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Identification of electronic waste (e-waste) generation from the household and non-household sectors in Indonesia and its sustainable management system

I Made Wahyu Widyarsana (wahyu.labb3@gmail.com)
Bandung Institute of Technology: Institut Teknologi Bandung https://orcid.org/0000-0003-2337-8500
Dewi Suryanindah Supramono
Bandung Institute of Technology: Institut Teknologi Bandung
Suci Ameliya Tambunan
Bandung Institute of Technology: Institut Teknologi Bandung
Aurilia Ayuanda Mulyadi
Bandung Institute of Technology: Institut Teknologi Bandung

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Abstract

The rapid development of technology has spurred competition among electronics manufacturers to innovate. The resulting electronic waste (e-waste) has potential hazards due to its composition. The prediction of e-waste generation is carried out using the Delay Model method, modified by applying end-of-life (EoL) value to the lifespan to adjust Indonesian society's treatment of e-waste. The calculations show that the prediction of hazardous material from Indonesia's household sector will reach 16,653.73 tonnes in 2040, while the non-household sector comes to 25,391.72 tonnes in 2040. The most e-product produced from the household sector is TV with 3,763.74 tonnes, while the non-household sector is also dominated by TV with 23,380.52 tonnes in 2040. The composition of materials obtained from e-waste, in general, is 1% hazardous materials, 31% ferrous metal, then 27% glass and plastic materials, 6% non-ferrous metals, and 8% other materials. Thus, the total generation of e-waste will reach 4,204,545.43 tonnes, and the hazardous components in e-products only reach 42,045.45 tonnes or about 1% of the total e-product generation. In the future, it is necessary to integrate and formalize the handling of e-waste from the informal sector, which has been developing into the formal sector. This research is expected to be used as a reference by the government to make regulations, plans, and strategies related to hazardous waste management to prevent harm to the environment and human health.

1. Introduction

The rapid development of technology has spurred competition among electronic product (e-product) manufacturers to innovate. Updated innovations often replace old e-product. This rapid development is not balanced with managing e-product that become waste due to damage or disuse from expiration. Electronic waste (e-waste) continues to be generated in line with the changing trends in the use of e-product, especially electronic communication and information products. E-products can now be obtained at low prices and is accessible to young audiences. This additional number of consumers significantly affects the decline in service life and the increasing diversity of e-products as reported by Dwivedy and Mittal [1].

The resulting e-wastes have potential hazards due to their composition. The presence of heavy metals can cause systemic diseases in the body; additionally, persistent organic pollutants (POPs) can accumulate in the body; furthermore, there is also indium glass which makes up screens that can cause various respiratory diseases. In Indonesia, e-waste processing has not been given much attention. One regulation related to e-waste is Governmental Decree Number 101 of 2014 concerning Management of Hazardous and Toxic Waste, where discussion of e-waste can only be found in the attachment section without a specific discussion on e-waste management. Inadequate regulation coupled with a lack of data on e-waste in Indonesia causes low public attention to the negative impact of e-waste.

This research aims to determine the generation of e-waste in the household and non-household sectors in Indonesia. In addition, a projection for e-waste generation will be carried out until 2040, followed by e-waste management plans, which is expected to be used as a reference by the government in making regulations, plans, and strategies related to hazardous waste management to prevent harm to the environment and human health.

2. Materials And Methods

Several methods can be used to estimate the generation of e-waste, such as the Time Step Model, Market Supply Model, Stock, Lifespan Model, Leaching Model, The Delay Model, etc. The Market Supply Model method and Stock and Lifespan Model require e-product data not available in Indonesia. In this research, the prediction of e-waste generation is carried out using The Delay Model method, which has been modified by applying the End of Life (EoL) value to the lifespan enabling the treatment to adjust to Indonesian society to e-waste, as can be seen in the following equation.

Outflow (t) = Inflow (t-EoL) 1
Where:

Outflow = E-waste generation (tonnes/year)

Inflow = Electronic purchase (tonnes/year)

t = Year

EoL = End-of-life

The prediction of e-waste generation requires detailed sample data for every unit of e-products owned by the household and non-household sector. The sample data in the prediction uses 12 samples of schools and offices in Bandung City for the non-household sector. The sample data for Bandung City for the household sector are 412 households. The scope of e-products types for the household sector are cell phones, TVs, laptops, refrigerators, rice cookers, washing machines, ACs, irons, fans, blenders, DVD / VCD players, radios, tape recorders, and personal computers. The scope of e-products types for the non-household sector are laptops and TVs (including personal computer monitors). In this research, a prediction of the age of e-product ownership is carried out using the Weibull distribution with the following equations.

$$F(t) = 1 - exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] \qquad (2)$$

$$E(T) = \sum_{i=1} T \, . \, [F(t_{i+1}) - F(t_i)] \qquad (3)$$

Where:

F(t) = Cumulative distribution function for the Weibull distribution

t = E-product age

α = Distribution parameter

β = Distribution parameter

E(t) = Expected average lifespan of e-products

After obtaining the EoL value and the purchase value of each e-product each year, the generation of e-waste can be calculated using the Delay Model method using the following equation.

$$T\ Indonesia\ Year\ i = \frac{N}{n}\ x\ T\ Sampel\ Year\ i \qquad (4)$$

Where:

T Indonesia Year I = The prediction of Indonesia's e-waste generation in Year I

(unit/year)

N = Population number

n = Sample number

T Sample Year i = The predicted sample e-waste generation in Year i (unit/year)

3. Results And Discussions

3.1 The Prediction of E-Waste from the Household and Non-household Sectors

The Leaching Model method is suitable for calculating the e-waste generation from e-products with a constant lifespan, as e-products' lifespan is factored by corrosion and damage as reported by Van Der Voet et al [2]. In this research, the Delay Model and Time Step Model are applied to predict e-waste generation as both consider the age of ownership under Indonesian people's treatment of e-products, such as reusing used e-products, donating, repairing, storing, disposing of, etc. Each method used to calculate hazardous waste prediction has a specific data requirement and a different accuracy level. The comparison of the projection methods is shown in Table 1 below.

Table 1
E-waste generation prediction methods [2]

Methods	Required Data			Used for		Accuracy
	Purchase	Ownership	Lifespan	Saturated Markets	Dynamic Markets	
Time Step Model	✓	✓		✓	✓	High
Market Supply Model	✓		✓	✓	✓	High
Stock and Lifespan Model		✓	✓	✓		Low
Leaching Model		✓	✓	✓		Low
Delay Model	✓		✓	✓		Intermediate

The prediction of e-waste generation is carried out using the Delay Model method by applying the EoL value to the lifespan to adjust the community's treatment of e-waste. The prediction concept of e-waste generation uses the Delay Model, namely the generation of waste in a year (outflow), a purchase (inflow) in a year, which is the difference between the predicted year of the e-waste generation and the EoL value. In this research, a predicted age of e-product ownership is also carried out using the Weibull Distribution. This prediction of the age of ownership is limited to first hand (first user) to second hand (second user) users. The age of ownership (End of Life) of each e-product is a variable used to calculate e-waste generation using the Delay Model. The calculation shows the age of ownership for each type of e-product, as seen in Table 2.

Table 2
End of life calculation results for each type of e-product with Weibull Distribution

Types of E-products	Age of Ownership of New E-product (Year)	Age of Ownership of Second Hand E-product (Year)	Age of Ownership of E-product (Year)
Household Sector			
Cell phones	2.88	2.95	5.83
PCs	4.75	3.68	8.43
Laptops	4.16	3.9	8.05
TVs	6.89	4.75	11.64
Refrigerators	7.78	5.55	13.33
Washing Machines	6.1	4.11	10.22
Radios	11.16	9.33	20.5
Tape Recorders	12.65	7.25	19.9
DVD/VDC Players	6.46	4.9	11.35
ACs	5.92	4.39	10.31
Rice Cookers	5.21	3.46	8.67
Irons	5.83	4.59	10.42
Fans	5.48	4.39	9.87
Blenders	5.96	2.07	8.04
Non-Household Sector			
Laptops	1.16	0.93	2.10
TVs and Screens	5.99	0.93	6.92

The prediction results of the generation of e-waste for 412 respondents were projected to present all Indonesian residents for the household sector and present all schools and offices for the non-household sector. The prediction result of e-waste will then be multiplied by the generation of e-waste with the average weight per unit of each type of e-product. The average weight per unit of 14 types of e-products can be seen in Table 3.

Table 3
Average weight of each type of e-product

Types of E-products	Average Weight (kg)	Source
Cell phones	0.1	[3]
PCs	27.2	[4]
Laptops	2.9	[4]
TVs	24	[4]
Refrigerators	30	[4]
Washing Machines	23	[4]
Radios	2	[3]
Tape Recorders	0.181	[5]
DVD/VDC Players	5	[6]
ACs	55	[3]
Rice Cookers	4	[7]
Irons	1	[3]
Fans	7	[8]
Blenders	1	[3]

Table 3 shows the average weight of each type of e-product consisting of cell phones, PCs, laptops, TVs, refrigerators, washing machines, radios, tape recorders, DVD / VCD players, air conditioners, rice cookers, irons, fans, and blenders. The calculations show that the prediction of e-waste in the household sector in Indonesia will reach 1,665,372.63 tonnes in 2040, while the non-household sector will come to 2,539,172.80 tonnes in 2040. The detailed calculation of e-waste predictions for the household sector and non-household sector is shown in Table 4 and Table 5 below.

Table 4
Prediction results of the intact e-waste generation in Indonesia’s household sector in 2020–2040

Year	E-waste Generation (tonnes/year)										
	Cell phones	PCs	Laptops	TVs	Refrigerators	Washing Machines	Radios	Tapes	DVD/ VCD Players	ACs	Rice Cookers
2020	1,675.79	102,781.55	15,722.82	63,088.42	44,359.05	120,919.47	1,642.93	59.47	9,857.57	54,216.61	7,886.05
2021	2,825.57	85,897.27	13,496.24	55,846.52	119,671.12	26,451.13	3,324.20	30.08	16,620.99	45,707.72	15,956.15
2022	3,429.77	100,606.64	15,114.53	193,681.24	50,437.82	71,795.94	2,017.51	30.43	8,406.30	110,963.21	16,140.10
2023	4,608.12	111,002.96	22,190.39	65,295.86	188,745.85	75,574.67	2,040.50	92.33	11,052.68	93,522.72	19,044.63
2024	6,035.64	187,087.69	23,437.55	152,696.57	61,904.01	98,247.07	2,407.38	62.25	17,195.56	113,490.69	44,708.45
2025	6,241.89	160,793.99	28,740.54	158,568.47	151,265.97	132,255.67	2,781.90	94.41	19,125.58	248,632.58	38,251.17
2026	4,768.60	167,343.83	27,527.36	232,031.36	137,109.44	90,689.60	3,867.19	63.63	16,699.23	116,015.68	43,593.77
2027	5,149.43	202,996.24	22,158.29	328,376.27	117,277.24	139,813.14	3,198.47	64.32	14,215.42	156,369.65	51,886.29
2028	5,537.31	156,326.71	26,493.53	254,318.27	231,688.25	124,698.21	2,873.65	32.51	15,266.28	227,198.17	40,231.14
2029	5,932.24	200,142.19	28,279.79	278,803.76	152,470.81	136,034.41	2,904.21	65.71	12,705.90	209,647.36	38,268.72
2030	6,334.20	212,982.67	30,097.55	224,507.91	220,105.79	119,604.47	2,934.74	99.60	4,585.54	188,104.25	40,454.27
2031	6,743.20	226,045.44	31,946.79	195,707.62	227,954.90	124,696.69	3,706.58	100.63	0.00	199,359.81	42,676.71
2032	7,159.23	239,330.33	33,827.48	261,081.78	185,363.57	129,788.92	2,995.77	67.78	0.00	210,805.75	44,936.02
2033	7,582.28	252,837.18	35,739.61	274,724.60	206,985.38	134,881.14	3,026.27	68.47	0.00	222,441.94	47,232.17
2034	8,012.34	266,565.82	37,683.15	288,587.38	216,972.98	139,973.36	2,292.56	69.16	0.00	234,268.24	49,565.13
2035	8,449.42	280,516.09	39,658.07	302,669.96	227,117.08	145,065.58	2,315.41	34.92	0.00	246,284.50	51,934.88
2036	8,893.51	262,907.76	41,664.36	316,972.18	237,417.56	150,157.80	1,948.54	35.27	0.00	258,490.59	54,341.38
2037	9,344.59	275,748.61	43,701.99	331,493.88	247,874.31	155,250.02	1,180.53	0.00	0.00	270,886.36	56,784.62
2038	9,802.68	288,786.75	45,770.93	346,234.89	258,487.21	160,342.24	1,191.94	0.00	0.00	283,471.67	59,264.56
2039	10,267.75	302,022.04	47,871.18	361,195.06	269,256.14	165,434.46	1,203.34	0.00	0.00	296,246.40	61,781.17
2040	10,739.82	315,454.34	50,002.69	376,374.23	280,181.00	170,526.69	809.82	0.00	0.00	309,210.39	64,334.44

Table 5
Prediction results of e-waste generation in the non-household sector in Indonesia in 2020–2040

Year	E-waste Generation (tonnes/year)		
	Laptops	TVs	Total E-waste Generation
2020	322,817.79	76,871.66	399,689.45
2021	98,254.82	38,435.83	136,690.65
2022	103,692.93	153,743.32	257,436.25
2023	109,128.34	230,614.98	339,743.33
2024	114,561.07	192,179.15	306,740.23
2025	119,991.12	653,409.12	773,400.24
2026	125,418.47	1,383,689.91	1,509,108.38
2027	130,843.15	1,537,433.23	1,668,276.38
2028	136,265.15	1,691,176.55	1,827,441.71
2029	141,684.48	1,276,415.50	1,418,099.98
2030	147,101.13	1,372,927.87	1,520,029.00
2031	152,515.11	1,469,440.24	1,621,955.36
2032	157,926.42	1,565,952.62	1,723,879.04
2033	163,335.07	1,662,464.99	1,825,800.06
2034	168,741.06	1,758,977.36	1,927,718.42
2035	174,144.39	1,855,489.73	2,029,634.12
2036	179,545.06	1,952,002.10	2,131,547.16
2037	184,943.07	2,048,514.47	2,233,457.54
2038	190,338.43	2,145,026.84	2,335,365.28
2039	195,731.15	2,241,539.21	2,437,270.36
2040	201,121.22	2,338,051.58	2,539,172.80

The prediction results exposed that the e-waste for the whole household sector in Indonesia will reach 1,665,372.63 tonnes in 2040, with the TV being the most produced e-product from the household sector with 376,374.23 tonnes, followed by PCs with 315,454.34 tonnes and ACs with 309,210.39 tonnes in 2040. The EoL analysis in the household sector demonstrated that tape recorders are predicted to no longer be traded in 2037, and DVD / VCD players are also considered to be no longer traded starting in 2030. Those two e-products will become obsolete and be replaced by modern e-products such as laptops, televisions, and PCs that have similar functions as tape recorders and DVD / VCD players.

The prediction of e-waste generation from the non-household sector is limited to 2 (two) e-products: laptops and TVs as they are considered to be mostly owned by offices schools; furthermore, this scope is applied due to limitations in the survey. The non-household sector is also dominated by TVs amounting to 2,338,051.58 tonnes in 2040. This dominating e-product (TV) may be due to TV’s significantly heavier weight than other e-products. The intact e-waste is not completely categorized as hazardous waste. If the hazardous materials in e-waste are separated during the dismantling process, other economic value materials will become non-hazardous waste. The composition of e-waste depends on the type and age of the unit. For example, computer equipment contains more metals, while household appliances such as refrigerators predominantly contain plastic components.

The composition of materials obtained from e-waste, in general, is 1% hazardous materials, 31% ferrous metal, then 27% glass and plastic materials, 6% non-ferrous metals, and 8% other materials as reported by Chatterjee [9]. The results of the predicted generation of hazardous material from the generation of intact e-waste from the household and non-household sectors in 2020–2040 can be seen in Table 6.

Table 6
Prediction results of Indonesian e-waste generation in 2020–2040

Year	Household and Non-Household Sectors (tonnes/year)						Household Sector	Non-Household Sector
	Hazardous Materials	Ferrous Metal	Glass	Plastic	Non-Ferrous Metal	Other Materials	Hazardous Materials	Hazardous Materials
2020	8,486.79	263,090.46	229,143.30	229,143.30	50,920.73	67,894.31	4,489.89	3,996.89
2021	5,388.06	167,029.93	145,477.68	145,477.68	32,328.37	43,104.50	4,021.16	1,366.91
2022	8,601.54	266,647.84	232,241.66	232,241.66	51,609.26	68,812.35	6,027.18	2,574.36
2023	9,594.40	297,426.55	259,048.93	259,048.93	57,566.43	76,755.24	6,196.97	3,397.43
2024	10,544.23	326,871.02	284,694.12	284,694.12	63,265.36	84,353.81	7,476.82	3,067.40
2025	17,792.68	551,573.04	480,402.32	480,402.32	106,756.07	142,341.43	10,058.68	7,734.00
2026	24,062.99	745,952.55	649,700.61	649,700.61	144,377.91	192,503.89	8,971.90	15,091.08
2027	27,753.50	860,358.44	749,344.44	749,344.44	166,520.99	222,027.98	11,070.73	16,682.76
2028	29,834.94	924,883.17	805,543.41	805,543.41	179,009.65	238,679.53	11,560.52	18,274.42
2029	25,603.01	793,693.45	691,281.39	691,281.39	153,618.09	204,824.12	11,422.01	14,181.00
2030	26,264.33	814,194.29	709,136.96	709,136.96	157,585.99	210,114.66	11,064.04	15,200.29
2031	27,403.89	849,520.60	739,905.04	739,905.04	164,423.34	219,231.12	11,184.34	16,219.55
2032	29,016.80	899,520.93	783,453.71	783,453.71	174,100.82	232,134.43	11,778.01	17,238.79
2033	30,767.61	953,795.76	830,725.34	830,725.34	184,605.63	246,140.84	12,509.60	18,258.00
2034	32,401.94	1,004,460.11	874,852.35	874,852.35	194,411.63	259,215.51	13,124.75	19,277.18
2035	34,052.57	1,055,629.53	919,419.26	919,419.26	204,315.39	272,420.52	13,756.22	20,296.34
2036	35,390.91	1,097,118.19	955,554.55	955,554.55	212,345.46	283,127.28	14,075.44	21,315.47
2037	37,036.23	1,148,123.06	999,978.15	999,978.15	222,217.37	296,289.82	14,701.65	22,334.58
2038	38,698.51	1,199,653.82	1,044,859.78	1,044,859.78	232,191.06	309,588.08	15,344.86	23,353.65
2039	40,369.60	1,251,457.74	1,089,979.32	1,089,979.32	242,217.63	322,956.84	15,996.90	24,372.70
2040	42,045.45	1,303,409.08	1,135,227.27	1,135,227.27	252,272.73	336,363.63	16,653.73	25,391.73

Table 6 shows that in 2040, the total generation of e-waste will reach 4,204,545.43 tonnes; the hazardous components in e-products only reach 42,045.45 tonnes or about 1% of the total e-product generation in 2040. The dominating material in the e-product generation is ferrous metal by 31% or around 1,303,409.08 tonnes in 2040. The next largest component is plastic and glass, each weighing 1,135,227.27 tonnes, followed by non-ferrous metals and other materials at 6% and 8% or 252,272.73 tonnes 336,363.63 tonnes, respectively, as seen in Fig. 1 below.

Therefore, the content of hazardous materials from e-products in Indonesia from 2020 to 2040 will increase. In 2020, hazardous materials in Indonesia reached 8,486.79 tonnes. The prediction results show a 395.42% increase of 33,558.66 tonnes, resulting in a total of 42,045.45 tonnes in 2040- a very significant increase. The detailed increase can be seen in Fig. 2 below.

Figure 3 shows a map of the distribution of e-waste generation in 34 provinces in Indonesia in 2019. It is known that the distribution of e-waste in Indonesia is not evenly distributed. The generation of e-waste is dominated in Java, which had 15,000 to 86,000 tonnes of e-waste in 2019. This is due to the majority of Indonesia's population being located in Java and having the dominant center of government activities. Meanwhile, the smallest generation of e-waste is in Maluku, North Maluku, Papua, and West Papua Provinces, which are in the range of 1,000 to 3,000 tonnes of e-waste. This is due to the small population and limited internet and electricity supply in those areas.

3.2 The Characteristics of E-Waste Generation from Household and Non-Household Sectors

The prediction of e-waste generation is carried out to estimate the generation of hazardous waste in the coming year. The prediction can be referenced to design hazardous waste management systems that can reduce the harm of hazardous waste content on human health and the environment. The obtained data shows that e-products in the form of TVs and laptops are one of the most dominant e-products from both the household and the non-household sectors. So, from these 2 (two) e-products, the characteristics of the e-waste generation generated from household and non-household sectors can be analyzed through statistical analysis.

Determining the relationship and comparison of the e-waste generation in each household and non-household sectors can be done through statistical analysis using a comparative test. This comparative test was conducted to compare e-waste generation from the household and non-household sectors through televisions and laptops. Before the comparative test, a normality test is essential to help determine whether the data is normally distributed or not. In parametric statistical analysis, normally distributed data is crucial to determine the method for data testing. Meanwhile, if the data is not normally distributed, the research hypothesis is tested using a non-parametric statistical analysis. One way to detect data normality can be done by using the Shapiro - Wilk method. This test is generally used for small samples of less than 50 data as reported by Santoso [10]. The normality test results for the household sector and the non-household sector can be seen in Table 7 below.

Table 7
E-waste normality test results for household and non-household sectors

E-waste Generating Sectors	Types of E-product	Significancy (Shapiro-Wilk)
Household Sectors	TVs	0.118
	Laptops	0.707
Non – Household Sectors	TVs	0.014
	Laptops	0.003

The normality test shows that the significance value of household e-product generation is greater than 0.05, which means the e-product generation data is normally distributed. Meanwhile, the significance value of non-household e-product generation is less than 0.05, which means the e-product generation data is not normally distributed. Simultaneous analysis of each sector concluded that the e-waste generation data is not normally distributed.

Furthermore, the method chosen for this correlation test is the Mann - Whitney, where the tested data are unpaired and are not normally distributed. The first correlation test will be conducted on television waste from the household sector and the non-household sector. The initial hypothesis (H0) in this analysis assumes that there is no difference in the average generation of television e-waste in the household and non-household sectors. On the other hand, the alternative hypothesis (Ha) assumes that there is a difference in the average generation of television waste from household and non-household sectors. The results of the Mann-Whitney correlation test for TV from both sectors can be seen in Table 8 below.

Table 8
Mann-Whitney test results on television e-products

No.	Parameters	Results
1	Mann – Whitney U	85
2	Wilcoxon W	316
3	Asymp. Sig. (2-tailed)	0.001

The Mann - Whitney correlation test in Table 8 shows Asymp. Sig (2-tailed) of 0.001, which means that the value of the alternative hypothesis (Ha) is accepted and the initial hypothesis (H0) is rejected as reported by Graventter and Wallnau [11]; in other words, there is a significant difference in the average generation of the television e-waste between the household and non-household sectors. This can be caused by the considerable difference between the household and non-household sectors from using television, considering that the non-household sector's data is taken from the office and school activities that require more e-product units due to the large number of activities in schools and offices.

The next correlation test was conducted on laptop waste from the household sector and the non-household sector. The initial hypothesis (H0) assumes that there is no difference in the average generation of laptop e-waste in the household and non-household sectors. Alternatively, the alternative hypothesis (Ha) assumes that there is a difference in the average generation of laptop waste from the household and non-household sectors. The Mann-Whitney correlation test results for laptops from both sectors can be seen in Table 9 below.

Table 9
Mann-Whitney test results on laptop e-products

No.	Parameters	Results
1	Mann – Whitney U	0
2	Wilcoxon W	231
3	Asymp. Sig. (2-tailed)	0.000

The Mann - Whitney correlation test in Table 9 shows the Asymp. Sig (2-tailed) of 0.000, meaning the value of the alternative hypothesis (Ha) is accepted, and the initial hypothesis (H0) is rejected as reported by Graventter and Wallnau [11]. In other words, there is a significant difference in the average generation of laptop e-waste between the household and non-household sectors. This can be caused by the considerable difference between the household and non-household sectors from using television, considering that the non-household sector's data is taken from the office and school activities that require more e-product units due to the large number of activities in schools and offices.

Thus, the e-product generated by the household and non-household sectors have significant differences. This difference may lie from the use of e-products, usually more in the non-household sector such as offices and schools, as the main facilities that support activities, compared to e-products in the household sector.

3.3 Electronic Waste Management

Electronic waste, especially cell phones, televisions, and laptops, has a huge potential for recycling. The recovery rate for electronic waste is very high, reaching 37.5% – 80% as reported by Friege [12]. E-waste can be reused because it contains materials of economic value such as e-plastic, glass, iron, aluminum, copper, precious metals such as silver, gold, and others. The recycling process design in this study is limited to e-product such as TVs and LCD screens. The recycling process begins with the cutting process. The important first step is decontamination by separating hazardous materials in electronic and electrical waste. Hazardous materials must be handled carefully, separated, packed, and closed so that they do not leak, have a label attached to the packaging, and have a hazardous waste symbol according to Governmental Decree Number 101 of 2014. The packaged hazardous materials will be stored at the hazardous waste transfer depots for transportation to the hazardous waste processor (third party). After separating the electronic and electric waste from the hazardous material, separation and sorting are done based on the type of e-waste material.

The LCD Television will be stripped down semi-automatically, resulting in the separation of different fractions. The LCD is then manually sorted and crushed using a shredding unit and a cutting mill, reducing the size of the waste. Afterward, the LCD particles are screened to separate the glass (containing indium) with e-plastic. The glass containing indium will be sold to the ceramic producing industry, while the e-plastic particles will be mixed with e-plastic particles separated from other components and then further processed.

The e-plastic mixture will be processed with a granulator unit and pelletizer, which produces e-plastic pellets that can be sold to the industry as a substitute for raw materials. Workers manually strip CRT televisions, then the CRT tubes are processed in a Hot Wire CRT unit to separate panel glass, funnel glass, electron gun, metal scrap, and lead dust. Panel glass and funnel glass will be processed in a glass crusher unit and can be used as a substitute for raw materials. Metal scrap will be further processed with metal scrap from other components to be used as metal ingots. The lead dust will be transported to a third party for storage in the hazardous waste landfill.

Technologies designed to recycle e-plastic include reducing the size of e-plastic and making plastic pellets by melting and printing. Plastic pellets are small pieces of plastic that can be further processed in the plastic processing industry to shape them into various everyday plastic objects. Plastic producers covet this product because it is ready to be processed into new plastic, thus the wider market. The examples of recycling diagrams of several types of electronic waste can be seen in Fig. 4. below.

To deliver e-waste to a recycling facility, an integrated e-waste collection concept is needed. The informal sector dominates recyclers as the recycling and e-waste utilization activities are quite dangerous. In the future, it is necessary to integrate and formalize the handling of e-waste from the informal sector, which has been developing into the formal sector, as shown in Fig. 5.

The integration of computer e-waste handling is carried out, especially at collectors and processors (recyclers) from the informal to the formal sectors. Any reduction of informal recyclers is proportional to the increase of formal recyclers. The e-waste generated at the source will be collected by the formal collectors at the collection station and then brought to the processing station before ending at the final processing facility. E-waste collection stations can take advantage of the existing informal sector, which has been fostered, facilitated, and verified to meet the requirements (efforts to formalize the informal system of waste management). The proposed scenario of formalization for e-waste management can be seen in Fig. 6.

The application of the above concepts can be implemented by integrating the informal sector's transition- which currently dominates the handling of e-waste- into a formal sector that is more familiar with hazardous waste management (in this case, e-waste management). The submission of this concept does not mean eliminating the informal sector, but rather empowering them by fostering, giving sufficient training and insight, and if necessary, facilitating and providing capital assistance; these activities should be, of course, verified by the relevant government.

The proposed concept may not necessarily integrate the informal sector into a formal sector. The proposal is planned in stages, with a target transition period of approximately 5 (five) years after being stipulated in a regulation. For the transition period and its implementation, both soft skills and financial support from related parties, like the government and producers, will be needed. Operational implementation should be handled by the private sector, which the government and producers control.

Maintaining the informal sector will go hand in hand with the formal sector. In this scenario, the collection will be regionally centralized, where the informal sector (scavengers and flea sellers) still play a role in collecting e-waste at the source as a mobile collector. In scenario 2, a local collection system (LCS) enables the e-waste from flea sellers and scavengers to go directly to the Regional Collection Station (RCS) located in each area. Then, the e-waste from RCS will go to the Intermediate Handling Station (IHS), Handling and Recycling Centre (HRC), and finally, the Final Disposal Facility (FDF). In Fig. 7 below, we can see the concepts that prioritize regional centralization in the collection.

As e-waste is categorized as hazardous waste based on Governmental Decree Number 101 of 2014, it is necessary to handle the e-waste properly. This research is expected to be used as a reference by the government to make regulations, plans, and strategies related to hazardous waste management to not harm the environment and human health.

4. Conclusion

The rapid development of technology has created competition among electronic product (e-product) manufacturers to innovate. The resulting e-wastes have potential hazards due to their composition. The presence of heavy metals can cause systemic diseases in the body, persistent organic pollutants (POPs) that can accumulate in the body, and indium glass, which makes up screens that can cause various respiratory diseases. This research aims to determine the generation of e-waste in the household and non-household sectors in Indonesia. In addition, a projection of the generation of e-waste will be carried out until 2040, followed by e-waste management plans. The prediction of e-waste generation is carried out using The Delay Model method, which has been modified by applying the end of life (EoL) value to the lifespan to adjust Indonesian society's treatment of e-waste. Based on these calculations, it is known that the prediction of hazardous material from the household sector in Indonesia will reach 16,653.73 tonnes in 2040. In comparison, the non-household sector's hazardous material from e-waste will accumulate to 25,391.72 tonnes in 2040. The most produced e-product from the household sector is TV with 3,763.74 tonnes, while the non-household sector is also dominated by TV with 23,380.52 tonnes in 2040. The composition of materials obtained from e-waste, in general, is 1% hazardous materials, 31% ferrous metal, then 27% glass and plastic materials, 6% non-ferrous metals, and 8% other materials. Thus, in 2040, the total generation of e-waste will reach 4,204,545.43 tonnes, and the hazardous components in e-products only reach 42,045.45 tonnes, or about 1% of the total e-product generation. Based on the statistical analysis, the e-product generated by the household and non-household sectors have significant differences. The use of e-products can cause this, usually more in the non-household sector, including offices and schools, as the main facilities that support activities, compared to e-products in the household sector. This follows the research results, which show that the generation of e-waste in the non-household sector is greater than the generation of e-waste in the household sector. The recycling process design in this study is limited to e-product such as TVs and LCD screens. The important first step is decontamination by separating hazardous materials in electronic and electrical waste. Hazardous materials must be handled carefully, separated, packed, and closed so that they do not leak, have a label attached to the packaging, and have a hazardous waste symbol according to Governmental Decree Number 101 of 2014. To deliver e-waste to a recycling facility, an integrated e-waste collection concept is needed. The informal sector dominates recyclers as the recycling and e-waste utilization activities fall into the dangerous category. In the future, it is necessary to integrate and formalize the handling of e-waste from the informal sector, which has been developing into the formal sector. The prediction can be referenced to design hazardous waste management systems that can reduce the harm of hazardous waste content on human health and the environment.

Declarations

Availability of data and materials

All data generated or analyzed during this study are available upon request.

Competing interest

The authors declare they have no competing interests.

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Authors' contributions

I Made Wahyu Widyarsana provided the data, processed the data, and wrote the draft. Dewi Suryanindah Supramono fulfilled the analysis and processed the data. Suci Ameliya Tambunan fulfilled the analysis, processed the data, wrote the draft, and performed proofreading. Aurilia Ayuanda Mulyadi performed proofreading. All authors read and approved the final manuscript.

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Figures

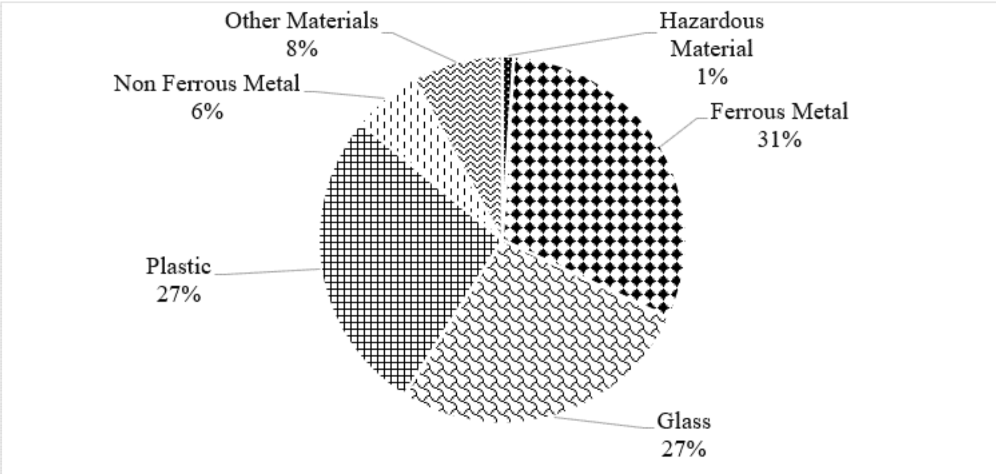

Figure 1

Percentage of material components in e-products in Indonesia in 2040

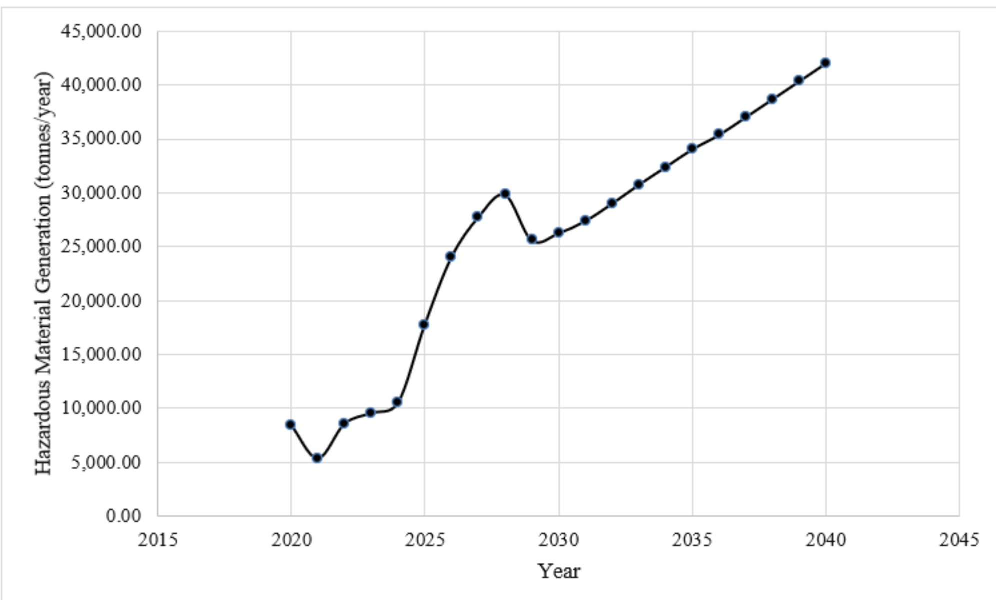

Figure 2

Prediction of the increase in hazardous materials in e-products in Indonesia

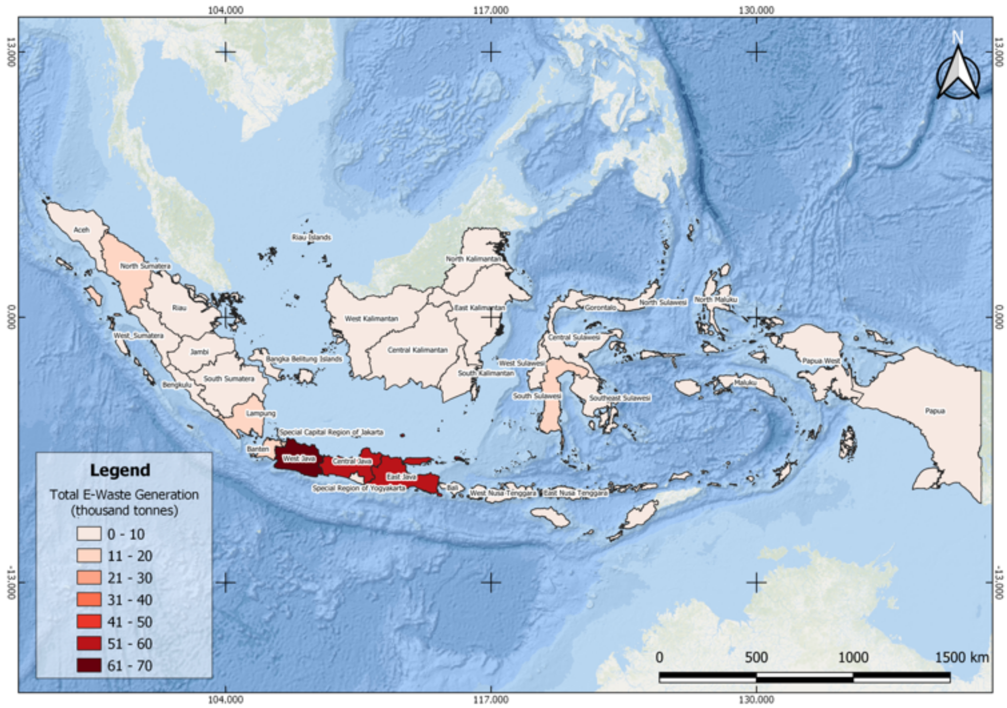

Figure 3

Map of estimated e-waste generation in each province in Indonesia in 2020. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

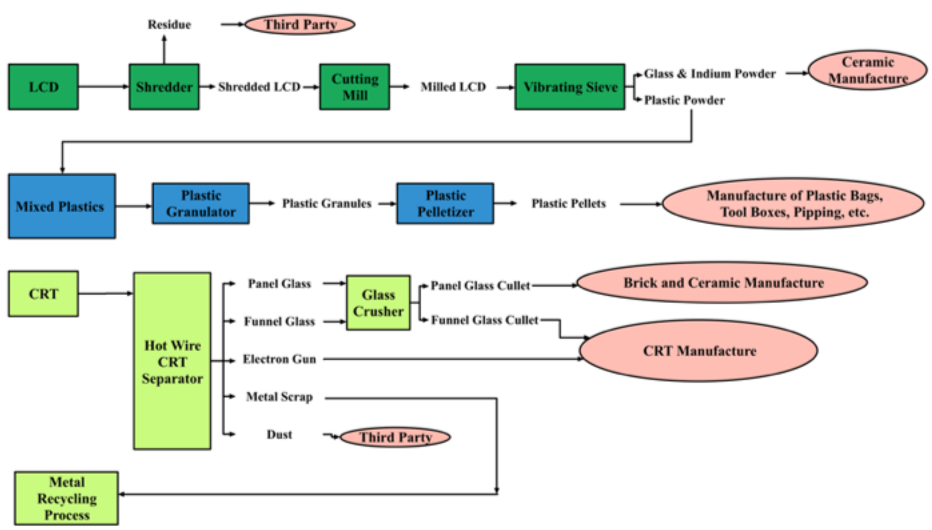

Figure 4

Recycling schemes of cell phones, laptops, and televisions

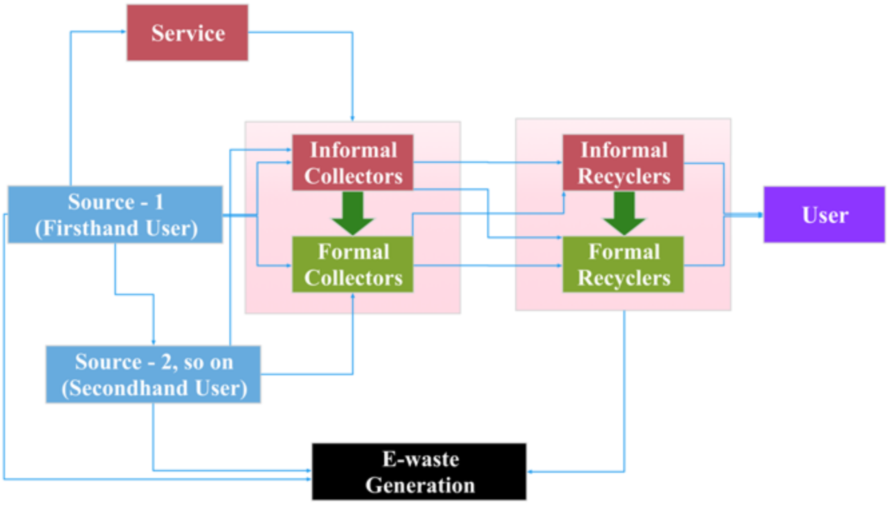

Figure 5

Concept of integration in e-waste handling

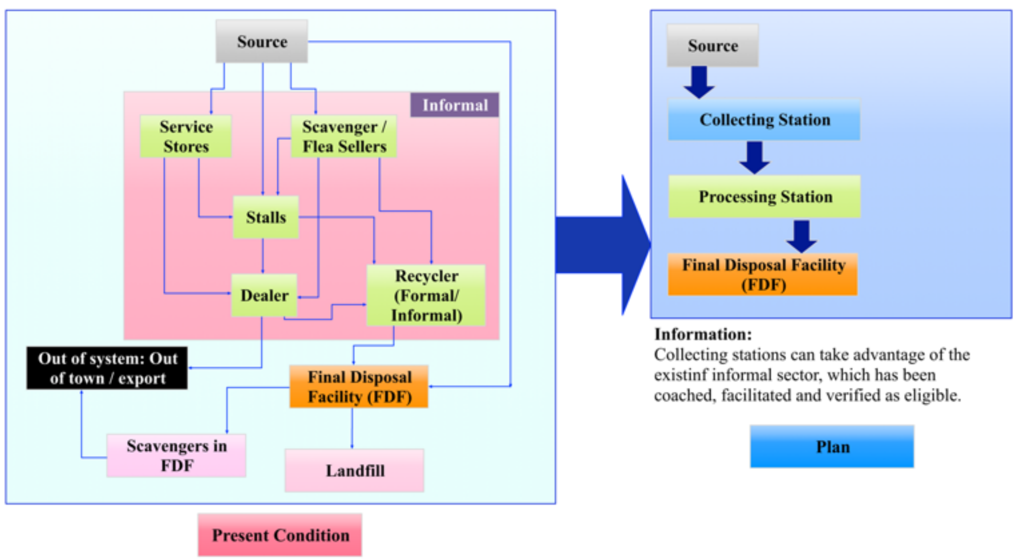

Figure 6

Concept of an integrated e-waste management

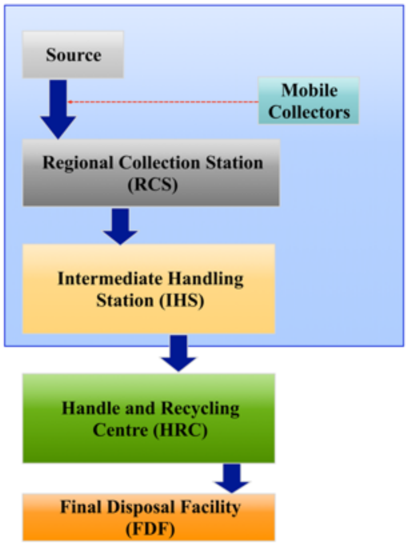

Figure 7

Electronic waste collection concept