International Journal on Advanced Science Engineering Information Technology

Vol.13 (2023) No. 3
ISSN: 2088-5334

Eco-Efficiency Comparative Analysis of Informal and Formal Smartphone Recycling Practices Using Life Cycle Assessment

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Abstract*—Due to a lack of environmental protection awareness and knowledge, many practices informally recycle smartphone waste to get precious metals. Smartphones are hazardous and toxic waste materials, so they require proper handling not to cause problems for the environment. This study aims to measure the environmental impact and eco-efficiency level of formal recycling practices carried out by licensed companies and compare them with informal recycling practices carried out by the community. Environmental impact measurement uses Life Cycle Assessment with the eco-cost method. The measurement results show informal recycling practices have a higher environmental impact than formal recycling practices. Informal recycling practices harm almost every category, while formal recycling has a significant positive impact on the acidification and metal scarcity categories. Based on the value of the eco-efficiency index, formal recycling practices are affordable and sustainable and have an eco-efficiency level of 100%. Economically, formal recycling provides higher financial benefits than informal recycling. Thus, formal recycling practices are better and more profitable than informal recycling practices from the economic and environmental aspects. So, it is time for Indonesia to switch to a formal recycling process carried out by licensed companies considering the vast potential for waste as a raw material. The government's role is to invite the public to distribute smartphone waste to licensed recycling companies.

***Keywords*—Eco-efficiency; life cycle assessment; environmental impact; recycling; formal; informal.**

Manuscript received 18 Mar. 2022; revised 22 May 2022; accepted 10 Jan. 2023. Date of publication 30 Jun. 2023.

I. INTRODUCTION

In this digital era, people's consumption of electronic devices has increased significantly. Electrical and electronic equipment is among the five sectors contributing more than 30% of Indonesia's Gross Domestic Income (GDP). Electrical and electronic equipment contributed to a GDP of 204 trillion rupiahs or 1.9% and could absorb 1.6 million workers or 1.3% in 2019. Televisions, fans, pump waters, refrigerators, washing machines, air conditioners, and smartphones dominate the domestic market for electronic products. Smartphones are estimated to have a 10% contribution to global e-waste [1]. Indonesia's domestic market demand was 101 million sets in 2019 and 97.6 million sets in 2020 for smartphones [2].

This increase in consumption can cause a considerable amount of electronic waste in Indonesia, considering that the population of Indonesia is the fourth most populous country in the world. In the 2020 Global E-Waste Monitor annual report released by the United Nations, it was stated that electronic waste in 2019 reached 53 million tons. The United Nations predicts that electronic waste (e-waste) will reach 74 million tons by 2030 and jump to 120 million tons by 2050. Only 17.4% of e-waste containing this mixture of hazardous substances and valuable materials is collected, treated, and recycled correctly. In Indonesia alone, the current generation of electronic waste is 1.8 million tons, projected to increase by 39% by 2030 [3]. Java Island will contribute up to 56% of the generation of electronic waste in 2021 [4]. Indonesia is included in the ten most e-waste-producing countries in 2019 and is Southeast Asia's highest e-waste producing country [5]. Good waste management has not matched the high potential of this flow [6].

In addition to containing hazardous materials that can pollute the environment, e-waste also contains materials of economic value that can be extracted through proper handling and treatment processes. An ordinary smartphone is estimated to contain 60 different metals with high economic value, such as gold, silver, palladium, platinum [7]–[9]. In Indonesia, no regulations govern the collection and transportation of electronic waste until the final process. Indonesia's regulation is Law Number 18 of 2008 concerning Waste Management [10]. United Nations University even classifies the waste management system in Indonesia as the lowest level. The electronic waste system in Indonesia is still limited to informal initiatives, so the United Nations University classifies the waste management system in Indonesia as the lowest. This management pattern is one of the differences between Indonesia and developed countries [11]. This is reinforced by a survey examining electronic waste's economic potential, especially smartphone waste.

Currently, there are many informal recyclers in Indonesia. Informal recycling involves manual disassembly, insulation of materials, open burning, heating of circuit boards, use of toxic acid baths for metal recovery, and disposal of open dumps. This unsafe recycling technique is used to recover valuable materials with little or no technology to minimize exposure, thereby allowing the emission of hazardous chemicals [12]. Improper handling of waste can lead to environmental pollution [13]. The environmental impacts caused by electronic waste are identified as ozone-depleting substances [14]. It is bad for health in the long term because electronic waste contains hazardous and toxic materials. Hazardous and toxic materials are substances, energy, and other components that, due to their nature, concentration, and quantity, can directly or indirectly pollute and damage the environment endangering the environment, health, and survival. Human life and other living creatures [15]. Hazardous elements and chemicals in e-waste harm ecosystems and people living near recycling areas [16]. Manual dismantling of electronic waste releases non-biodegradable plastics and persistent chemicals into the environment, polluting air, water, and soil quality [17]. Informal recycling practices, such as incineration and washing electronic components, can also spread chemical compounds in the environment. These chemicals can be inhaled, absorbed through the skin, or even ingested through atmospheric particulates [12]. Once these chemicals are absorbed, toxins accumulate in human tissues and body fluids [18]. As a result, these toxins can cause problems related to human health, such as skin diseases, brain retardation in children, respiratory problems, skin diseases, carcinogenic diseases, weakened immune systems, heart problems, shorter lifespans, damage to the nervous system, kidneys, disorders endocrine, miscarriage, etc. [19]–[23].

Looking at the environmental impact that will arise with informal recycling practices, it is appropriate to switch to formal channels for formal recycling activities. In addition, the formal processing of end-of-life (EoL) can result in better disposal of hazardous substances and higher recovery of valuable materials due to proper recycling facilities [24], [25]. However, formal recycling facilities are rare in developing countries due to high construction and operating costs [26]. Integrating the informal and formal sectors will be an intelligent solution in e-waste management, considering the many actors in the informal sector. The informal sector is given space for the initial process, which includes waste collection, while the formal sector carries out recycling activities. Thus, integrating the formal and informal sectors can be socially and economically beneficial for people in developing countries while reducing environmental and human health risks [19], [25].

Formal recycling activities require a relatively expensive investment cost, so assessing the level of eco-efficiency of formal recycling activities to assess aspects of sustainability and affordability is necessary. This significant investment is expected to provide economic benefits with minimal environmental impact. Thus, there will be double benefits, namely economic and ecological (environmental) benefits, because eco-efficiency aims to reduce environmental impacts per unit produced and consumed. Eco-efficiency is the ratio between the added value obtained from the economic side with the required added value from the physical side. Based on the Environmental Dictionary of the Ministry of Environment of the Republic of Indonesia, an efficiency concept includes aspects of natural resources and energy or a production process that minimizes the use of raw materials, water, and energy, and environmental impacts per unit product so that in the industrial world, eco-efficiency can be said as a strategy that has more value because it uses less natural resources and reduces the amount of waste and environmental pollution. Eco-efficiency is an effort to produce goods and services using resources more efficiently and producing minimal or no waste (used as a resource for other processes). Eco-efficiency provides a new paradigm for our perspective on utilizing resources and outputs that are not utilized (often called waste). Eco-efficiency views waste as a resource, and resources must be used wisely to produce a minimum amount of waste.

This study aims to assess the environmental impact of formal recycling practices compared to the environmental impact of informal recycling practices by calculating the eco-cost and measuring the level of eco-efficiency. The impact of e-waste recycling activities is measured using the Life Cycle Assessment (LCA) method. LCA is a powerful tool for measuring environmental impact across a product's life cycle from raw material acquisition to production, use, end-of-life maintenance, recycling, and final disposal [27]. LCA helps decision-makers identify and measure the environmental impact of a product, process, or activity during its entire life cycle [28] because LCA aims to explore the category of environmental sustainability by evaluating inputs, outputs, and potential environmental impacts [29]. LCA is an internationally recognized standard for estimating the environmental impact, process, or activity [30]. LCA is concerned with identifying the environmental impact of a given product or process at each stage of the product life cycle [31]. LCA studies can support a framework for understanding project benefits toward a better environment [32]. LCA starts with defining goals and scope, then inventory analysis, the next step is impact assessment, and the last step is interpretation to achieve the initial use goals [33]. Eco-cost is the cost of the environmental burden of a product. Eco-cost carried out in the impact calculation is a method that explains the cost burden to avoid any possible environmental impacts [34]. These costs must be incurred to reduce environmental pollution and the depletion of materials in terms of economic and environmental capacity.

Eco-efficiency is used to measure sustainability by looking at achieving economic and environmental targets [35]. Eco-efficiency is the ratio between added economic value and environmental load during a specific period [36]–[38]. Eco-efficiency analyzes complex ecosystems' economic, resource, and environmental inputs and outputs [37]. The goal of eco-efficiency is to reduce material costs, energy, and the ecological impact of production during all life cycle stages [39], [40]. The eco-efficiency index reflects the economic results achieved by human economic activities and the environmental impacts caused by these economic activities, coordinates economic development well, utilizes natural resources rationally, and protects the ecological environment [41]

II. Materials and Method

This study begins with data collection, then the life cycle assessment processing data, and the last is eco-efficiency measurement.

A. Data Collection

Data collection is carried out by identifying and collecting data needed for research. Primary data were obtained by interviewing and observing the informal recycling process to obtain gold material from printed circuit board (PCB) waste, while formal recycling used data from recycling practices in developed countries. The secondary data needed are material, energy, and processing data, as well as production costs, material costs, and selling prices of the recycled products produced for the formal recycling process, used secondary data. The required data is divided based on the method used. In the life cycle assessment method, the weight of the smartphone waste raw material is the weight used for purification on the informal channels. The cost-benefit analysis method is used to find the advantages of smartphone waste recycling practices. The data needed are the cost of materials and energy, production cost, and selling price of the product. The selling price of the secondary material produced uses the metal market price. Meanwhile, the data needed for eco-efficiency calculation is the net product value obtained from the previous cost-benefit analysis (CBA), the eco-costs value obtained from the life cycle assessment (LCA) measurement output on SimaPro version 9, and the eco-efficiency index (EEI) and eco-efficiency ratio rate (EVR) values from the calculation. Data collection techniques and data needed in the study are described in Table 1.

TABLE I
DATA COLLECTION TECHNIQUE

Methods	Input	Collection Technique
LCA	Material quantity (kg) Energy quantity (kg) Waste quantity (kg)	Survey and secondary data collection
CBA	Production cost (IDR) Material cost (IDR) Overhead cost (IDR) Product selling price (IDR)	Secondary data collection
EEI	Net value (IDR) Eco-cost (IDR)	Results of LCA and CBA
EVR	Eco-cost (IDR) Net value (IDR)	Results of LCA and CBA
Eco-efficiency rate	Nilai EVR Net value (IDR)	Results of CBA and EVR

B. Life Cycle Assessment Data Processing

Life Cycle Assessment (LCA) is an approach to thoroughly examine the environmental impact of several production activities in a company [31]. LCA was used to determine the product effect on its materials, resources, and waste flows [42]. LCA has several stages: defining goals and scope, inventory analysis, impact assessment, and interpretation to achieve the initial use goals [33], [43]. LCA is shown in Fig. 1.

The first step is defining the goal, scope, and boundary. At this stage, it is also necessary to select the impact category that will be measured from the related product life cycle [44]. This study compares the environmental impact of the informal and formal recycling of smartphone waste. The functional unit measured is 1 ton of smartphone waste, and the functional unit is a quantitative value related to the system's function [45].

Next is the Life Cycle Inventory (LCI) stage, which collects data and calculates input and output quantification for material and energy flows from informal and formal process systems. These LCI results are input and output information in a resource flow from and to the environment in the unit process in this study [44]. The third stage is the Life Cycle Impact Assessment (LCIA). This stage is carried out by discussing the potential impacts on the environment [44]. The LCIA phase explains the mandatory elements: classification and characterization, normalization, weighting, and a single score. The first phase is classification. Classification is grouping substances on the LCI in a predetermined impact category. Characterization is an assessment of the impact's magnitude through the contribution's value. A normalization is a uniform unit for the contribution value of all impact categories. The weighting is done by multiplying the impact category by the weighting factor and adding the total value. At the same time, the single score is a classification of impact category values based on activities or processes. The last stage, namely interpretation, is a technique of identifying, measuring, examining, and evaluating the information on the results of measuring the impact of the product life cycle. This stage is the conclusion and recommendation stage of the overall measurement [44].

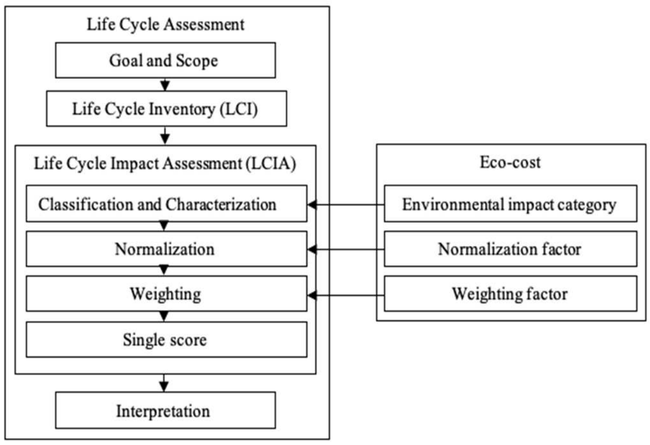

Fig. 1 Life cycle assessments stage

The Eco-cost method is used in the LCIA calculation stage. Eco-cost is a method that explains the cost burden to avoid any possible environmental impacts [34]. The eco-cost model describes the amount of the marginal cost of environmental prevention in the life cycle of a product. The categories described in the eco-cost are harmful emissions, material depletion, energy consumption, land use, etc. The advantage of eco-cost is an explanation expressed in standardized monetary values that are easy to understand. In addition, the calculations are also transparent and easy to compare with damage-based models with complex calculations [34].

C. Eco-efficiency Measurement

Eco-efficiency is one of the clean production strategies, where clean production is a preventive and integrated environmental management strategy that is continuously applied to the production process and product life cycle to reduce risks to humans and the environment [46]. Eco-efficiency is the ratio of variation between economic performance and environmental performance [47]. The balance between economic development and the environment is important [47]. Meanwhile, the eco-efficiency principle is the principle of material and energy efficiency to save the level of energy and wasted material and reduce the environmental impact. The purpose of eco-efficiency is to reduce environmental impacts due to the production and consumption processes. There are seven critical factors in eco-efficiency: reducing the amount of material used, reducing the amount of energy used, reducing pollution, increasing material recycling, maximizing the use of renewable natural resources, extending product life, and increasing service intensity [48]. The steps for calculating eco-efficiency are shown in Fig.2[34].

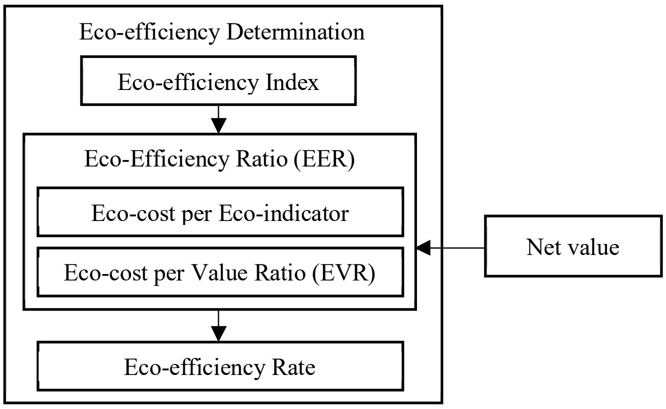

Fig. 2 Eco-efficiency calculation steps

The calculation of eco-efficiency begins with the eco-efficiency index (EEI), which determines the affordable and sustainable value of product processing. The EEI calculation formula is described in eq. (1) [34].

$$EEI = \frac{price - cost}{cost + Ecocost} \tag{1}$$

Price is the selling price of the product, while cost is the cost needed in production. Eco-cost in the formula is the cost incurred to reduce pollution and reduce material on earth, and Eco-costs are virtual costs, namely prevention and damage costs in free trade. This EEI calculation is described in Table 2 in terms of several criteria.

TABLE II
ECO-EFFICIENCY INDEX CRITERIA

EEI	Affordability	Sustainability
EEI > 1	Affordable	Sustainable
0 < EEI < 1	Affordable	Not Sustainable
EEI < 0	Not Affordable	Not Sustainable

The value of eco-efficiency can be considered in assessing the sustainability of a system. An eco-efficiency value of less than 1 means the system is not affordable. Suppose the value ranges from 0-1 means affordable. The system is affordable and sustainable if the value is more than one [49].

Next is the calculation of the product's eco-efficiency ratio (EER). The EER calculation is done by calculating the eco-cost per eco-indicator ratio of the product. This calculation compares eco-costs and eco-indicators, namely the calculation of EVR or eco-costs per product value ratio. Finally, the net value is obtained by subtracting the selling price from the cost of production or price and cost. The EVR calculation formula is described in eq. (2) [34].

$$EVR = \frac{Ecocost}{Net\ Value} \tag{2}$$

Then the calculation of the eco-efficiency rate is the final calculation of the eco-efficiency measurement of the processing process. The calculation of the eco-efficiency rate is obtained by reducing the net value with the eco-cost value or obtained by calculating the EVR reduced by 1. The calculation of the eco-efficiency rate is described in eq. (3) [34].

$$Eco - efficiency = 1 - EVR \tag{3}$$

The higher the ratio, the better the eco-efficiency and otherwise. Higher environmental efficiency also means that the environmental impact and costs are shallow [50]

III. RESULTS AND DISCUSSION

A. Life Cycle Inventory

Life cycle inventory (LCI) is the stage of compiling and quantifying all inputs and outputs of a product throughout its life cycle [51]. The average smartphone weight without a battery is 125 gr [52], so 1 ton of smartphone waste contains about 8000 units of smartphones. The process at the informal stage includes the manual disassembly of the smartphone, the PCB leaching process, and the process of burning electronic waste other than PCBs. Dismantling 1 ton of smartphone phones will produce 190 kg [53]; the rest is electronic waste. Dismantled PCB will be leached using aqua regia solution, while electronic waste incineration uses coal with an energy of 6960 MJ [9], [54]. Aqua regia, often referred to as king water, is a solution made from a mixture of concentrated hydrochloric acid (HCl) and concentrated nitric acid (HNO_3) in a ratio of 3:1 [55]–[58]. Solid/liquid ratio of 1 gr solid to 2 or 4 ml aqua regia [55], in this study, using 3 ml of aqua regia for 1 g of PCB [55], [58].

The specific gravity of HCl is 1.18 gr/cm^3, while the specific gravity of HNO_3 is 1.51 gr/cm^3 [58]. So, 504.45 kg of HCl is needed for PCB leaching, and 215.175 kg of HNO_3 is needed. The gold potential obtained from informal processing is 25% of the potential gold recovery rate [59]. Potential gold per ton of smartphones is between 340-360 gr [7], [59]. Based on a survey, 1 ton of smartphone waste will produce around 158.8 gr of gold. The input of material and energy data in the informal 1-ton smartphone waste treatment process is shown in Table 3.

The formal waste recycling process adopts the Umicore recovery facility in Hoboken. It begins with mechanically disassembling smartphones at the company, then smelting the material in a smelter, followed by a converting process, fire refining, anode casting, copper refining, silver refining, gold refining, and platinum gold metal (PGM) extraction.

TABLE III
LIFE CYCLE INVENTORY (INFORMAL)

Process	Inventory		Value	Unit
Dismantling of smartphones manually	Input	Smartphones (EoL)	1,000	kg
	Output	Dismantled PCB	190	kg
		Electronic waste	810	kg
Incineration of electronic waste	Input	Heat, hard coal	6,960	MJ
		Electronic waste	810	kg
	Output	Electronic waste residue	810	kg
Leaching PCB	Input	Nitric acid	143.45	kg
		Hydrochloric acid	336.3	kg
		Dismantled PCB	190	kg
	Output	Gold, secondary	0.1588	kg
		PCB Residue	189	kg

The process used is pyrometallurgy. With the same material input, namely 1 ton of smartphone waste, using electricity (medium voltage) and heat energy of 7431 MJ [60], with details of 137 MJ for the demolition process [7], [61], 1393 MJ for the smelting process [7], [60], [62], 500 MJ for the conversion process [7] and 5,401 MJ for the purification process [7]. One ton of smartphones will produce 147 kg of black copper, 17 kg of lead bullion, and 396 kg of slag from the smelting process material in the smelter. Slag weighting 396 kg consists of the main components' silica (116 kg, coming from the plastic of printed wiring boards), iron (65 kg), and aluminum oxide (47 kg). The lead bullion contains 6 kg of lead, 10 kg of tin, and 1 kg of antimony. The black copper fraction contains 128 kg of copper, 15 kg of nickel, 3.6 kg of silver, 347 gr of gold, 151 gr of palladium, and 5 gr of platinum, resulting from a series of refining processes [7]. The LCI of the formal recycling process for 1 ton of smartphone waste is shown in Table 4.

B. *Life Cycle Impact Assessment*

Life Cycle Impact Assessment (LCIA) measures the negative environmental impact generated by the selected process life cycle. This research will explain the impact of each stage and the overall impact. The results of the LCIA are explained in several measurement stages, namely characterization, normalization, weighting, and a single score. Table 5 shows the measurement results of a single score per impact category, while a single score per damage is shown in Table 6. Based on these calculations, the value of eco-cost in Euro units will be obtained, which will be used to calculate eco-efficiency. Eco-efficiency will then be calculated to determine whether the resulting product is efficient, sustainable, and affordable from the economic and environmental aspects.

TABLE IV
LIFE CYCLE INVENTORY (FORMAL)

Process	Inventory		Value	Unit
Dismantling of phones mechanically at a plant	Input	Electricity	137	kWh
		Smartphones (EoL)	1,000	kg
	Output	Shredded E-waste	1,000	kg
Smelting of materials in a smelter	Input	Natural gas	1,393	MJ
		Shredded e-waste	1,000	kg
	Output	Heat, natural gas	9,257	MJ
		Lead, Secondary	17	kg
		Black copper	192	kg
		Slag	396	kg
Converting process	Input	Natural gas	500	MJ
		Black copper	192	kg
	Output	Blister copper	192	kg
Fire refining and anode casting	Input	Natural gas	958	MJ
		Blister copper	192	kg
	Output	Copper anode	192	kg
Copper refining	Input	Electricity	1481	MJ
		Copper anode	147	kg
	Output	Copper, secondary	128	kg
		Silver-Gold-PGM alloy	5.41	kg
Silver Refining	Input	Electricity	490	kWh
		Silver-Gold-PGM alloy	5.41	kg
	Output	Silver, secondary	3.63	kg
		Gold-PGM alloy	1.78	kg
Gold Refining	Input	Electricity	17.7	kWh
		Gold-PGM alloy	1.78	kg
	Output	Gold, secondary	0.35	kg
		PGM alloy	1.433	kg
PGM Extraction	Input	Electricity	41.6	kWh
		PGM alloy	1.433	kg
	Output	Palladium, secondary	0.151	kg
		PGM Residue	1.282	kg

TABLE V
LCIA SINGLE SCORE RESULTS PER IMPACT CATEGORY (MIDPOINT)

Impact Category	***Single Score*** **(Euro)**	
	Formal	**Informal**
Climate Change	1.300×10^8	7.934×10^7
Acidification	-3.405×10^9	3.488×10^7
Eutrophication	4.957×10^8	1.957×10^6
Photochemical Oxidant Formation	1.610×10^6	8.811×10^5
Fine Dust	2.797×10^7	7.780×10^6
Human Toxicity	5.296×10^7	1.159×10^7
Ecotoxicity (freshwater)	5.581×10^7	3.993×10^6
Metal Scarcity	-5.693×10^7	1.679×10^8
Oil & Gas Depletion excl. energy	3.971×10^6	6.727×10^6
Waste	0	0
Land-use	0	0
Water Stress Indicator	1.679×10^7	3.719×10^6
Total	-3.123×10^9	3.188×10^8

TABLE VI
LCIA SINGLE SCORE RESULTS PER DAMAGED CATEGORY (ENDPOINT)

Damaged Category	Formal (Euro)	Informal (Euro)
Climate change	1.3×10^8	7.934×10^7
Human health	8.254×10^7	2.025×10^7
Ecosystems	-3.3×10^9	4.083×10^7
Resource depletion	-3.616×10^7	1.784×10^8
Total	-3.123×10^9	3.188×10^8

C. Environmental Efficiency Index

Eco-efficiency is a calculation to determine the costs that must be paid to avoid damage due to emissions or production activities and the reduction of raw materials that exist in nature. Eco-efficiency calculations are performed using the Eco-cost database from SimaPro's output. Recycling practices can be categorized as emissions that are released into nature. The eco-cost value at SimaPro is presented in Euros, which is IDR. 16,152.33 (as of December 8, 2021). The eco-efficiency value is calculated based on the product's cost-benefit analysis (CBA) and the eco-cost of all stages. The CBA value is obtained from the calculation of the selling price of the product minus the cost of production. Production costs include raw materials, energy, labor, depreciation, and overhead [28].

For formal recycling, the operational cost to process 1 ton of smartphone waste informal recycling is US$ 1,490.85 [63]. If the weight of 1 ton of smartphones contains 8000 smartphones, the operational cost per smartphone is US$ 0.186. If 1 US$ is IDR. 14,234.50 [64], then one smartphone costs IDR. 2,647.62. The overhead cost used in processing is the sum of the depreciation costs for the pyrometallurgical equipment used in the recycling company. The investment cost of the Umicore recovery facility in Hoboken requires an investment of more than US$1 billion [65] with a capacity of 350,000 tons per year. The investment cost of equipment and buildings for a recycling facility in developed countries is US$ 700,000 [63]. Machine life can be up to 25 years [66]. If the procurement cost is US$1 billion, it is equivalent to IDR. 14,234.5 billion. Suppose 1 ton of smartphones takes less than 1 hour. The depreciation expense used is straight-line depreciation expense without residue, which is IDR. 8,237.56. So the total cost of production per product is IDR. 10,885.18. Secondary material produced from recycling 1 ton of smartphone waste is shown in Table 7. The total revenue from recycling 1 ton of smartphones is IDR. 503,087,381.10. If 1 ton contains 8000 smartphones, the income per smartphone from recycling activities is IDR. 62,885.92. The net value is obtained from reducing the price to cost, so the net value is IDR. 52,000.74.

TABLE VII
SECONDARY MATERIAL PRODUCED PER TON OF SMARTPHONE WASTE

Metals	Quantity (g)	Price/kg (US$)	Price/gr (Rupiah)
Copper (Cu)	128,000	9.73	138.55
Nickel (Ni)	15,000	19.51	277.64
Silver (Ag)	3,630	780.62	11,111.74
Gold(Au)	347	58,450.06	832,008.38
Palladium (Pd)	151	67,034.31	954,199.89
Platinum (Pt)	5	34,047.64	484,651.13
Lead (Pb)	6,000	2.37	33.76
Tin (Sn)	10,000	37.35	531.70
Antimon (Sb)	1,000	8.35	118.86

(Source: [67] [68])

Furthermore, the Eco-efficiency Index (EEI) value is calculated using eq. (1) by dividing the net value by cost and Eco-cost. This EEI value describes the affordability and sustainability of this recycling practice. The eco-cost value is € -3.123 x 10^9 or the equivalent of IDR. -5.044 x 10^{13} for 8000 units of smartphone waste. So, the eco-cost per unit is IDR. -6.305 x 10^9 or per unit provides a profit of IDR. 6.305 billion. Because the eco-cost value is negative, the eco-cost is considered zero for the following calculation. By using eq. (1), the EEI value is 4.77. So, it can be concluded that formal recycling is affordable and sustainable because the EEI value is 4.77. This shows that formal recycling practices are affordable and sustainable because the value exceeds 1. After calculating the EEI value, the Eco-cost Value Ratio and Eco-efficiency Ratio Rate values are calculated. The EVR and eco-efficiency rate calculation value using eq. (2) and (3). With an eco-cost value of zero, the EVR and the eco-efficiency rate value of 100% will be zero. Based on these results, the eco-efficiency rate value of formal recycling is very efficient because it can reach 100%.

Meanwhile, looking at the vast eco-cost value for informal recycling, namely € 3.188 x 10^8 or equivalent to IDR. 5.149 x 10^{12} for 8000 units, so that per-unit costs IDR. 6.436 x 10^8 or the equivalent of 0.644 billion. One ton of smartphone waste produces 158.8 gr of gold, if the gold price is IDR. 832,008.38 per gr, it will generate an income of IDR. 132.122,930.74 or equivalent to IDR. 16,515,366 per unit of smartphone waste. Assuming the waste is not paid as in the formal channel if the production per ton is IDR. 13,046,510, then per unit IDR. 1,630.81. Burning electronic waste using coal, the energy produced from coal is Energy 24.8 MJ/kg [69]. So to produce energy as much as 6960 MJ, it takes 320,968 kg of coal at US$ 61.63/ton per October 2021 [70]. The price of nitric acid per 37,000 gr is IDR. 490,000 [71]. Meanwhile, the price of hydrochloric acid per 1200 gr is IDR. 22,500 [72]. Total production costs per ton are IDR. 13,046,510. In the informal process, not much equipment investment is needed; for example, the investment cost of equipment used for 1 ton of smartphones is IDR. 1,000,000.00, so for one smartphone, it costs IDR. 125.00. So, the total cost of production per unit is IDR. 1,755.81.

Informal recycling can produce a net value of IDR using the same calculation method as formal recycling. 14,759.56, an EEI value of 2.29 x 10^{-5}, an EVR value of 4.362 x 10^4, and an eco-efficiency rate of -436.19%. Based on the EEI value, it can be said that informal recycling is still affordable, but the value is close to zero and is not environmentally friendly. Based on these results, the eco-efficiency rate value of formal recycling is very inefficient because of its large negative value. A recapitulation of the value comparison between formal and informal recycling can be shown in Table 8. The eco-efficiency rate is negative when the eco-costs are higher than the value, 0% when the eco-costs are equal to the value, and 100% when there are no eco-costs [34].

TABLE VIII
COMPARISON OF ECO-EFFICIENCY COMPARISON BETWEEN FORMAL AND INFORMAL RECYCLING

Value	Formal	Informal
Net value	52.000,74	14.759,56
EEI	4,77	2,29 x 10^{-5}
EVR	0	4,362 x 10^4
Eco-efficiency	100%	negative

D. Discussion

LCA is very useful for assessing and identifying environmental burdens [73]. LCA determines environmental impact, energy consumption, and product costs [74]. The results of the environmental impact of recycling smartphone waste using SimaPro with the eco-cost method provide positive and negative values. A positive value indicates a lousy impact, and a negative value indicates a positive environmental impact. From the impact measurement results in the LCIA for informal recycling, it hurts the environment in almost all categories.

Meanwhile, for formal recycling, two categories positively impact the environment: acidification and metal scarcity. The acidification category is caused by an accumulation exceedance (AE) [44]. The AE value is obtained based on the amount of sulfur and nitrogen that is wasted in production activities [44], so the main parameters that contribute to acidification are SO_2 and NO_x [75], [76]. Acidification is an environmental problem caused by the acidification of rivers/streams and soil due to anthropogenic air pollutants such as SO_2, NH_3, and NO_x [77]. Acidification results from the presence of sulfur oxides (SO_2) in the atmosphere [76], [78]. The acidification value in the informal process is higher than in the formal process due to using fossil fuels (coal) in the smartphone waste combustion stage and exacerbated by aqua regia for the PCB leaching process.

In contrast, the formal process uses natural gas for metal refining. The greater the amount of fossil fuel consumed, the greater the SO_2 emissions released. The value of acidification can be caused by burning and leaching to produce SO_2, which is harmful to the environment [79]. Therefore, the acidification value resulting from formal is much smaller than informal. The use of natural gas as an energy source makes it possible to reduce the adverse effects of gas in nature; this is in line with research [80], [81]. Besides SO_2 emission, another parameter that contributes to acidification is NO_x emission. These emissions result from the smartphone combustion stage and leaching openly on informal lines. This research aligns with [82], [83].

Formal recycling also has a negative value for the metal scarcity category, positively impacting the environment. The scarcity of metals in LCA decreases ore grades due to increased extraction of that metal; the amount of metal used in LCI includes only virgin materials [84]. The negative value of metal scarcity is due to recycling smartphone waste that produces secondary metal. So it can replace primary metal, which must be taken from nature (virgin mining), and can reduce metal scarcity [65], [85].

When viewed from the impact of damage, informal recycling practices have a positive value for the four impacts: climate change, human health, ecosystems, and resource depletion. Meanwhile, there are two negative impacts of damage to formal recycling: ecosystems and resource depletion. So it can be said that formal recycling practices are not harmful or safe for ecosystems and resource depletion. This is in line with [86] that acidification is one of the midpoints of endpoint ecosystems, and metal scarcity is one of the midpoints of resource depletion endpoints. The overall impact on the environment is that formal practices are harmful and informal practices are positive, so it can be concluded that formal recycling practices are safer, more friendly, and more profitable for the environment. According to the Ecoinvent organization, negative values in SimaPro results are commonly found due to more credits or profits than the burden to be borne for the related category [87].

The calculation results show that formal recycling gives a much better value than informal recycling. After that, the EVR or Eco-costs per Value Ratio and eco-efficiency rate are calculated. The EVR value in this formal recycling is zero because the eco-cost is considered zero. The smaller the EVR value, the better and more feasible the practice. Based on the EVR value, it can be concluded that the practice of formal recycling is very feasible and efficient to do. Furthermore, from the EVR value, the product eco-efficiency rate is calculated, which is 100%. Based on the eco-efficiency rate, it can be concluded that all processes are good, which is indicated by the maximum level of efficiency.

The sustainable performance of a process can be seen in various aspect dimensions, such as economic, environmental, and social. The feasibility of formal and informal recycling practices, if assessed based on sustainability aspects, can be seen in Table 9. On the economic dimension, it can be seen that the benefits derived from reduced prices minus costs for informal recycling practices are much lower than for formal ones. This is because only gold is taken as secondary material in the informal route, and the amount is lower than in the formal route. In the informal channel, it only produces 158.8 gr of gold, while for the formal channel, apart from producing 347 gr of gold, it also produces other precious metals. The environmental dimension shows that informal recycling hurts almost every category, while formal recycling has a significant negative value in acidification and metal scarcity. This is because the formal recycling process uses fossil fuels, burns, and leaches in the open.

Meanwhile, natural gas is used for formal recycling, and the production process produces secondary material in a larger volume to replace virgin metal from nature. Require materials and energy and emit emissions at one stage of their life cycle. The main contribution of this paper is that apart from analyzing the environmental impact aspect, a comparative analysis is from another sustainable aspect, such as the economic and social aspects. Formal recycling practices are more profitable than informal ones from an environmental and economic aspect.

TABLE IX
COMPARISON OF INFORMAL AND FORMAL RECYCLING SUSTAINABILITY PERFORMANCE

Dimension	Informal	Formal
Economy	Profit per unit of IDR. 14,759.56	Profit per unit of IDR. 52,000.74
Environment	It hurts almost all categories.	Good impact on acidification and metal scarcity categories or suitable on ecosystems damage categories and resource depletions
Social	Absorb labor around the production area and reduce the volume of waste in the community because the materials used are garbage from the community.	

So, it is time for Indonesia to switch to a formal recycling process carried out by licensed companies considering the vast potential for waste as a raw material. Actors on the informal channel are given space for repairing, buying, and selling secondhand products, considering that the secondhand product market in Indonesia is still quite large, at 44% [88]. Product price is one of the considerations for buying secondhand products [88], [89]. In recent years, the circular economy of the secondhand consumption model has become a culture [90]. The secondhand market plays an important role in the circular economy with significant economic and environmental benefits[91]. The formal recycling process can start with the e-waste collection process at the recycling center at an affordable distance [92], [93]. The government's role is to invite the public to distribute smartphone waste to licensed recycling companies. Several studies have concluded that the government driver is a factor that has a significant favorable influence on consumer intentions to participate in electronic waste collection programs[94], waste sorting behavior [95], and construction waste recycling [96].

IV. Conclusion

Currently, the most common recycling practice in Indonesia is the informal route. After calculating the environmental impact with a life cycle assessment, informal recycling practices have a higher environmental impact than formal recycling practices that developed countries have carried out. Informal recycling hurts almost every category, while formal recycling has a significant negative value in the acidification and metal scarcity categories. The formal recycling eco-efficiency index has a value greater than one, so it can be said that this recycling practice is affordable and sustainable. Economically, formal recycling practices are also more profitable than informal recycling practices. On the social dimension, informal and formal recycling absorbs labor around the production area and utilizes hazardous waste in the environment. However, the formal route is safer for workers because they already use modern tools for the safety side. So, it is time for Indonesia to use a formal recycling process; a licensed company carries recycling because of the vast potential for waste as a raw material.

Further research can be carried out by taking other research objects. A formal recycling method can be compared using other methods, such as electrometallurgy or hydrometallurgy. Therefore, the most suitable formal recycling method can be applied in Indonesia. The government's role is needed to invite the public to distribute smartphone waste to licensed recycling companies**.**

Acknowledgment

The authors thank Educational Fund Management Institution for the BUDI-DN scholarship and the Universitas Gadjah Mada Grant.

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