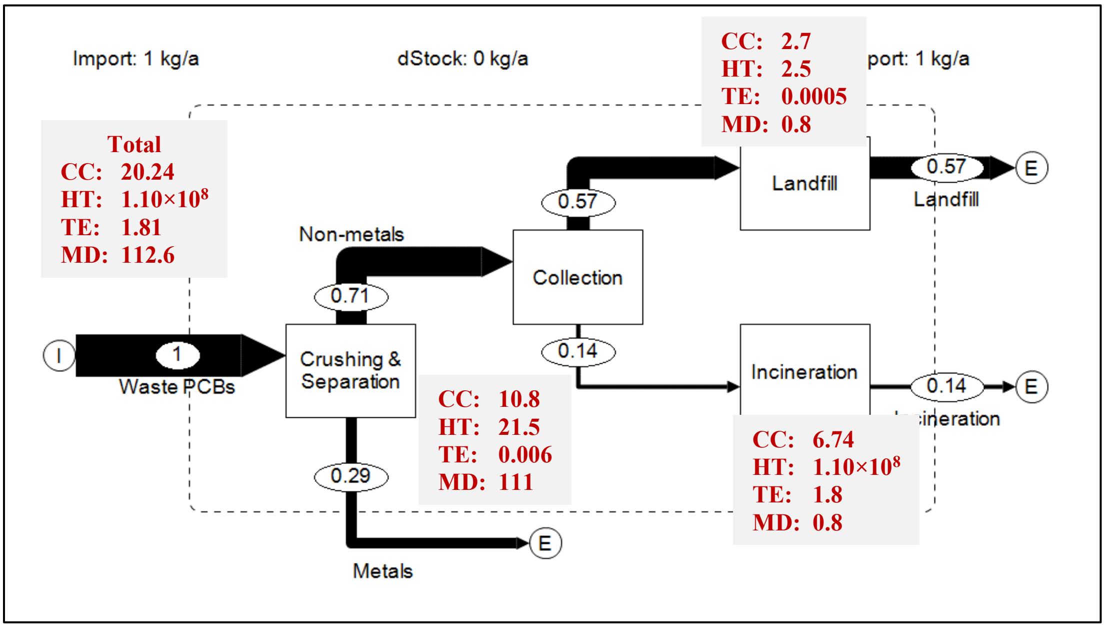


Figure 4.20 Combined MFA and LCA in disposal waste PCBs management (Option II); CC: Climate change (kg CO_2-eq), HT: Human toxicity (kg 1,4-Db-eq), TE: Terrestrial ecotoxicity (kg 1,4-DB-eq), MD: Metal depletion (kg Fe-eq).

Option III was divided into treatment of waste PCBs and physical recycling the NM-PCBs to the plastic compound resins. The treatment was counted only for crushing process. For the recycling process, the emissions mainly generated from the extrusion and injection molding process of the plastic compound and the virgin HDPE production. The climate change impact (10.8 kg CO_2-eq) caused by the crushing process was rather equal to the net climate change of the recycling process (2.6, 3.5, 4.7 kg CO_2-eq). The metal depletion result corresponds to Option II. After separation of the waste PCBs, the NM-PCBs treatment process had less contribution to the metal depletion impact. The waste PCBs at 1 kg can be used to as a filler 0.71 kg to produce the plastic compound about 7.08 kg. Therefore, the recycling process has the lowest net impact on human toxicity, terrestrial ecotoxicity when compared with the other options. For the chemical recycling (Khoo, 2019), the plastic waste was recycled into valuable fuels and other products by pyrolysis and gasification process. The environmental impacts such as climate change also decrease when compared with the scenario without waste treatment. Overall, the recycling option is applied to reduce the environmental impacts due to its positive benefit obtained through the displacement of virgin HDPE and the utilization of waste PCBs.

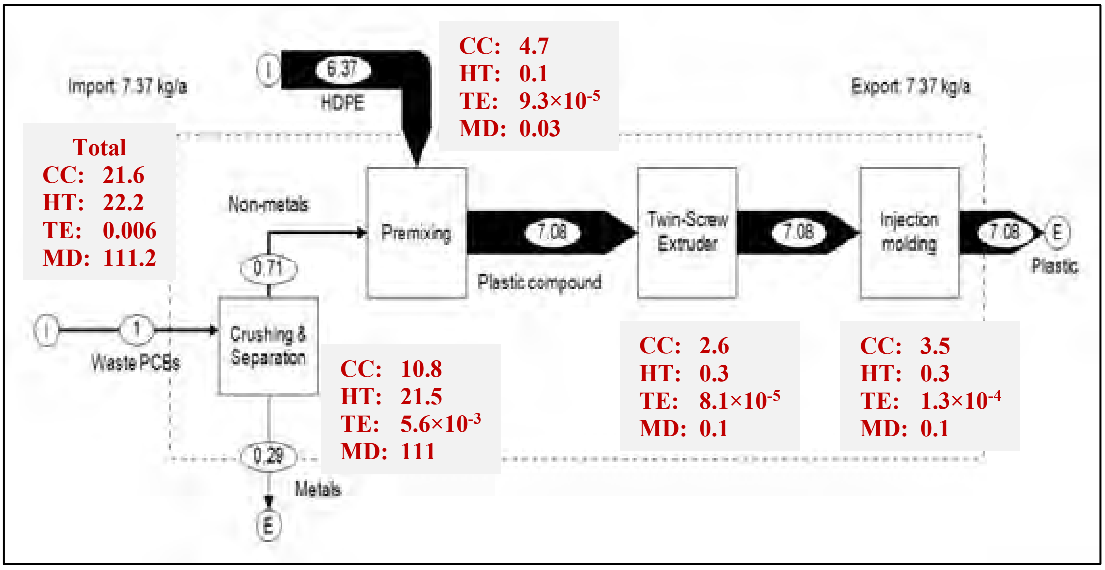


Figure 4.21 Combined MFA and LCA in recycling of waste PCBs management (Option III); CC: Climate change (kg CO_2-eq), HT: Human toxicity (kg 1,4-Db-eq), TE: Terrestrial ecotoxicity (kg 1,4-DB-eq), MD: Metal depletion (kg Fe-eq).

4.6 Environmental Impacts for Recycling of Non-Metallic Waste PCBs with Virgin HDPE (Option III) in Different Ratio

For the application of NM-PCBs (Nithitanakul *et al.*, 2017), they applied NM-PCBs in virgin HDPE at various ratios. To find the uncertainty on environmental impacts from the different mixing ratios, the weight ratio of NM-PCBs and virgin HDPE was calculated with 10:90, 30:70 and 40:60, respectively. The results of the four environmental impacts on the different mixing ratio of the compounded resin are shown in Figure 4.22 which indicated that the aggregate environmental impacts from the different mixing ratio significantly increased or decreased linear. At the higher ratio of NM-PCBs, climate change impact from the virgin HDPE production decreased, but from injection molding and extrusion of compounded plastic resin increased when compared with 10:90 ratio. Furthermore, more amount of NM-PCBs added was found to reduce the emissions. So, the overall climate change impact decreased when the ratio of NM-PCBs in virgin HDPE increased. Moreover, 30:70 and 40:60 mixing ratios of compounded plastic can be reduce the GHG emission by 8 and 10%, respectively which greater than 10:90 ratio that only reduce 3% of emission. In contrast, human toxicity and terrestrial ecotoxicity impacts from the injection molding and extrusion process increased as the ratio of NM-PCBs in virgin HDPE increased. It indicates that the injection molding and extrusion from production of the compounded plastic resin are the processes that could lead to the impacts. The metals mostly contaminated in NM-PCBs; therefore, the ratio of NM-PCBs increased, the contaminated metals also increased. This suggests that metal depletion impact had greatly influenced by the high ratio of NM-PCBs than the low ratio of NM-PCBs.

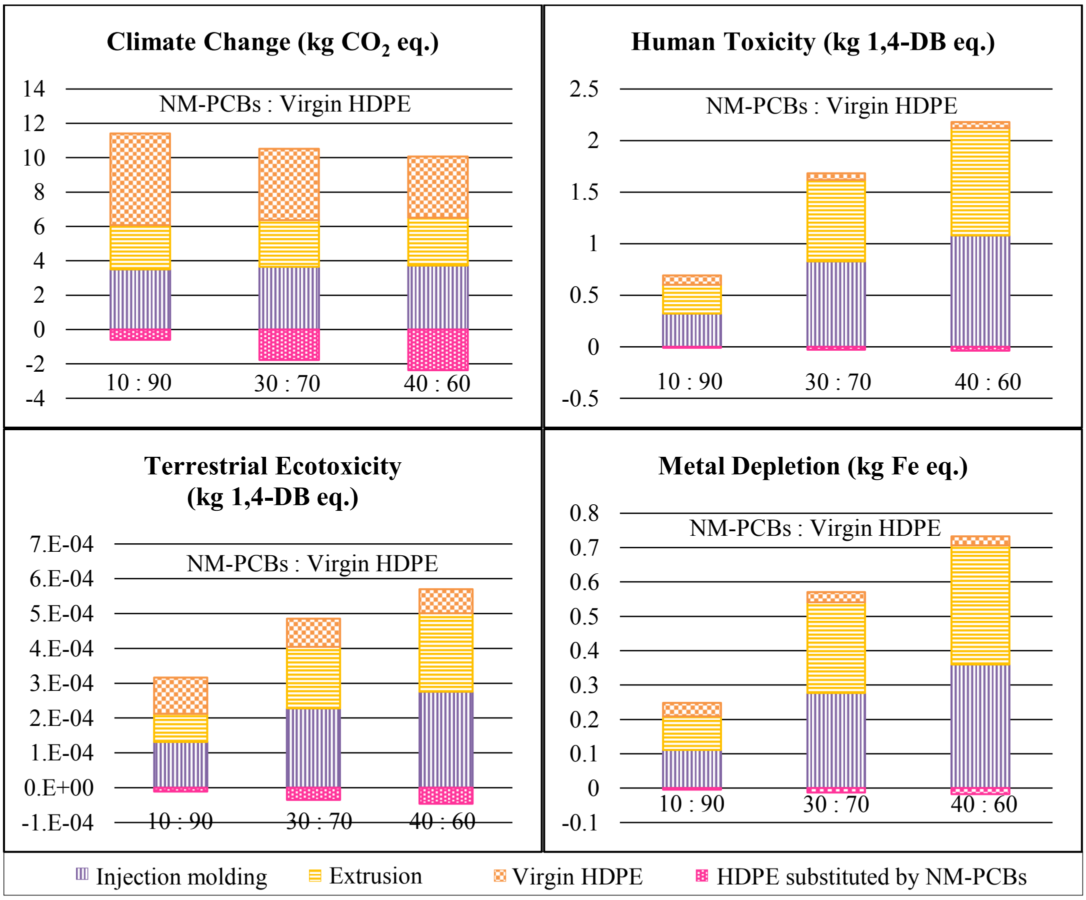


Figure 4.22 Environmental impacts in the recycling of NM-PCBs with virgin HDPE at different ratios.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The waste PCBs from Waste Electrical and Electronic Equipment (WEEE) have been discarded in large amounts and increase significantly every year. It needs to be managed properly through appropriate disposal and treatment option not only to prevent adverse environmental impacts but also increase the value-added of waste utilization. According to the current end-of-life treatment, the waste PCBs is divided into metallic part (M-PCBs) and non-metallic part (NM-PCBs). The M-PCBs can be recycled as secondary raw material in the metallurgical application, while the NM-PCBs is still be treated by combustion and/or landfilling process which can cause many environmental impacts. Therefore, the NM-PCBs must be treated properly. This study demonstrated the analysis of the waste flow and environmental impacts for the NM-PCBs by the combined analysis of material flow analysis (MFA) and life cycle assessment (LCA) methods as an assessment tool. The scenarios were developed into three options including the disposal of waste PCBs by incineration and landfill (Option I), separation as M-PCBs and NM-PCBs before disposal of waste PCBs (Option II) and physical recycling NM-PCBs by utilizing as filler in compounded HDPE resins (Option III).

In this study, MFA was used as a tool to thoroughly assess the waste PCBs flow from waste generation to its final disposal and recycled product using STAN software. For Option I, the waste PCBs was disposed of by incineration and landfilling process. It was estimated from the literature that the amount of waste PCBs landfill and incineration was 80 wt.% and 20 wt.%, respectively. In Option II, the separation of waste PCBs into M-PCBs and NM-PCBs can decrease the amount of waste that has been disposed of by landfill and incineration. Moreover, this process will obtain a surplus or separated metal substances in waste PCBs as secondary material (by-product). For Option III, the NM-PCBs was utilized (in this case, a filler). It was used as a filler by mixed with HDPE resin at 10:90 wt.% ratio to produce a plastic compound. Due to the separation process of waste PCBs, the compound resin had been contaminated with less amount of Cu and Fe.

The waste flow from MFA results was used as a dataset in the inventory data to evaluate their environmental impacts at the end-of-life stage using SimaPro software. The results indicated that there is an environmental advantage for recycling NM-PCBs (Option III) rather than consigning to landfill and incineration. The recycling option had the least impacts on climate change, human toxicity, terrestrial ecotoxicity and metal depletion due to the lower emissions generated from the incineration by the recycling process compared to Option I and II. As noted, the incineration process is the most contribution to all of the environmental impact categories. However, the separation of waste PCBs in Option II and III can rather reduce the impacts to the incineration process and, climate change and metal depletion impacts were mainly caused by the crushing process.

Moreover, the MFA was calculated to obtain the dataset used to combined with the life cycle inventory for evaluating the environmental impacts generated by three options. Although waste from Option I and II was consigned to burn in an incinerator only for 20 wt.%, the incineration had stills the highest terrestrial ecotoxicity and human toxicity impacts when compared with disposed to landfill 80 wt.%. The emissions from the crushing process of which is obtained the NM-PCBs about 71 wt.% from the waste PCBs in Option II and III is mainly contributed to the impacts. For utilization of waste PCBs, 1 kg of waste can obtain the NM-PCBs at 0.71 kg which can be used to produce the compounded plastic resin about 7.08 kg. For the recycling option, the impacts were caused by the crushing treatment rather than the recycling process (extrusion and injection molding of the compounded plastic resin and the virgin HDPE production). In addition, the variation of NM-PCBs in virgin HDPE ratios has a linear effect on the environmental impacts. At high ratio of NM-PCBs in virgin HDPE caused to the decreasing in climate change but the reduction in human toxicity and terrestrial ecotoxicity.

Therefore, the recycling of waste PCBs is an alternative route to achieve an environmentally sound alternative. The end-of-life treatment option should be developed properly to avoid environmental impacts. Furthermore, the combined MFA and LCA methods offer the assessment of waste flow and environmental impact analysis that support the alternative selection of waste PCBs management.

5.2 Recommendations

This study, the waste PCBs utilization or recycle using as an additive in a plastic composite materials can be assessed many routes based on their best archived able technology (BAT) or available products. Therefore, the recycling of waste PCBs should be developed and paid more attention from people and government to reduce the environmental impacts and protect the environment.

Furthermore, SimaPro software can be used to evaluate the environmental impacts by various methods depending on the area of interestes such as USEtox method which developed under the auspieces of the United Nations Environment Program (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC). This method is an environmental model for the characterization of human toxicity and ecotoxicological impacts through its end of life assessment and comparative risk assessment of the data used including impacts for emissions to urban air, rural air, freshwater and agricultural soil.

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APPENDIX

Appendix A The Impact Category Meaning of SimaPro Software Results by European, ReCiPe Method

The environmental impact results of waste PCBs in this study are obtained from SimaPro software which analyzed by the European, ReCiPe midpoint method with Hierarchist version (developed by RIVM, CML, Pre Consultants, Radboud University Nijmegen and CE DelftC, 2016). ReCiPe method comprises eighteen of impact categories;

1. Climate Change (kg CO_2-eq)

   Climate change causes a number of environmental mechanisms that affect both the endpoint human health and ecosystem health. They are interested in the marginal effect of adding a relatively small amount of CO_2 or other greenhouse gasses, and not the impact of all emissions.

2. Ozone Depletion (kg CFC-11-eq)

Emissions of Ozone Depleting Substances (ODSs) ultimately lead to damage to human health because of the resultant increase in UVB-radiation. Chemicals that deplete ozone are relatively persistent and have chlorine or bromine groups in their molecules that interact with ozone (mainly) in the stratosphere.

3. Terrestrial Acidification (kg SO_2-eq)

Atmospheric deposition of inorganic substances, such as sulphates, nitrates and phosphates, cause a change in acidity in the soil. For almost all plant species, there is a clearly defined optimum level of acidity. This change in acidity can affect the plant species living in the soil, causing them to disappear.

4. Freshwater Eutrophication (kg P-eq)

Freshwater eutrophication occurs due to the discharge of nutrients into soil or into freshwater bodies and the subsequent rise in nutrient levels, such as phosphorus and nitrogen. Emission impacts to fresh water are based on the transfer of phosphorus from the soil to freshwater bodies, its residence time in freshwater systems and on the potentially disappeared fraction following an increase in phosphorus concentrations in fresh water.

5. Marine Eutrophication (kg N-eq)

Marine eutrophication occurs due to the runoff and leach of plant nutrients from soil, and to the discharge of those into riverine or marine systems, and the subsequent rise in nutrient levels, such as phosphorus and nitrogen. Impacts to marine water are based on the transfer of dissolved inorganic nitrogen (DIN) from the soil and freshwater bodies, or directly to marine water.

6. Human Toxicity (kg 1,4-DB-eq)

This category concerns effects of toxic substances on the human environment. The Human Toxicity Potential is a calculated index that reflects the potential harm of a unit of chemical released into the environment, and it is based on both the inherent toxicity of a compound and its potential dose.

7. Photochemical Oxidant Formation (kg NMVOC)

Ozone is not directly emitted into the atmosphere, but it is formed as a result of photochemical reactions of NOx and Non-Methane Volatile Organic Compounds (NMVOCs). This formation process is more intense in summer. Ozone is a health hazard to humans because it can inflame airways and damage lungs. Ozone concentrations lead to an increased frequency and severity of humans with respiratory distress. Ozone formation is a non-linear process which depends on meteorological conditions and background concentrations of NOx and NMVOCs.

8. Particulate Matter Formation (kg PM_{10}-eq)

Fine Particulate Matter with a diameter of less than 10 μm (PM_{10}) represents a complex mixture of organic and inorganic substances. PM_{10} causes health problems as it reaches the upper part of the airways and lungs when inhaled. PM has both anthropogenic and natural sources. Although both may contribute significantly to PM levels in the atmosphere, this method focuses on attributive effects of PM from anthropogenic sources, since only this fraction may be influenced by human activity.

9. Terrestrial Ecotoxicity (kg 1,4-DB-eq)

This category refers to impacts of toxic substances on terrestrial ecosystems. This provides a method for describing fate, exposure and the effects of toxic substances on the environment. Characterization factors are expressed using the reference unit, kg 1,4-dichlorobenzene equivalent (1,4-DB).

10. Freshwater Ecotoxicity (kg 1,4-DB-eq)

This category indicator refers to the impact on fresh water ecosystems, as a result of emissions of toxic substances to air, water and soil.

11. Marine Ecotoxicity (kg 1,4-DB-eq)

The potential impact in the marine environment may strongly depend on the statement that additional inputs of (essential) metals to oceans also lead to toxic effects. The hierarchic scenarios include the sea and oceanic compartments in the calculation of the marine ecotoxicological impacts.

12. Ionising Radiation (kBq U235-eq)

Anthropogenic emissions of radionuclides are generated in the nuclear fuel cycle, as well as during other human activities, such as the burning of coal and the extraction of phosphate rock. Due to the longevity of some radionuclides, the fate models all use a long time horizon of 100,000 years. However, that this time horizon is relatively short compared with the half-lives of the longest lived radionuclides, such as uranium-235 (half-life 7.1·108 years).

13. Agricultural Land Occupation (m^2a)

The amount of agricultural land occupied for a certain time. This impact considers the analysis of the land area to be altered and observations of biodiversity that could be damaged.

14. Urban Land Occupation (m^2a)

The amount of urban land occupied for a certain time. This impact considers the analysis of the land area to be altered and observations of biodiversity that could be damaged.

15. Natural Land Transformation (m^2)

The amount of natural land transformed and occupied for a certain time.

16. Water Depletion (m^3)

This impact category in referred to the consumption of water resource. The value of the abiotic resource consumption of a substance (e.g. lignite or coal) is a measure of the scarcity of a substance. That means it depends on the amount of resources and the extraction rate. It is formed by the amount of resources that are depleted and measured in antimony equivalents in water consumption (in m3).

17. Metal Depletion (kg Fe-eq)

This impact category in referred to the consumption of metal resource. The value of the abiotic resource consumption of a substance (e.g. lignite or coal) is a measure of the scarcity of a substance. That means it depends on the amount of resources and the extraction rate. It is formed by the amount of resources that are depleted and measured in antimony equivalents in kg of Fe depletion.

18. Fossil Depletion (kg oil-eq)

This impact category they base the characterization factor on the projected change in the supply mix between conventional and unconventional oil sources. This transition is already ongoing as the conventional oil resources seem to be unable to satisfy the total amount. They focus on the re-placement of conventional fossil resources with unconventional fossil resources, mainly because in most scenarios these are expected to be much more important on a global scale.

Appendix B The Inventory Data Input in SimaPro Software

The inventory data in section 4.3 was described in this section which shows the name that used to input in SimaPro software. It divided into material input, electricity and heat input, emission to air and soil, and waste to treatment.

- Material input

Table B1 The material name in SimaPro software

Name	Name (SimaPro software)
Epoxy resin	Epoxy resin insulator, SiO2 {RoW}| production | Alloc Def, S
Glass fiber	Glass fibre {RoW}| production | Alloc Def, S
Copper	Copper {RoW}| production, primary | Alloc Def, S
Tin	Tin {RoW}| production | Alloc Def, S
Lead	Lead {GLO}| primary lead production from concentrate | Alloc Def, S
Ferrite	Ferrite {GLO}| production | Alloc Def, S
Nickel	Nickel, 99.5% {GLO}| smelting and refining of nickel ore | Alloc Def, S
Chromium	Chromium {RoW}| production | Alloc Def, S
Molybdenum	Molybdenum {RoW}| production | Alloc Def, S
Silver	Silver {GLO}| processing of anode slime, primary copper production | Alloc Def, S
Gold	Gold {RoW}| production | Alloc Def, S
Palladium	Palladium {RoW}| treatment of precious metal from electronics scrap, in anode slime, precious metal extraction | Alloc Def, S
Polyethylene, high density, granulate	Polyethylene, high density, granulate {RoW}| production | Alloc Def, S
Injection molding processing	Injection moulding {RoW}| processing | Alloc Def, S
Extrusion, co-extrusion of plastic sheets	Extrusion, co-extrusion {RoW}| of plastic sheets | Alloc Def, S

- Electricity and heat input

Table B2 The electricity and heat name in SimaPro software

Name	Name (SimaPro software)
Diesel fuel	Diesel, burned in agricultural machinery {GLO}| market for diesel, burned in agricultural machinery | Alloc Def, S
Electricity	Electricity, medium voltage {RoW}| electricity voltage transformation from high to medium voltage | Alloc Def, S

- Emission to air and soil

Table B3 The air and soil emission name in SimaPro software

Name	Name (SimaPro software)
Methane	Methane
Carbon dioxide	Carbon dioxide
Carbon monoxide	Carbon monoxide
NM-VOC	NMVOC, non-methane volatile organic compounds, unspecified origin
Nitrogen	Nitrogen, atmospheric
Dinitrogen monoxide	Dinitrogen monoxide
Hydrogen chloride	Hydrogen chloride
Sulfur dioxide	Sulfur dioxide
Deltamethrin	Deltamethrin
Benzene	Benzene
Cadmium	Cadmium
Chromium	Chromium
Copper	Copper
Nickel	Nickel
Zinc	Zinc
Benzo (a) pyrene	Benzo(a)pyrene
Ammonia	Ammonia (NH3)
Selenium	Selenium
PAH	PAH, polycyclic aromatic hydrocarbons
Nitrogen oxides	Nitrogen oxides
Particulates, < 2.5 µm	Particulates, < 2.5 um
Mercury	Mercury
Dioxin	Dioxins (unspec.)
Furan	Furan
Particulates	Particulates
Sulfuric acid	Sulfuric acid

- Waste to treatment

Table B4 The waste treatment name in SimaPro software

Name	Name (SimaPro software)
Waste plastic, mixture, sanitary landfill	Waste plastic, mixture {RoW}| treatment of waste plastic, mixture, sanitary landfill | Alloc Def, S
Waste plastic, consumer electronics, incineration	Waste plastic, consumer electronics {RoW}| treatment of, municipal incineration | Alloc Def, S
Waste electric and electronic equipment, shredding	Waste electric and electronic equipment {GLO}| treatment of, shredding | Alloc Def, S

Appendix C The Environmental Impact Results of Waste PCBs from SimaPro Software

The environmental impacts from waste PCBs management were evaluated using SimaPro software. The results from SimaPro was shown eighteen environmental impacts and divided into three options included the variation of ratio between NM-PCBs and virgin HDPE. These results were shown the value from treatment process and recycling process. The list of environmental impacts and unit was shown in Table C1

Table C1 Environmental impacts and unit from ReCiPe method

No.	Impact category	Unit
1	Climate change	kg CO2 eq
2	Ozone depletion	kg CFC-11 eq
3	Terrestrial acidification	kg SO2 eq
4	Freshwater eutrophication	kg P eq
5	Marine eutrophication	kg N eq
6	Human toxicity	kg 1,4-DB eq
7	Photochemical oxidant formation	kg NMVOC
8	Particulate matter formation	kg PM10 eq
9	Terrestrial ecotoxicity	kg 1,4-DB eq
10	Freshwater ecotoxicity	kg 1,4-DB eq
11	Marine ecotoxicity	kg 1,4-DB eq
12	Ionising radiation	kBq U235 eq
13	Agricultural land occupation	m2a
14	Urban land occupation	m2a
15	Natural land transformation	m2
16	Water depletion	m3
17	Metal depletion	kg Fe eq
18	Fossil depletion	kg oil eq

- **Option I**

Table C2 The SimaPro software results of landfill for disposal of waste PCBs (Option I)

No.	Total	Landfill	Epoxy resin	Glass fiber	Copper	Tin	Lead	Ferrite	Nickel	Chromium	Molybdenum	Silver	Gold	Palladium	Waste plastic, mixture, sanitary landfill
1	12.796	2.01425	0.87605	0.95760	0.74309	1.33674	0.04877	0.07593	0.22991	0.11428	0.01260	0.02180	2.98651	3.28940	0.08871
2	0.000	0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00001	0.00000
3	0.202	0.020	0.00506	0.00643	0.07037	0.02606	0.00109	0.00045	0.02263	0.00055	0.00027	0.00094	0.02968	0.01837	0.00008
4	0.054	0	0.00001	0.00005	0.00838	0.00006	0.00004	0.00000	0.00013	0.00001	0.00030	0.00009	0.04395	0.00050	0.00000
5	0.005	0	0.00018	0.00019	0.00098	0.00041	0.00002	0.00001	0.00007	0.00001	0.00003	0.00002	0.00225	0.00097	0.00013
6	21.405	1.01E-08	0.07941	0.64909	17.55236	0.08871	0.27525	0.00569	0.02514	0.00756	0.00663	0.12831	2.03185	0.55408	0.00120
7	0.092	0.0058	0.00557	0.00435	0.01370	0.01119	0.00038	0.00042	0.00342	0.00031	0.00027	0.00024	0.03402	0.01245	0.00013
8	0.079	0.0041	0.00283	0.00323	0.02161	0.01869	0.00031	0.00048	0.00498	0.00037	0.00036	0.00030	0.01389	0.00761	0.00004
9	0.006	5.93E-08	0.00002	0.00012	0.00335	0.00008	0.00001	0.00002	0.00004	0.00001	0.00000	0.00004	0.00161	0.00028	0.00000
10	0.029	3.08E-08	0.00034	0.00110	0.00349	0.00080	0.00019	0.00008	0.00018	0.00009	0.00007	0.00004	0.02107	0.00128	0.00008
11	0.225	5.10E-08	0.00023	0.00108	0.18746	0.00066	0.00027	0.00014	0.00054	0.00007	0.00010	0.00139	0.02616	0.00671	0.00004
12	0.390	0	0.00103	0.02983	0.02559	0.06001	0.00104	0.00375	0.00910	0.00345	0.00046	0.00128	0.16895	0.08432	0.00105
13	0.409	0	0.00122	0.02872	0.06876	0.04720	0.00351	0.00413	0.01126	0.00349	0.00127	0.00455	0.13903	0.09510	0.00100
14	0.821	0	0.00103	0.00709	0.06370	0.07395	0.00069	0.00229	0.00699	0.00094	0.00216	0.00100	0.62118	0.03625	0.00381
15	0.008	0	0.00001	0.00017	0.00031	0.00490	0.00001	0.00002	0.00008	0.00002	0.00001	0.00001	0.00189	0.00037	-0.00004
16	0.135	0	0.01985	0.00822	0.01641	0.01624	0.00050	0.00054	0.00133	0.00073	0.00040	0.00038	0.02667	0.04345	0.00028
17	110.683	0	0.00178	0.06866	7.02669	83.97318	0.05611	2.61640	0.19416	0.12812	0.24864	0.09301	15.37220	0.90345	0.00067
18	3.430	0	0.34411	0.26157	0.17732	0.34065	0.00964	0.02012	0.05827	0.02798	0.00283	0.00647	0.84840	1.32630	0.00617

Table C3 The SimaPro software results of incineration for disposal of waste PCBs (Option I)

No.	Total	Landfill	Epoxy resin	Glass fiber	Copper	Tin	Lead	Ferrite	Nickel	Chromium	Molybdenum	Silver	Gold	Palladium	Diesel	Waste plastic, consumer, incineration
1	13.792	0.0012	0.87560	0.95769	0.74429	1.33674	0.04878	0.07593	0.22987	0.11444	0.01240	0.02180	3.06118	3.21630	0.00323	3.09226
2	0.000	0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00001	0.00000	0.00000
3	0.183	9.98E-06	0.00505	0.00643	0.07049	0.02606	0.00109	0.00045	0.02262	0.00055	0.00026	0.00094	0.03042	0.01796	0.00002	0.00062
4	0.055	0	0.00001	0.00005	0.00839	0.00006	0.00004	0.00000	0.00013	0.00001	0.00030	0.00009	0.04505	0.00049	0.00000	0.00000
5	0.005	6.68E-07	0.00018	0.00019	0.00098	0.00041	0.00002	0.00001	0.00007	0.00001	0.00003	0.00002	0.00231	0.00095	0.00000	0.00008
6	111664822.564	1.12E+08	0.07937	0.64916	17.58077	0.08871	0.27529	0.00569	0.02514	0.00757	0.00653	0.12831	2.08264	0.54177	0.00038	1.09245
7	0.088	1.83E-05	0.00557	0.00435	0.01372	0.01119	0.00038	0.00042	0.00342	0.00031	0.00027	0.00024	0.03487	0.01218	0.00002	0.00096
8	0.075	5.54E-06	0.00283	0.00323	0.02164	0.01869	0.00031	0.00048	0.00498	0.00037	0.00036	0.00030	0.01424	0.00744	0.00001	0.00025
9	368.955	368.946	0.00002	0.00012	0.00336	0.00008	0.00001	0.00002	0.00004	0.00001	0.00000	0.00004	0.00165	0.00027	0.00000	0.00365
10	12.704	12.442	0.00034	0.00110	0.00350	0.00080	0.00019	0.00008	0.00018	0.00009	0.00007	0.00004	0.02160	0.00125	0.00000	0.23275
11	2136.812	2136.532	0.00023	0.00108	0.18776	0.00066	0.00027	0.00014	0.00054	0.00007	0.00010	0.00139	0.02682	0.00656	0.00000	0.05455
12	0.392	0	0.00103	0.02983	0.02564	0.06001	0.00104	0.00375	0.00910	0.00345	0.00045	0.00128	0.17317	0.08245	0.00013	0.00088
13	0.411	0	0.00122	0.02872	0.06887	0.04720	0.00351	0.00413	0.01126	0.00350	0.00125	0.00455	0.14251	0.09299	0.00049	0.00079
14	0.833	0	0.00103	0.00709	0.06380	0.07395	0.00069	0.00229	0.00699	0.00094	0.00213	0.00100	0.63671	0.03545	0.00010	0.00061
15	0.008	0	0.00001	0.00017	0.00031	0.00490	0.00001	0.00002	0.00008	0.00002	0.00001	0.00001	0.00194	0.00036	0.00000	0.00000
16	0.136	0	0.01984	0.00822	0.01643	0.01624	0.00050	0.00054	0.00133	0.00073	0.00040	0.00038	0.02734	0.04249	0.00002	0.00191
17	111.057	0	0.00178	0.06867	7.03806	83.97318	0.05612	2.61640	0.19413	0.12830	0.24481	0.09301	15.75650	0.88337	0.00038	0.00263
18	3.428	0	0.34394	0.26159	0.17760	0.34065	0.00965	0.02012	0.05826	0.02802	0.00279	0.00647	0.86962	1.29683	0.00091	0.01160

- **Option II**

Table C4 The SimaPro software results of crushing for separation of waste PCBs before disposal (Option II)

No.	Total	Landfill	Epoxy resin	Glass fiber	Copper	Tin	Lead	Ferrite	Nickel	Chromium	Molybdenum	Silver	Gold	Palladium	Electricity	WEEE, shredding
1	10.809	0	0.87615	0.95769	0.74328	1.33674	0.04885	0.07601	0.23008	0.11444	0.01248	0.02180	3.07611	3.21630	0.04510	0.05352
2	0.000	0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00001	0.00000	0.00000
3	0.183	5.93E-05	0.00506	0.00643	0.07039	0.02606	0.00109	0.00045	0.02264	0.00055	0.00026	0.00094	0.03057	0.01796	0.00024	0.00027
4	0.055	0	0.00001	0.00005	0.00838	0.00006	0.00004	0.00000	0.00013	0.00001	0.00030	0.00009	0.04527	0.00049	0.00000	0.00000
5	0.005	3.97E-06	0.00018	0.00019	0.00098	0.00041	0.00002	0.00001	0.00007	0.00001	0.00003	0.00002	0.00232	0.00095	0.00001	0.00001
6	21.472	0	0.07942	0.64916	17.55685	0.08871	0.27571	0.00570	0.02516	0.00757	0.00657	0.12831	2.09280	0.54177	0.00157	0.01320
7	0.087	9.70E-05	0.00557	0.00435	0.01370	0.01119	0.00038	0.00042	0.00343	0.00031	0.00027	0.00024	0.03504	0.01218	0.00013	0.00014
8	0.075	2.20E-05	0.00283	0.00323	0.02161	0.01869	0.00031	0.00048	0.00498	0.00037	0.00036	0.00030	0.01431	0.00744	0.00010	0.00017
9	0.006	0	0.00002	0.00012	0.00336	0.00008	0.00001	0.00002	0.00004	0.00001	0.00000	0.00004	0.00166	0.00027	0.00000	0.00002
10	0.029	0	0.00034	0.00110	0.00349	0.00080	0.00019	0.00008	0.00018	0.00009	0.00007	0.00004	0.02170	0.00125	0.00003	0.00004
11	0.226	0	0.00023	0.00108	0.18751	0.00066	0.00027	0.00014	0.00054	0.00007	0.00010	0.00139	0.02695	0.00656	0.00003	0.00021
12	0.396	0	0.00103	0.02983	0.02560	0.06001	0.00104	0.00376	0.00911	0.00345	0.00046	0.00128	0.17401	0.08245	0.00091	0.00306
13	0.420	0	0.00122	0.02872	0.06878	0.04720	0.00352	0.00413	0.01127	0.00350	0.00126	0.00455	0.14320	0.09299	0.00519	0.00443
14	0.836	0	0.00103	0.00709	0.06371	0.07395	0.00069	0.00230	0.00699	0.00094	0.00214	0.00100	0.63981	0.03545	0.00023	0.00051
15	0.008	0	0.00001	0.00017	0.00031	0.00490	0.00001	0.00002	0.00008	0.00002	0.00001	0.00001	0.00195	0.00036	0.00001	0.00001
16	0.136	0	0.01985	0.00822	0.01641	0.01624	0.00050	0.00054	0.00133	0.00073	0.00040	0.00038	0.02747	0.04249	0.00056	0.00041
17	111.129	0	0.00178	0.06867	7.02849	83.97318	0.05621	2.61912	0.19430	0.12830	0.24634	0.09301	15.83336	0.88337	0.00044	0.00281
18	3.448	0	0.34415	0.26159	0.17736	0.34065	0.00966	0.02014	0.05831	0.02802	0.00281	0.00647	0.87386	1.29683	0.01453	0.01336

Table C5 The SimaPro software results of landfill for separation of waste PCBs before disposal (Option II)

No.	Total	Landfill	Epoxy resin	Glass fiber	Copper	Ferrite	Waste plastic, mixture, sanitary landfill
1	2.743	0	1.23590	1.35124	0.06396	0.00367	0.08871
2	0.000	0	0.00000	0.00000	0.00000	0.00000	0.00000
3	0.022	0	0.00713	0.00908	0.00606	0.00002	0.00008
4	0.001	0	0.00001	0.00006	0.00072	0.00000	0.00000
5	0.001	0	0.00026	0.00026	0.00008	0.00000	0.00013
6	2.540	0	0.11203	0.91592	1.51068	0.00027	0.00120
7	0.015	0	0.00786	0.00613	0.00118	0.00002	0.00013
8	0.010	0	0.00399	0.00455	0.00186	0.00002	0.00004
9	0.000	0	0.00003	0.00016	0.00029	0.00000	0.00000
10	0.002	0	0.00048	0.00155	0.00030	0.00000	0.00008
11	0.018	0	0.00033	0.00152	0.01613	0.00001	0.00004
12	0.047	0	0.00145	0.04209	0.00220	0.00018	0.00105
13	0.049	0	0.00172	0.04053	0.00592	0.00020	0.00100
14	0.021	0	0.00145	0.01000	0.00548	0.00011	0.00381
15	0.000	0	0.00001	0.00024	0.00003	0.00000	-0.00004
16	0.041	0	0.02800	0.01160	0.00141	0.00003	0.00028
17	0.831	0	0.00251	0.09689	0.60477	0.12631	0.00067
18	0.877	0	0.48546	0.36909	0.01526	0.00097	0.00617

Table C6 The SimaPro software results of incineration for separation of waste PCBs before disposal (Option II)

No.	Total	Incineration	Epoxy resin	Glass fiber	Copper	Ferrite	Electricity	Waste plastic, consumer electronics, incineration
1	6.739	0.950	1.23691	1.35205	0.06402	0.00367	0.03946	3.09226
2	0.000	0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
3	0.023	1.42E-07	0.00714	0.00908	0.00606	0.00002	0.00021	0.00062
4	0.001	0	0.00001	0.00006	0.00072	0.00000	0.00000	0.00000
5	0.001	0	0.00026	0.00026	0.00008	0.00000	0.00000	0.00008
6	1.10E+08	1.10E+08	0.11212	0.91647	1.51221	0.00028	0.00137	1.09245
7	0.016	1.20E-08	0.00786	0.00614	0.00118	0.00002	0.00012	0.00096
8	0.011	2.84E-08	0.00399	0.00456	0.00186	0.00002	0.00009	0.00025
9	1.750	1.75	0.00003	0.00016	0.00029	0.00000	0.00000	0.00365
10	0.833	0.60	0.00048	0.00155	0.00030	0.00000	0.00002	0.23275
11	1.804	1.73	0.00033	0.00152	0.01615	0.00001	0.00002	0.05455
12	0.048	0	0.00146	0.04212	0.00221	0.00018	0.00080	0.00088
13	0.054	0	0.00172	0.04055	0.00592	0.00020	0.00455	0.00079
14	0.018	0	0.00146	0.01000	0.00549	0.00011	0.00020	0.00061
15	0.000	0	0.00001	0.00024	0.00003	0.00000	0.00001	0.00000
16	0.043	0	0.02802	0.01161	0.00141	0.00003	0.00049	0.00191
17	0.834	0	0.00251	0.09694	0.60538	0.12660	0.00038	0.00263
18	0.896	0	0.48586	0.36931	0.01528	0.00097	0.01271	0.01160

- **Option III**

Table C7 The SimaPro software results of injection molding for mixture plastic (Option III, NM-PCBs: HDPE = 10: 90)

No.	Total	Injection Molding	Epoxy resin	Glass fiber	Copper	Ferrite	Polyethylene, high density	Injection moulding processing
1	3.506	0	0.12371	0.13522	0.00640	0.00037	1.73520	1.50542
2	0.000	0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
3	0.015	0	0.00071	0.00091	0.00061	0.00000	0.00533	0.00699
4	0.000	0	0.00000	0.00001	0.00007	0.00000	0.00000	0.00008
5	0.000	0	0.00003	0.00003	0.00001	0.00000	0.00012	0.00014
6	0.321	0	0.01121	0.09166	0.15114	0.00003	0.00822	0.05876
7	0.014	0	0.00079	0.00061	0.00012	0.00000	0.00778	0.00428
8	0.007	0	0.00040	0.00046	0.00019	0.00000	0.00178	0.00461
9	0.000	0	0.00000	0.00002	0.00003	0.00000	0.00000	0.00008
10	0.002	0	0.00005	0.00016	0.00003	0.00000	0.00033	0.00146
11	0.003	0	0.00003	0.00015	0.00161	0.00000	0.00014	0.00095
12	0.075	0	0.00015	0.00421	0.00022	0.00002	0.00019	0.06974
13	0.227	0	0.00017	0.00406	0.00059	0.00002	0.00041	0.22179
14	0.014	0	0.00015	0.00100	0.00055	0.00001	0.00018	0.01167
15	0.000	0	0.00000	0.00002	0.00000	0.00000	0.00000	0.00029
16	0.029	0	0.00280	0.00116	0.00014	0.00000	0.01065	0.01419
17	0.111	0	0.00025	0.00970	0.06050	0.01266	0.00133	0.02676
18	1.977	0	0.04859	0.03694	0.00153	0.00010	1.43165	0.45780

Table C8 The SimaPro software results of extrusion for mixture plastic (Option III, NM-PCBs: HDPE = 10: 90)

No.	Total	Extrusion	Epoxy resin	Glass fiber	Copper	Ferrite	Polyethylene, high density	Extrusion of plastic sheets
1	2.570	0	0.12371	0.13522	0.00640	0.00037	1.73520	0.56907
2	0.000	0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
3	0.010	0	0.00071	0.00091	0.00061	0.00000	0.00533	0.00260
4	0.000	0	0.00000	0.00001	0.00007	0.00000	0.00000	0.00003
5	0.000	0	0.00003	0.00003	0.00001	0.00000	0.00012	0.00006
6	0.282	0	0.01121	0.09166	0.15114	0.00003	0.00822	0.01983
7	0.011	0	0.00079	0.00061	0.00012	0.00000	0.00778	0.00144
8	0.005	0	0.00040	0.00046	0.00019	0.00000	0.00178	0.00178
9	0.000	0	0.00000	0.00002	0.00003	0.00000	0.00000	0.00003
10	0.001	0	0.00005	0.00016	0.00003	0.00000	0.00033	0.00036
11	0.002	0	0.00003	0.00015	0.00161	0.00000	0.00014	0.00028
12	0.035	0	0.00015	0.00421	0.00022	0.00002	0.00019	0.03034
13	0.034	0	0.00017	0.00406	0.00059	0.00002	0.00041	0.02861
14	0.006	0	0.00015	0.00100	0.00055	0.00001	0.00018	0.00435
15	0.000	0	0.00000	0.00002	0.00000	0.00000	0.00000	0.00007
16	0.019	0	0.00280	0.00116	0.00014	0.00000	0.01065	0.00416
17	0.098	0	0.00025	0.00970	0.06050	0.01266	0.00133	0.01335
18	1.657	0	0.04859	0.03694	0.00153	0.00010	1.43165	0.13845

Table C9 The SimaPro software results of injection molding for mixture plastic (Option III, NM-PCBs: HDPE = 30: 70)

No.	Total	Injection Molding	Epoxy resin	Glass fiber	Copper	Ferrite	Polyethylene, high density	Injection moulding processing
1	3.652	0	0.37109	0.40563	0.01920	0.00110	1.34959	1.50542
2	0.000	0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
3	0.018	0	0.00214	0.00272	0.00182	0.00001	0.00414	0.00699
4	0.000	0	0.00000	0.00002	0.00022	0.00000	0.00000	0.00008
5	0.000	0	0.00008	0.00008	0.00003	0.00000	0.00009	0.00014
6	0.827	0	0.03364	0.27495	0.45358	0.00008	0.00639	0.05876
7	0.015	0	0.00236	0.00184	0.00035	0.00001	0.00605	0.00428
8	0.009	0	0.00120	0.00137	0.00056	0.00001	0.00139	0.00461
9	0.000	0	0.00001	0.00005	0.00009	0.00000	0.00000	0.00008
10	0.002	0	0.00014	0.00047	0.00009	0.00000	0.00025	0.00146
11	0.006	0	0.00010	0.00046	0.00484	0.00000	0.00011	0.00095
12	0.084	0	0.00044	0.01264	0.00066	0.00005	0.00015	0.06974
13	0.237	0	0.00052	0.01217	0.00178	0.00006	0.00032	0.22179
14	0.017	0	0.00044	0.00300	0.00165	0.00003	0.00014	0.01167
15	0.000	0	0.00000	0.00007	0.00001	0.00000	0.00000	0.00029
16	0.035	0	0.00841	0.00348	0.00042	0.00001	0.00828	0.01419
17	0.277	0	0.00075	0.02908	0.18158	0.03793	0.00103	0.02676
18	1.833	0	0.14576	0.11080	0.00458	0.00029	1.11350	0.45780

Table C10 The SimaPro software results of extrusion for mixture plastic (Option III, NM-PCBs: HDPE = 30: 70)

No.	Total	Extrusion	Epoxy resin	Glass fiber	Copper	Ferrite	Polyethylene, high density	Extrusion of plastic sheets
1	2.716	0.0	0.37109	0.40563	0.01920	0.00110	1.34959	0.56907
2	0.000	0.0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
3	0.013	0.0	0.00214	0.00272	0.00182	0.00001	0.00414	0.00260
4	0.000	0.0	0.00000	0.00002	0.00022	0.00000	0.00000	0.00003
5	0.000	0.0	0.00008	0.00008	0.00003	0.00000	0.00009	0.00006
6	0.788	0.0	0.03364	0.27495	0.45358	0.00008	0.00639	0.01983
7	0.012	0.0	0.00236	0.00184	0.00035	0.00001	0.00605	0.00144
8	0.006	0.0	0.00120	0.00137	0.00056	0.00001	0.00139	0.00178
9	0.000	0.0	0.00001	0.00005	0.00009	0.00000	0.00000	0.00003
10	0.001	0.0	0.00014	0.00047	0.00009	0.00000	0.00025	0.00036
11	0.006	0.0	0.00010	0.00046	0.00484	0.00000	0.00011	0.00028
12	0.044	0.0	0.00044	0.01264	0.00066	0.00005	0.00015	0.03034
13	0.043	0.0	0.00052	0.01217	0.00178	0.00006	0.00032	0.02861
14	0.010	0.0	0.00044	0.00300	0.00165	0.00003	0.00014	0.00435
15	0.000	0.0	0.00000	0.00007	0.00001	0.00000	0.00000	0.00007
16	0.025	0.0	0.00841	0.00348	0.00042	0.00001	0.00828	0.00416
17	0.264	0.0	0.00075	0.02908	0.18158	0.03793	0.00103	0.01335
18	1.513	0.0	0.14576	0.11080	0.00458	0.00029	1.11350	0.13845

Table C11 The SimaPro software results of injection molding for mixture plastic (Option III, NM-PCBs: HDPE = 40: 60)

No.	Total	Injection Molding	Epoxy resin	Glass fiber	Copper	Ferrite	Polyethylene, high density	Injection moulding processing
1	3.725	0	0.49492	0.54089	0.02559	0.00147	1.15680	1.50542
2	0.000	0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
3	0.019	0	0.00286	0.00363	0.00242	0.00001	0.00355	0.00699
4	0.000	0	0.00000	0.00003	0.00029	0.00000	0.00000	0.00008
5	0.000	0	0.00010	0.00011	0.00003	0.00000	0.00008	0.00014
6	1.080	0	0.04486	0.36664	0.60454	0.00011	0.00548	0.05876
7	0.016	0	0.00315	0.00245	0.00047	0.00001	0.00519	0.00428
8	0.010	0	0.00160	0.00182	0.00074	0.00001	0.00119	0.00461
9	0.000	0	0.00001	0.00007	0.00012	0.00000	0.00000	0.00008
10	0.003	0	0.00019	0.00062	0.00012	0.00000	0.00022	0.00146
11	0.008	0	0.00013	0.00061	0.00646	0.00000	0.00009	0.00095
12	0.088	0	0.00058	0.01685	0.00088	0.00007	0.00013	0.06974
13	0.241	0	0.00069	0.01622	0.00237	0.00008	0.00027	0.22179
14	0.019	0	0.00058	0.00400	0.00219	0.00004	0.00012	0.01167
15	0.000	0	0.00000	0.00010	0.00001	0.00000	0.00000	0.00029
16	0.038	0	0.01121	0.00464	0.00057	0.00001	0.00710	0.01419
17	0.360	0	0.00101	0.03878	0.24202	0.05056	0.00089	0.02676
18	1.761	0	0.19440	0.14774	0.00611	0.00039	0.95443	0.45780

Table C12 The SimaPro software results of extrusion for mixture plastic (Option III, NM-PCBs: HDPE = 40: 60)

No.	Total	Extrusion	Epoxy resin	Glass fiber	Copper	Ferrite	Polyethylene, high density	Extrusion of plastic sheets
1	2.789	0	0.49492	0.54089	0.02559	0.00147	1.15680	0.56907
2	0.000	0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
3	0.015	0	0.00286	0.00363	0.00242	0.00001	0.00355	0.00260
4	0.000	0	0.00000	0.00003	0.00029	0.00000	0.00000	0.00003
5	0.000	0	0.00010	0.00011	0.00003	0.00000	0.00008	0.00006
6	1.041	0	0.04486	0.36664	0.60454	0.00011	0.00548	0.01983
7	0.013	0	0.00315	0.00245	0.00047	0.00001	0.00519	0.00144
8	0.007	0	0.00160	0.00182	0.00074	0.00001	0.00119	0.00178
9	0.000	0	0.00001	0.00007	0.00012	0.00000	0.00000	0.00003
10	0.002	0	0.00019	0.00062	0.00012	0.00000	0.00022	0.00036
11	0.008	0	0.00013	0.00061	0.00646	0.00000	0.00009	0.00028
12	0.049	0	0.00058	0.01685	0.00088	0.00007	0.00013	0.03034
13	0.048	0	0.00069	0.01622	0.00237	0.00008	0.00027	0.02861
14	0.011	0	0.00058	0.00400	0.00219	0.00004	0.00012	0.00435
15	0.000	0	0.00000	0.00010	0.00001	0.00000	0.00000	0.00007
16	0.028	0	0.01121	0.00464	0.00057	0.00001	0.00710	0.00416
17	0.347	0	0.00101	0.03878	0.24202	0.05056	0.00089	0.01335
18	1.442	0	0.19440	0.14774	0.00611	0.00039	0.95443	0.13845

Table C13 The SimaPro software results of injection molding for virgin HDPE (Option III)

No.	Total	Injection molding	Polyethylene, high density	Injection moulding processing
1	3.433	0	1.92800	1.50542
2	0.000	0	0.00000	0.00000
3	0.013	0	0.00592	0.00699
4	0.000	0	0.00000	0.00008
5	0.000	0	0.00013	0.00014
6	0.068	0	0.00913	0.05876
7	0.013	0	0.00864	0.00428
8	0.007	0	0.00198	0.00461
9	0.000	0	0.00001	0.00008
10	0.002	0	0.00036	0.00146
11	0.001	0	0.00015	0.00095
12	0.070	0	0.00021	0.06974
13	0.222	0	0.00045	0.22179
14	0.012	0	0.00020	0.01167
15	0.000	0	0.00000	0.00029
16	0.026	0	0.01183	0.01419
17	0.028	0	0.00148	0.02676
18	2.049	0	1.59072	0.45780

Table C14 The SimaPro software results of extrusion for virgin HDPE (Option III)

No.	Total	Extrusion	Polyethylene, high density, production	Extrusion, co-extrusion of plastic sheets
1	2.497	0	1.92800	0.56907
2	0.000	0	0.00000	0.00000
3	0.009	0	0.00592	0.00260
4	0.000	0	0.00000	0.00003
5	0.000	0	0.00013	0.00006
6	0.029	0	0.00913	0.01983
7	0.010	0	0.00864	0.00144
8	0.004	0	0.00198	0.00178
9	0.000	0	0.00001	0.00003
10	0.001	0	0.00036	0.00036
11	0.000	0	0.00015	0.00028
12	0.031	0	0.00021	0.03034
13	0.029	0	0.00045	0.02861
14	0.005	0	0.00020	0.00435
15	0.000	0	0.00000	0.00007
16	0.016	0	0.01183	0.00416
17	0.015	0	0.00148	0.01335
18	1.729	0	1.59072	0.13845

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Proceeding:

1. Charoensaeng, A., Khaodhiar, S., and Nithitanakul, M. (2019, May 30) Evaluation of Environmental Impacts for end of life treatment of Non-metallic Part from Waste Printed Circuit Boards (PCBs) through Enhanced using Life Cycle assessment (LCA). Proceedings of The 25th PPC Symposium on Petroleum, Petrochemicals, and Polymers and The 10th Research Symposium on Petrochemicals and Materials Technology, Bangkok, Thailand.