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Recycling Mobile Phone Impact on Life Cycle Assessment

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Abstract

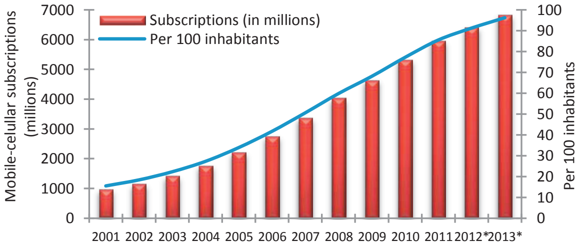
Electronic waste (e-waste) is one of the fastest growing waste streams in the world due to the rapid pace of technology enhancement and development. The exponential growth of e-waste contributes to a rapid increase in the rate of contaminants and waste entering landfills. This paper assesses the waste produced from the recycling of mobile phones in different countries highlighting the material flows and the amount of waste released to the environment. A comparison of mobile phone Printed Circuit Boards (PCBs) recycling through the formal recycling facilities in Malaysia and Australia were used as case studies. The results presented highlight the toxicity of waste and the impact to the environment.
A life cycle assessment (LCA) approach was carried out focusing on the end-of-life (EOL) phase of mobile phone PCBs. The IMPACT 2002+ version 2.10 was used as the assessment tool to indicate the environmental impacts quantitatively. The results show the toxicity of the waste produced from the mobile phone PCBs recycling in Malaysia and Australia. This study identifies that the demand for recycled materials, law enforcement, and the e-waste recycling system are significant drivers to reduce the environmental impact of mobile phone recycling.

Keywords: Life Cycle Assessment; e-waste; recycling; waste

1. Introduction

Electronic waste better known as e-waste has been one of the major contributors to the waste stream since the rapid growth of advanced technology products [1][2]. E-waste includes various sizes of electrical and electronic products such as washing machines, televisions, desktop computers, laptops and mobile phones. It is estimated that every 5 years, an increment of 16-28% of e-waste is further produced in the European region [3]. The exponential growth of e-waste in many countries is at a concerning stage due to the challenges facing e-waste disposal. The impacts of e-waste disposal in Asia has been known, however this issue is growing beyond the Asia region [4].

The use phase of mobile phones is one of the shortest for electronic products, and it is getting shorter leading to an increase of e-waste. The use phase of mobile phone is on average 3 years in developing countries [5] or less than 2 years in developed countries [6][7]. This phenomenon is due to the technology advances and high market demand for newer features and styles [7][8][9], making phones obsolete prior to the end of their functional life span. Coupled with the growth in mobile phone subscriptions (Figure 1), it is one of the fastest growing global waste streams [6].



Note: * Estimate
Source: ITU World Telecommunication /ICT Indicators database

Figure 1: Global Mobile-Cellular Subscriptions, Total and per 100 Inhabitants, 2001-2013 [10].

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The toxicity of waste produced by mobile phones is driven by the recycling systems in different countries. In developing countries, mobile phones are usually not disposed through the right waste stream for recycling due to the dominance of informal recycling sectors [9][10]. Informal recycling sectors have no proper materials recovery facilities and often produce more waste with higher toxicity. The formal recycling sectors struggle to compete with the informal sectors because of the unwillingness to pay for recycling fee to treat waste before it is discarded [10]. In contrast, developed countries have better mobile phone collection systems through the high exposure and awareness via programs such as extended producer responsibility [11]. Moreover, collaboration between manufacturers creates a more cohesive program that encourages a higher mobile phone collection rate among consumers. Therefore, the material flows of obsolete mobile phone into the formal and informal sectors largely determine the final disposal of e-waste. The treated waste stream in formal facilities reduces the toxicity of waste being landfilled in line with local legislation.

The end-of-life (EOL) phase for mobile phones generates a high amount of toxic waste which imposes severe impacts on human health and the environment [12][13]. EOL recycling is crucial to recover materials and avoid extraction of natural resources. Formal recycling facilities have the provision to retrieve precious metals and treat the waste before being released to the environment. However, waste treatment process reduces the revenue of recycling companies and does not generate financial gain. Moreover, the material flows of obsolete mobile phones play a major role in contributing to the overall environmental impact.

This paper aims to investigate the toxicity of waste produced at the EOL phase from the perspective of material flows using the standard life cycle assessment method [14]. There are many life cycle assessments (LCA) of e-waste or specifically mobile phones carried out. Most of the research analyses the overall environmental impact throughout all phases of the life-cycle. In this paper, the material flows of mobile phone Printed Circuit Boards (PCBs) through the formal recycling facilities in Malaysia and Australia will be used as the case study comparison. The influential factors that reduce the emission of hazardous toxic waste at the EOL phase and the overall LCA of mobile phones will be identified.

2. Mobile Phones Recycling in Malaysia

Malaysia is one of the developing countries that have a rapid growth of e-waste streams, especially mobile phones leading to the introduction of e-waste related legislations. Statistical data has shown that consumers have the ability to afford more than one mobile phone at a time [15]. This issue has initiated the government to establish e-waste related legislations such as, Environmental Quality (Scheduled Wastes) Regulations 2005 to replace the 1989 regulation to enable Malaysia to control transnational movements of e-waste; Custom Order (Prohibition of Import/Export) Order 2008 to prohibit importation and exportation of e-waste illegally in Malaysia; and guidelines for classification of used Electrical and Electronic Equipment in Malaysia [16]. Nevertheless, Malaysia still receives and dispatches e-waste illegally [17].

The e-waste recycling system in Malaysia is driven by three major aspects: incentives for take-back, law enforcement and the level of public awareness among consumers [9]. The collection rate for obsolete mobile phones is still low especially into formal recycling facilities due to the incentives offered by the informal sector. Despite of the effort by the Department of Environment Malaysia (DOE) to increase the collection rate such as multiple recycle bins located in variety public locations, there has been no significant growth, possibly because of factor such as incomplete collection infrastructure [18]. The collaboration between DOE and manufacturers such as NOKIA and SONY Ericsson to encourage mobile phones collection through service centres, collection bins and take-back schemes only generate small scale collection input and mostly are piloted by NOKIA [19][20]. A survey carried out has shown that Malaysians are not aware of e-waste recycling [19]. Moreover, weak environmental law enforcement by DOE is still ineffective to ensure industrial sectors conform to the regulations outlined [21].

2.1. Mobile Phones Flow

The two main recycling flows of obsolete mobile phones in Malaysia are namely, formal and informal sector. Formal recycling sector is licensed e-waste companies which have full recovery facilities (capable of retrieving valuable materials through chemical processes) and partial recovery facilities (capable to disassemble e-waste materials) [9]. In contrary, informal sector uses basic processes to retrieve materials without treating the waste [9]. Most of the collected mobile phones remain in Malaysia for downstream recycling. The Penang E-waste Project carried out has demonstrated that most of the obsolete mobile phones from households ended in junk shops or scrap traders (informal sector) that have low recycling facilities, as shown in Figure 2.

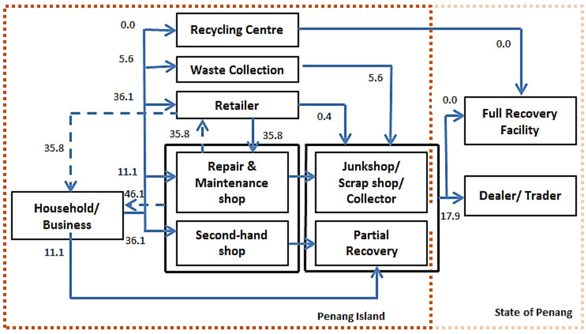

Figure 2: Household E-waste Flow of Mobile Phones in Penang in Year 2011 [22].

The collections of obsolete mobile phones into formal recycling facilities in Malaysia are mostly from industry [22] due to the larger volume of e-waste that generates a large

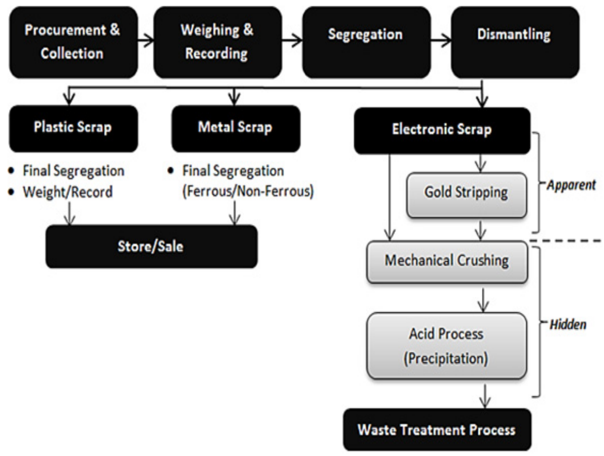

Figure 3: The current practice of full recovery facilities.

scale of revenue. The current practice of full recovery facilities in Malaysia uses hydrometallurgy process - wet chemical processes and electrolysis that facilitate high volume of e-waste recycling [9]. The overall e-waste process flow at one of the Malaysia firm is as shown in Figure 3.

3. Mobile Phones Recycling in Australia

Australia is one of the developed countries with elevated growth of e-waste streams and has been listed among the highest number of latest technology consumers [23]. The exponential growth of e-waste is estimated to be triple the amount of other municipal waste in the country [24]. The high mobile phone penetration rate since mid-1990s has initiated Australian Commonwealth legislation such as Hazard Status of Waste Electrical and Electronics Assemblies or Scrap, October 1999; and Hazardous Waste (Regulations of Exports and Imports) Act 1989 which is aligned with the Basel Convention standards [25]. The outlined e-waste related regulations are similar to Malaysia's environmental standards except that in Australia, the e-waste issue arose earlier compared to developing countries such as Malaysia.

In comparison to the e-waste recycling system in Malaysia, Australia's mobile phone collection goes through an official product stewardship program, MobileMuster. It is funded by mobile phone industry in Australia such as NOKIA, Samsung Electronics Australia, LG Electronics, Motorola, HTC, Huawei, ZTE, Force Technology, Telstra, Optus, Vodafone and Virgin Mobile [26]. It is a not-for-profit organisation which aims to ensure obsolete mobile phones are collected for ethical recycling. Moreover, it has operated nationwide across Australia since 1999 with more than 3500 drop-off points such as mobile phone retailers, government agencies, business centres and others [20]. Furthermore, MobileMuster has collaborated with local councils and Australia Post to provide free parcel services to encourage consumers to return their unwanted mobile phones for proper recycling [26]. Hence, Australia has a centralised official program that efficiently manages the collection of obsolete mobile phones. Since 2005, the collection rate of mobile phones in Australia has increased gradually from 42 tonnes to 123 tonnes and has received participation from manufacturers and mobile network carriers [27].

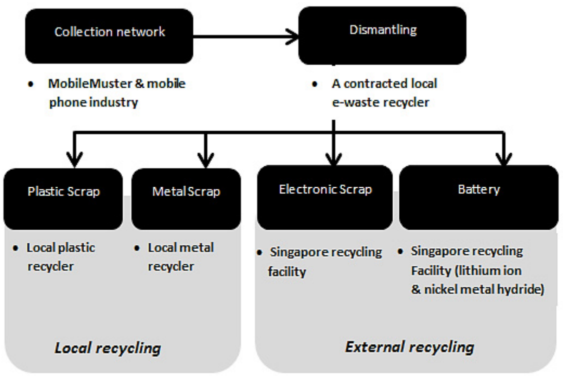

Figure 4: High Level E-waste Flow at Australia.

3.1. Mobile Phones Flow

The material flows of mobile phone in Australia are divided into two main paths: local recycling and external recycling (Figure 4). The collected mobile phones by MobileMuster are sent to an accredited and contracted recycling company in Australia. Then, the components of the obsolete mobile phones are disassembled into parts such as circuit boards, lithium ion and nickel metal hydride batteries, and accessories that will be shipped to their Singapore facility for further recycling and recovery of valuable materials [27]. Other disassembled materials such as plastics and metal frames are recycled by the respective recycling companies locally in Australia [28].

4. Scope

4.1. Objective of study

The environmental performance of mobile phone PCBs recycling in Australia and Malaysia was carried out using the life cycle assessment method in accordance to the ISO 14040 series [14][29][30][31]. The environmental impact assessment of emissions produced through the mobile phone PCBs recycling system in Malaysia and Australia involved 4 major steps: goal and scope definition, inventory analysis, impact assessment and interpretation, as shown in Figure 5. Since e-waste's precious metals are usually recovered from PCBs, the findings can be valuable for a range of general e-waste products.

4.2. System boundary

This study only took into the consideration of the EOL phase of mobile phone PCBs through the recycling systems in Malaysia and Australia (Figure 6). In addition, the toxicity of emissions produced through the e-waste recycling systems of both countries was assessed based on formal recycling facilities.

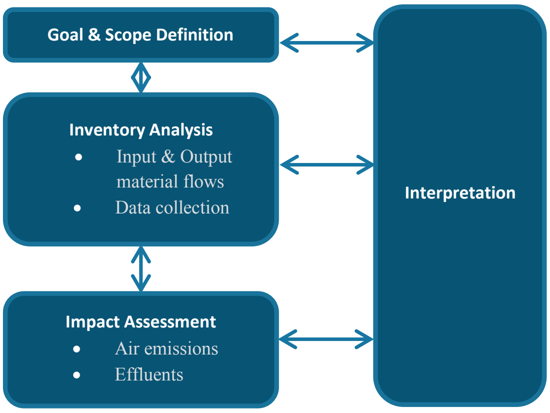

Figure 5: LCA Steps [14].

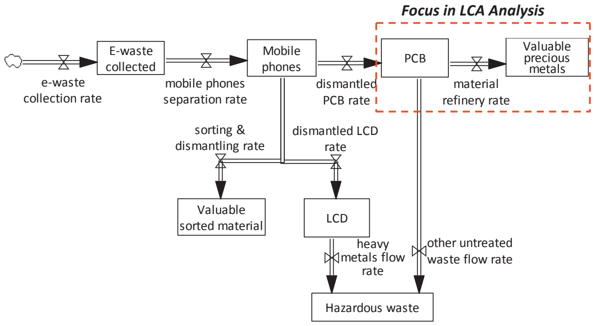

Figure 6: Mobile Phone Material Flows at the Formal Recycling Facilities.

The dismantled mobile phone PCBs underwent further processing for valuable metals recovery. Other valuable materials such as plastics, metal frames and batteries were excluded from this study because they were sent to other recyclers for further recovery processes. Liquid Crystal Displays (LCDs) that contain heavy metals such as mercury were treated at another waste treatment plant before being landfilled.

4.3. Functional Unit

The functional unit for this study was set as 1 tonne of mobile phone PCBs recycled in the formal recycling facilities. Therefore, the flow of mobile phone PCBs into the informal recycling facilities in Malaysia were not included. Mobile phone was assumed to have an average life span of 3 years in this study.

5. Method

5.1. Life Cycle Inventory (LCI)

LCI analysis involves the tracking of input and output flows of a product system that include materials, water, energy, and wastes released to the air, land and water [14]. In this study, energy consumption and resources consumption were not considered in the analysis. Data gathering for the mobile phone PCBs recycling process in Malaysia and Australia was essential to trace the recycling inventory of obsolete mobile phones. Based on the data gathered from the sources mentioned in Table 1, only material flows analysis were carried out. Moreover, mass flow rate in the recycling facilities were estimated based on a research paper of valuable materials recovery from PCBs that has a close proximity to this study [32]. The recycling processes of both countries were full recycling facilities that have a waste treatment plant to treat the substances before disposing them.

In the LCI analysis, local transportation was excluded because of the assumption that they travelled the same distance in both countries. However, for the Australian mobile phone recycling system through MobileMuster, dismantled PCBs were shipped to a formal recycling facility in Singapore for valuable materials recovery. The additional international shipping was included to consider the toxic substances that have a significant environmental impact.

5.2. Life Cycle Impact Assessment (LCIA)

LCIA is used to evaluate and interpret the environment impacts of a product system by assigning quantifiable measurement [14]. IMPACT 2002+ version 2.1 method was used as the main life cycle impact assessment of the e-waste processes quantitatively. It is used to connect the input and output material inventories to obtain the damage points of a specified boundary system. This method consists of 14 midpoint categories that can be allocated to four main damage categories namely, human health, ecosystem quality, climate change, and resources consumption [33]. However, climate change and resources consumption were excluded since they were not analysed.

The midpoint damage categories provide the magnitude of substances that contribute to the environmental impacts according to the groups (Figures 13 and 14). The list of substances that were obtained from the monitoring results was included into the relevant categories; a substance can fit into multiple categories [34].

Table 1: Data Sources for LCI.

End-of-life (EOL) Stage	Malaysia	Australia	Description
Mobile phone material flows	Penang E-waste Project	MobileMuster	-
Transportation	A Malaysian firm	MobileMuster	Local transportation to other recyclers was excluded.
Mobile phone PCBs recycling	A Malaysian firm	A Singaporean firm	Malaysia: Local formal e-waste recycler. Australia: Shipped to a Singaporean e-waste recycler.
Waste Treatment	A Malaysian firm	A Singaporean firm	Monitoring results of effluents and air emissions were obtained.

The endpoint damage categories indicate the quality changes of the environment [33]. The midpoint damage categories were further aggregated to the respective endpoint damage categories (Figure 13-15).

Normalisation was carried out to understand the respective proportion of each damage categories. The presented results were normalised and in accordance to the European standards [33][35]. This step is crucial to facilitate the comparability of different recycling routes for this study.

6. Life Cycle Inventory Results

6.1. Materials Recovery

The life cycle inventory showed that the materials recovered were value focused (Table 2). Valuable materials were retrieved whereas other materials were treated as waste. The recycling facilities have also generated a market and thus a value for fibrous materials that were converted to pallets to be reused.

Table 2: Output Materials Inventory of Recycling Facility.

Valuable Materials	Amount (%)	Waste	Amount (%)
Ferrous metals	2.79E+01	Rubber	5.90E+00
Copper	2.37E+01		
Gold	1.46E-02		
Silver	1.04E-01		
Platinum	1.00E-04		
Palladium	1.00E-04		
Fibrous/trace metals	4.24E+01		

6.2. Emissions from Shipping

The emissions from cargo shipping were estimated based on the distance travelled and an analysis of carbon dioxide emissions from freight transport in United Kingdom [36]. Subsequently, the different types of substances emitted during cargo shipping were approximated according to the annual emissions from international shipping (Table 3 and Appendix A) [37]. The major contribution of carbon dioxide emission (fuel consumption) has a large impact to the overall shipping emissions, which was about 95.5%.

Table 3: Estimated Shipping Emissions from Sydney to Singapore.

Type of Substances	Amount (*kg/ 1 tonne PCB*)
Fuel consumption	229.67
Particular matters	0.45
Hydrocarbons	0.53

6.3. Effluents and Air Emissions Analysis

Based on the monitoring results, the estimated air substances released to the environment after treatment in the scrubber system as shown in Figure 7 (see Appendix B for calculations). The estimated duration to recycle 1 tonne of PCB materials was 8 hours [32].

The Malaysian firm has a significant emission of particular matters through air followed by nitrogen oxides, hydrochloric acid and sulphuric acid. In contrast, the Singaporean firm has the monitoring results for two air substances only: chlorine and volatile organic compounds (VOC) which were not tested by the Malaysian firm.

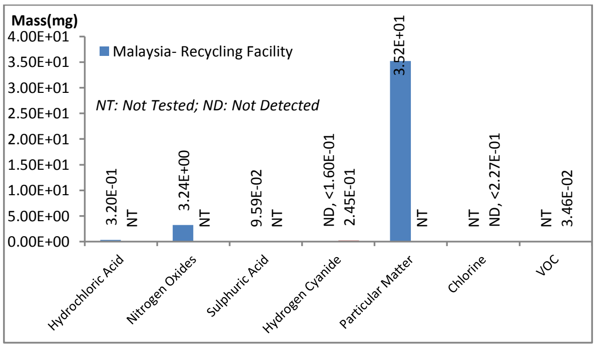

Figure 7: Parameters of Air Emissions.

The effluents were categorised by type into Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), metals, non-metals, metalloids, solid particles, and others. Each substances emitted through effluents were estimated for 1 tonne of PCB (Appendix C) based on the data gathered from the recycling facilities.

The amount of COD and BOD emitted in the Malaysian firm were significantly larger compared to the Singaporean firm, that was assumed to be none (undetectable), as shown in Table 4. However, there is a possibility that the Singaporean firm released greater amount of COD because the monitoring equipment used has limited detectable region.

Table 4: Estimated BOD and COD Emitted Through Effluents.

Recycling Facility	COD (*g/1tonne PCB*)	BOD (*g/1tonne PCB*)
A Malaysia firm	80.64	20.16
A Singapore firm	ND, <144	ND, <5.76

The emissions of solid particles, metalloids, metals, non-metals and others show a similar trend by observing the high-emission substances (Figures 8 to 12); there were substantial amounts emitted in the Singaporean firm but not tested in the Malaysian firm. Contrarily, not detectable substances were generally constant for both facilities.

7. Life Cycle Impact Assessment Results

The magnitude of environmental impact of each substance was carried out based on the material outflow analysis from both recycling facilities (section 6). Substances that were not detectable were assumed to be 0 for the minimum case and highest for the maximum case. The environmental performance indicators for midpoint damage categories are

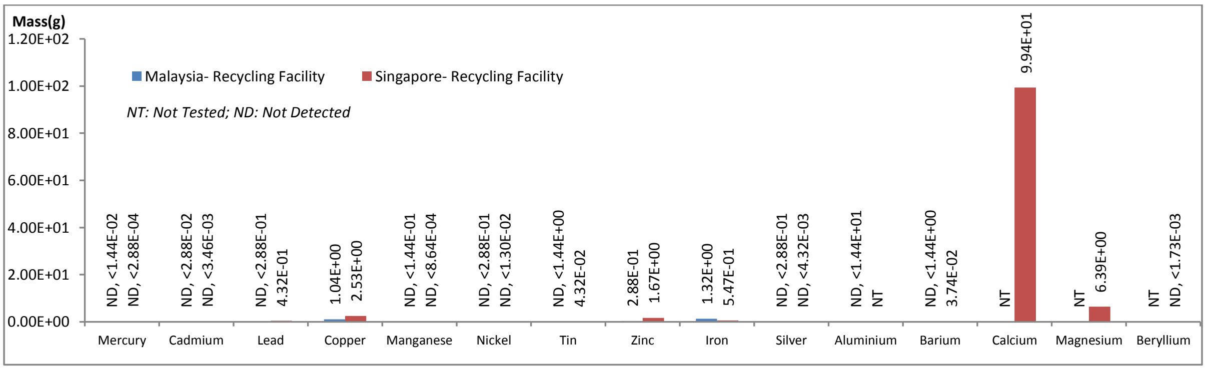

Figure 8: Estimated Metal Emitted Through Effluents.

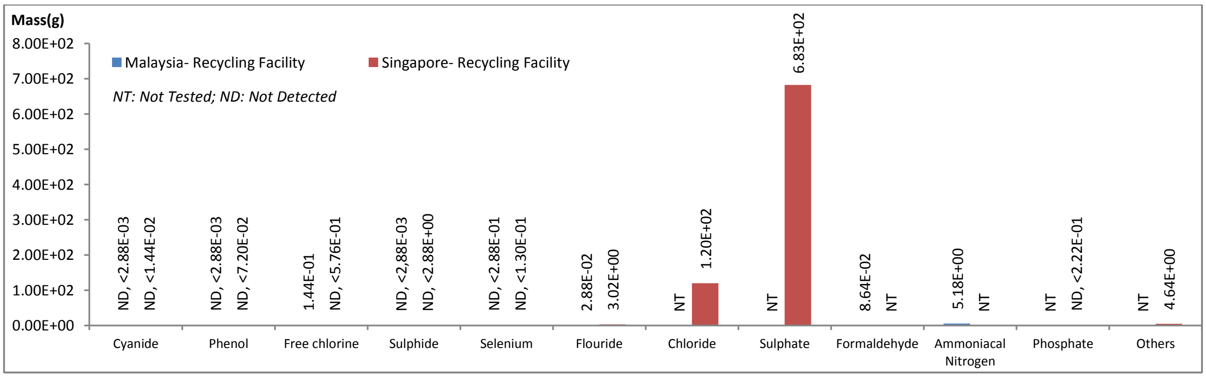

Figure 9: Estimated Non-metals Emitted Through Effluents.

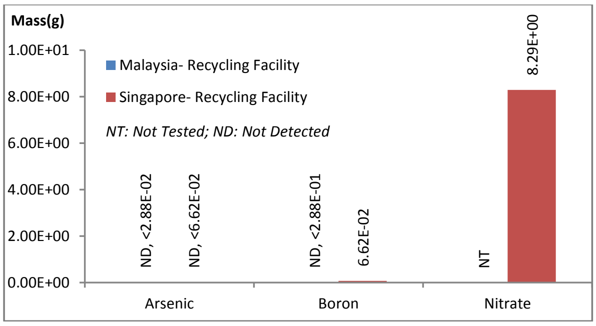

Figure 10: Estimated Metalloids Emitted Through Effluents.

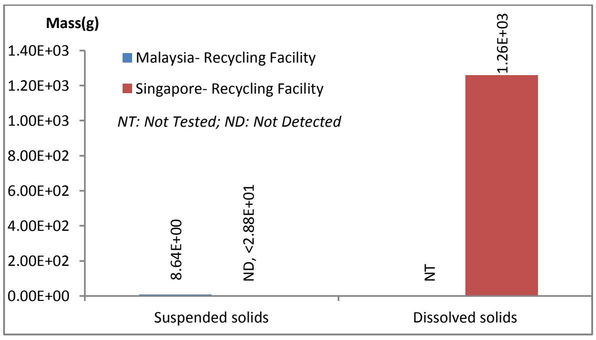

Figure 11: Estimated Solid Particles Emitted Through Effluents.

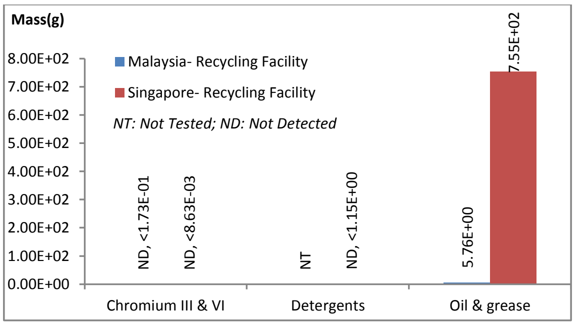

Figure 12: Estimated Other Materials Emitted Through Effluents.

interpreted in Figures 13 and 14. All presented results were with reference to “person years” or also known as “points” to indicate the average environmental impacts produced by a person for a period of 1 year in Europe [35].

For midpoint damage analysis, aquatic ecotoxicity category has the greatest environmental impact followed by aquatic acidification and non-carcinogen categories. Aquatic ecotoxicity measurement was largely contributed by toxic substances such as copper, mercury, nickel, zinc, aluminium, selenium and barium. By comparing the minimum case to the maximum case (Figures 13 and 14), the Singaporean firm produced significantly more environmental impact that was shown as carcinogen, non-carcinogens and aquatic acidification. However, for the maximum case, Malaysian firm produced noticeably higher amount of aquatic ecotoxicity. This is because the analysis conducted for both firms did not consider highly toxic substances (minimum case) that were below the detectable region.

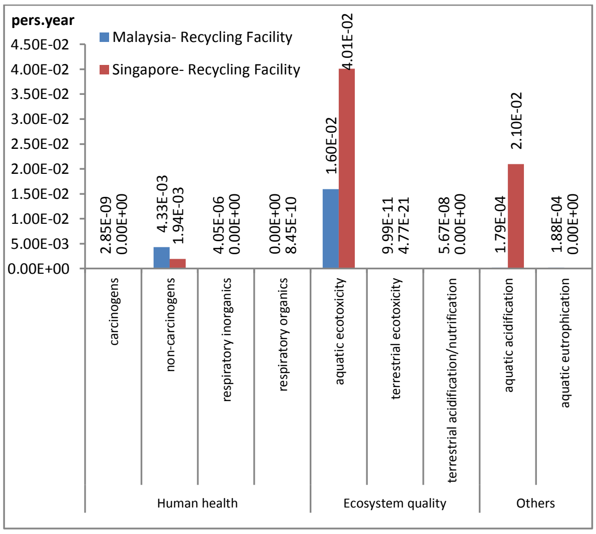

Figure 13: Normalised Midpoint Damage Categories (Minimum Case).

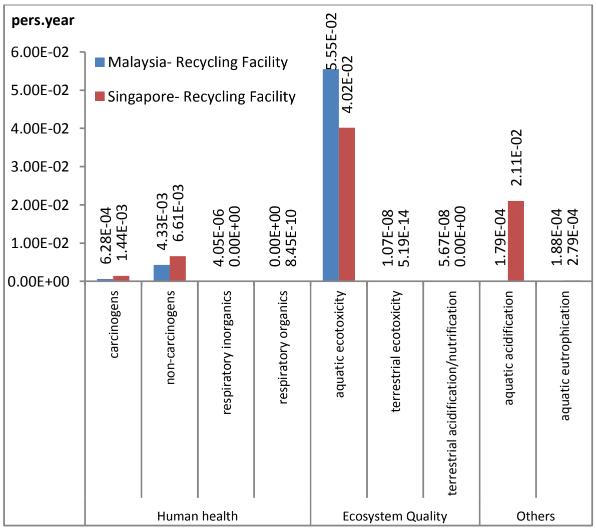

Figure 14: Normalised Midpoint Damage Categories (Maximum Case).

Based on the endpoint damage categories (Figure 15), the Malaysian firm produced more damage to human health; conversely, the Singaporean firm was more detrimental to the ecosystem quality. The quantitative indicator results for minimum case were used for the endpoint damage assessment due to the uncertainty of undetectable substances. The non-carcinogen category for the Malaysian firm is higher compared to the Singaporean firm which has contributed to the higher damage for human health. In contrast, the high amount of aquatic ecotoxicity from the Singaporean firm has contributed significantly to the damage of ecosystem quality.

There was a tremendous increment to the endpoint damage assessment when shipping was included in the LCIA analysis (Figure 16). The hydrocarbons emitted via shipping had largely affected to human health and ecosystem quality.

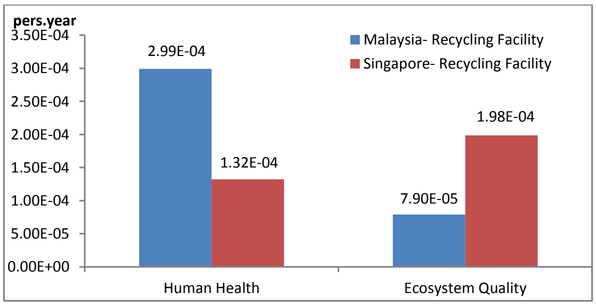

Figure 15: Normalised Endpoint Damage Categories.

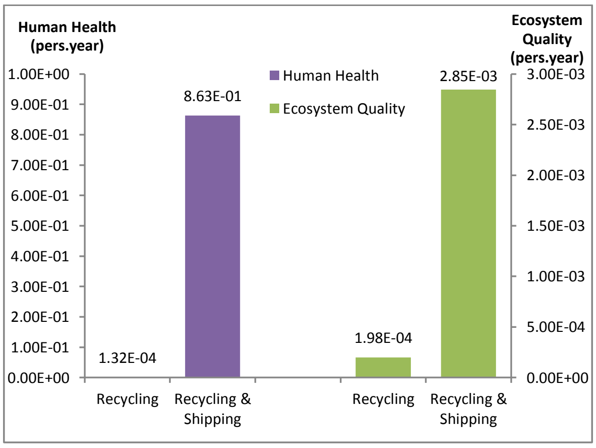

Figure 16: Normalised Endpoint Damage Categories for Singapore-Recycling Facility (Includes Shipping).

8. Discussion

The materials recovered from e-waste recycling are strongly related to financial motivation. Valuable materials retrieved (Table 2) generate high revenue to the recycling facility whereas toxic substances released to the environment (Figures 8 to 12) increase costs due to the waste treatment process. Fibrous materials that are converted to pallets created a market value and demand thereby providing financial gain to recyclers. By creating a market value for materials, they are likely to be reused and therefore have a reduced environmental impact.

The limits to waste treatment and emissions with reduced toxicity are driven by legislation. The output substances monitored are closely related to the environmental guidelines of a particular country [16]. With respect to the LCIA analysis, similar recycling facilities have different environmental impact outcomes. From the case studies, the allowable substances' limit in Singapore is generally higher compared to Malaysia that can be seen from the higher emission of substances (Figures 8 to 12).

Material flows of e-waste recycling have a significant contribution to the environmental impact. Mobile phone PCBs collected by MobileMuster in Australia were shipped to a Singaporean recycling firm that produced greater emissions due to the shipping transportation (Figure 16).

In this study, 2 midpoint categories: aquatic eutrophication and acidification were neglected at the endpoint damage category for ecosystem quality assessment. The inclusion of these midpoint categories were updated in the later version, IMPACT 2002+ version 2.21 [38] that will further contribute to the ecosystem quality category. Consequently, the damage caused to the ecosystem quality by the Singaporean firm will further increase (Figure 13).

Substances that were assessed in this paper for environmental impacts are strictly based on the substances listed in IMPACT 2002+ version 2.1 only. Substances such as boron, oil and grease, chlorine and others were not included. Hence, sensitivity analysis could be carried out using other assessment tools to validate the results.

9. Conclusion

The substances released to the environment that contribute to the toxicity indicator are largely influenced by the following factors:

Recycled materials' demand - The extraction of materials for reuse is strongly based on their financial gains in the industry that has high market demand.

Government legislation - Recycling facilities tend to oblige to the substances' limit outlined in the environmental guidelines only.

E-waste recycling system - Additional environmental impacts caused by transnational transportation can be avoided through local recycling of e-waste.

Acknowledgements

The authors would like to thank MobileMuster Australia and the Malaysian and Singaporean recycling firm for providing vital information in this project. This study was supported by the Commonwealth Government CRC Program (AutoCRC) and The Australia National University to understand the LCA approach in real scenarios.

Appendix A.

Table 5: Estimated Substance Emissions from International Shipping [37].

Substance Emissions from Shipping, *EI*	Amount (*Tg*)	Percentage (*%*)
Fuel Consumption		
Nitrogen dioxide (NO_2)	21.380	2.512
Carbon dioxide (CO_2)	812.630	95.493
Carbon monoxide (CO)	1.310	0.154
Sulfur dioxide (SO_2)	12.030	1.414
Particular matters(PM)		
Black Carbon (BC)	0.050	0.006
Organic Carbon (OC)	0.134	0.016
Sulfate (SO_4)	0.785	0.092
Ash	0.100	0.012
Other particular matter	0.601	0.071
Hydrocarbons		
Methane (CH_4)	0.223	0.026
Hexanes higher alkanes	0.525	0.062
Ethene	0.364	0.043
Propene	0.398	0.047
Ethyne	0.010	0.001
Other alkenes	0.038	0.004
Benzene	0.163	0.019
Toluene	0.090	0.011
Xylene	0.075	0.009
Trimethylbenzenes	0.064	0.008
Other nonmethane hydrocarbon(NHMC)	0.010	0.001

A.1. Formula Representation

Based on Appendix A, each substance emission in mass was calculated using (1).

$$EI = \frac{(e_{co_2} * d)}{x_{co_2}} * x \tag{1}$$

e_{co2} = Estimated emission rate of CO2 for international shipping [g/tonne-km]

d = Distance travelled by ship from Sydney, Australia to Singapore [km] = 6293 km.

x = Percentage of emission for each substance from international shipping [%]

x_{co2} = Percentage of carbon dioxide emission from international shipping [%]

EI = Estimated emission for each substance from international shipping [g]

Appendix B.

$$\dot{m}_A = V_A * c_A \tag{2}$$

Where $\dot{m}_A$ is the mass flow rate of each substance emitted through air [mg/8 hours], V_A is the air volume for each air substance for a specific sampling rate [Nm^3], and c_A is the concentration of each air substance for a specific sampling rate [mg/Nm^3].

Appendix C.

The effluents outflowed from the WWTP, as shown in Figure 17 were assumed to contain mostly water, with a density of 1L/kg, while remaining their masses from the inflow. Hence, the volume flow rate of treated effluents, $\dot{v}_T$ [L/8 hours] is approximated from the following expression, (3).

Figure 17: Wastewater Treatment Process Flow.

$$\dot{m}_U = \dot{m}_T = \dot{v}_T \qquad (3)$$

Where $\dot{m}_U$ is mass flow rate of untreated effluents [kg/8 hours] and $\dot{m}_T$ is mass flow rate of treated effluents [kg/8 hours].

The mass flow rate of each particular effluent substance was estimated from equation (3) and the effluents monitoring results obtained from the firms, as shown in equation (4).

$$\dot{m}_E = \dot{v}_T * c_E \qquad (4)$$

Where $\dot{m}_E$ is the mass flow rate of each effluent substance [mg/8 hours] and c_E is the concentration of each effluent substance [mg/L].

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