Identification of industrial hazardous waste and material flow analysis based on hazardous waste producing businesses in Indonesia

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Identification of industrial hazardous waste and material flow analysis based on hazardous waste producing businesses in Indonesia

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Abstract
This research was conducted to (1) determine the hazardous waste generation from the industrial sector in Indonesia in 2019, (2) predict the hazardous waste generation in 2040, and (3) determine the waste material flow. This study's secondary data comes from past studies related to hazardous waste management in Indonesia's industrial sector. In this study, predicting hazardous waste generation used 2 (two) methods: the Annual Average Growth Rate and the Unit Gross Industrial Output Value. The last method used the assumption that Micro and Small Enterprises (MSEs) generate 10% of the total hazardous waste in Indonesia's industrial sector, while the Medium and Large Enterprises (MLEs) generate 85% of the total hazardous waste. In 2019, the total hazardous waste generation reached 573,351,835.37 tonnes yr^{-1}. The hazardous waste projection from Indonesia's industrial sectors in 2040 reached 1,066,603,307.02 tonnes yr^{-1} to 1,298,591,111.95 tonnes yr^{-1}. Based on the Material Flow Analysis, 68.66% of the hazardous waste was managed by disposing 11% of the hazardous waste in landfill, utilizing 31.44% of the waste, while 31.37% of the hazardous waste goes to hazardous waste transfer depots, and only 1.24% of the hazardous waste was processed. Meanwhile, 31.34% of the hazardous waste is considered to be unmanaged and pollute the land. Thus, it is necessary to have a reliable and integrated hazardous waste management system to reduce the negative impacts on the environment and human health.

Keywords: Hazardous, Waste, Generation, Industrial, Projection, Indonesia.

1. Introduction

Barely any research on hazardous wastes that focuses on Indonesia's industrial sector is available, despite the government providing various platforms for data collection of hazardous waste generated by industry. According to Governmental Decree Number 101 of 2014, any person who generates hazardous waste is required to provide storage, collection, transportation, utilization, processing, disposal, and dumping facility using a permit obtained from the government. However, in reality, not all businesses or industrial activities carry out these management systems. Moreover, not all the Micro and Small Enterprises (MSEs) carry environmental permits related to hazardous waste management. Another obstacle is the lack of knowledge from businesses in Indonesia regarding hazardous waste management.

Based on Economic Census (2016), there are 18,933,219 industries that have the potential to produce hazardous waste in Indonesia, which are estimated to produce hazardous waste of 229,907 tonnes yr^{-1}. One of Indonesia's largest company that provides services for disposal, collection, and recycling of hazardous waste and non-hazardous waste that is equipped with international standard is located in West Java Province. However, these facilities have certain processing capacity, where not all hazardous waste produced by industries in Indonesia can be managed by the company. There is not enough plant to manage hazardous wastes from West Java, let alone hazardous waste from Indonesia. Therefore, it is impossible to treat, store and dispose of these wastes safely. As a result, there is potential severe environmental contamination causing health hazards as reported by

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Widyatmoko [1]. The real impact of poor hazardous waste management can be seen in Cinangka Village, Bogor Regency. This village is known for its illegal lead-acid battery smelting businesses, which pollutes soil and river in the surrounding community. According to ongoing research in Cinangka Village by an NGO, the village's soil contains 100,000 ppm of lead and 3,700 ppm of arsenic, a drastic margin from WHO's standard of 400 ppm for lead and 2 ppm for arsenic.

Based on previous research that identified the hazardous content of hazardous waste to human health and the environment in Asia, it showed that in 7 (seven) countries in Asia, 679 of the regions were contaminated with hazardous waste. And there are 169 areas contaminated by the heavy metal lead, it is estimated that hazardous waste has affected 245,949 children aged 0 – 4 years reported by Fazzo et al. [2]. Lead poisoning causes multisystemic organ disease with non-specific symptoms of neurological disorders, such as decreased IQ (intelligence quotient), learning disabilities, slow growth, hyperactivity, antisocial behaviour, impaired hearing and high levels of exposure can cause ADHD (Attention-Deficit/ Hyperactivity Disorder).

Challenges faced by developing countries in environmental law enforcement are low legal awareness and legal compliance. The essence of environmental law enforcement is structuring the values of protecting the carrying capacity of ecosystems and environmental functions. Thus, it can protect the environment from pollution and damage which has implications for the increased quality of human health. Law enforcement intervention in the form of regulations on hazardous waste management is very important in order to create a sense of justice for all parties, including the community, companies, and the environment as reported by Sutrisno et al. [3].

This research aims to identify the total hazardous waste generation from Indonesia's industrial sector based on previous researches. In addition to calculating the total generation of hazardous waste in 2019, this research will also consider the total generation of hazardous waste in the future, namely until 2040. This research can be used as a reference in policymaking and concrete steps for central and local governments regarding hazardous waste management.

2. Materials and Methods

2.1 Hazardous waste generation in the industrial sector

In this research, Indonesia's hazardous waste generation was obtained from various free access research journals regarding the hazardous waste generation in several regions in Indonesia. After obtaining data for hazardous waste generated in 2019, a projection of hazardous waste generation was carried out from 2020 to 2040.

The required data to determine the hazardous waste generation are the number of industries and the hazardous waste generation for each type of industry. The types of industry are grouped according to the Indonesian Standard Classification of Business Fields (ISCBF), specifically for the business sector that produces hazardous waste following the Governmental Decree Number 101 of 2014 concerning Hazardous Waste Management. The projection of hazardous management in this study used 2 (two) methods: the Annual Average Growth Rate (AGR) method and the Unit Gross Industrial Output Value (UGIOV) methods. Waste projection was made by identifying MSEs and Medium, and Large Enterprises (MLEs) that can produce hazardous waste in Indonesia. It is assumed that MLEs generate 85% of the total waste of the population while considering not all industries in each industry category (ISCBF) produce the same hazardous waste. Meanwhile, MSEs are assumed to generate 10% of the total waste of the population while considering that not all MSEs, such as smaller production MSEs, produce hazardous waste.

MSEs Hazardous Waste Generation (tonnes yr^{-1}) = number of industries x industry's hazardous waste generation (tonnes yr^{-1}) x 10% Eq. (1)

MLEs Hazardous Waste Generation (tonnes yr^{-1}) = number of industries x industry's hazardous waste generation (tonnes yr^{-1}) x 85% Eq. (2)

The projection model for hazardous waste generation is very diverse and focuses on specific types of hazardous waste. Several mathematical models calculate industrial hazardous waste generation projections, namely the Unit Gross Industrial Output Value Method and the Annual Average Growth Rate Method as reviewed by Liu S et al. [4].

2.1.1 Unit Gross Industrial Output Value Method

This method calculates the predicted annual hazardous waste production after multiplying the predicted annual gross industrial output value by the production coefficient of hazardous wastes per unit of gross industrial output value as reviewed by Liu S et al. [4].

$$W_n = \varepsilon_n \, x \, M_n \quad \text{Eq. (3)}$$

$$\varepsilon_n = \frac{W_0}{M_0} \, x \, (1 - \delta_1)^n \quad \text{Eq. (4)}$$

$$M_n = M_0 \, x \, (1 + \delta_2)^n \quad \text{Eq. (5)}$$

Where:

W_n = predicted annual emission intensity of hazardous waste per unit of gross industrial output value (tonnes yr^{-1}).

W_0 = base-year production of industrial hazardous wastes (tonnes yr^{-1}).

M_n = predicted annual gross industrial output value (IDR).

M_0 = base-year gross industrial output value (IDR).

ε_n = predicted annual emission intensity of hazardous waste per unit of gross industrial output value (tonnes per IDR).

δ_1 = attenuation coefficient, which mainly refers to the decline of hazardous waste emission intensity resulting from industrial transformation and chemical engineering regulation.

δ_2 = annual average growth rate of gross industrial output value in the predicted period.

n = period of prediction (year).

The required data for the method above include the attenuation coefficient, the annual average growth rate of the industrial gross output value, the industrial gross output value in IDR (Indonesian Rupiah), and the hazardous waste generation as the basic value. The assumptions used are as follows:

a) The attenuation coefficient is a coefficient that mainly refers to the decline of hazardous waste emission intensity resulting from industrial transformation and chemical engineering regulation. The attenuation coefficient is determined by greenhouse gas emissions resulting from hazardous waste from incineration activities. The attenuation coefficient was calculated with an approach from the journal of "Emission from Waste Incineration" as reviewed by Bernt Johnke [5]. This calculation requires historical data on the incineration of hazardous waste. Further processed hazardous waste data was obtained from the Ministry of Environment and Forestry (2020) that shown in Table 1 as reported by Indonesia Central Bureau of Statistics [6].

Furthermore, based on the Ministry of Environmental and Forestry data, the percentage of hazardous waste originating from the industrial sector processed by incinerators was 1.24%. Thus,

the amount of hazardous waste processed through incinerator is 209,448.96 tonnes in 2016, 714,019.74 tonnes in 2017, 818,331.55 tonnes in 2018, and 1,125,071.43 tonnes in 2019. Furthermore, the incinerated hazardous waste can also identify the greenhouse gas emissions from CO and NO_x gases, and the percentage change in emissions considered as the attenuation coefficient value is shown in Table 2 based on calculation revied by Entreprises pour l'Environnement[[7]. Thus, from these calculations, CO_2 gas emissions from incineration activities and an attenuation coefficient of 0.79% are obtained.

b) The annual average growth rate of gross industrial output value was obtained from historical data processing of the industrial sector's Gross Domestic Product (GDP), which can produce hazardous waste according to Governmental Decree Number 101 of 2014. The Compound Growth Annual Rate (CAGR) method is shown in the following equation. And the results of the CAGR value in 2019 are shown in Table 3 as reported by Indonesia Central Bureau of Statistics [8].

$$CAGR = \left(\frac{V_{final}}{V_{begin}}\right)^{\frac{1}{t}} - 1 \qquad \text{Eq. (6)}$$

Where:
CAGR = *Compound Growth Annual Rate*
V_{begin} = initial value
V_{final} = final value
T = time (year)

The industrial gross output value (IDR) was obtained from the industrial sector GDP data, which can produce hazardous waste based on Governmental Decree Number 101 of 2014 reported by Indonesia Central Bureau of Statistics (2020). The GDP value of the industrial sector in 2019 can be seen in Table 4.

2.1.2 Annual Average Growth Method

In this method, the predicted annual hazardous waste production was calculated by multiplying the base-year industrial hazardous waste production by the annual average growth rate index of hazardous waste production in the predicted period. The prediction model is as follows as reviewed by Liu S et al. [4].

$$W_n = W_0 \, x \, (1 + \mu)^n \qquad \text{Eq. (7)}$$

W_n = predicted annual industrial hazardous waste production (tonnes yr^{-1}).
W_0 = base-year production of industrial hazardous waste (tonnes yr^{-1}).
μ = annual average growth rate of industrial hazardous waste in the predicted period.
n = year

This method assumed that the average growth rate of hazardous waste is 3% which was adapted from the growth rate of hazardous waste in India of 2-5% per year as reported by Kerthikeyan et al. [9]. One consideration was that both India and Indonesia are members of the G20 forums, which is a forum for countries with the largest economy, which in total reaches 90% of the world's gross product, 80% of world trade, ⅔ of the world's population, and half of the land on earth. This means that Indonesia and India are similar in terms of population and economic growth. Other considerations are the value of GDP, GDP per capita, and the GDP rate at constant prices, which show similarities between Indonesia and India, as shown in Table 5.

The AGR method is beneficial as it is accurate enough to be used in long-term projections, does not require new data or coefficients, and is relevant to many metric analyses that calculate growth rates. Meanwhile, due to the simple calculations, this method's projection results disregard risk factors caused by the fluctuation of the hazardous waste generation caused by time changes during the projection. On the other hand, the UGIOV method is also beneficial as it describes the industrial contribution to the projected hazardous waste because it uses many coefficients; however, those many coefficients may be challenging to find in Indonesia as reported by Siegel et al. [10].

2.2 Hazardous Waste Material Flow for Industrial Sector

In this research, apart from calculating the hazardous waste generation from the industrial sector and projecting the hazardous waste generation by 2040, an analysis of the hazardous waste material flow was also carried out. Brunner and Rechberger (2004) explain that the material flow is a long process starting from the entry (input) of material to its output. In an ideal material flow, the material input release value will be the same as the output value. However, having another process after the input will affect the output. In calculating the Material Flow Analysis (MFA), it is necessary to pay attention to the main components of MFA, namely input, storage, and output. The purpose of material balance is to calculate the material flow and storage at any time and point in the system. The general process in a material flow can be seen in Figure 1 as reported by Rechberger [11].

Material flow analysis in Indonesia's industrial sector in this study refers to the generation of hazardous waste from previous calculations from various studies in Indonesia. Meanwhile, determining the percentage and hazardous waste generation in each treatment system used the data from the Ministry of Environment and Forestry and data from one of the largest companies in Indonesia that provide services for disposal, collection, and recycling of hazardous waste and non-hazardous waste as reported by Widyatmoko [1]. The percentage of each treatment system based on the data explained above is shown in Table 6.

The Ministry of Environment and Forestry data (2020) shows that hazardous waste polluting the soil from the industrial sector reached 5,849,656.49 tonnes and 180,498.52 tonnes from the non-industrial sector. Additionally, this study also used the data from one of the largest companies in Indonesia that provide services for disposal, collection, and recycling of hazardous waste and non-hazardous waste to create the material flow analysis to identify the continued hazardous waste processing carried out by the company. The MFA only used the processed data due to the amount of hazardous waste managed by that company from the industrial and non-industrial sectors. The amount of processed waste is shown in Table 7.

The amount of hazardous waste in each treatment was used as a base assumption of the waste processing that is most widely used in treating hazardous waste in Indonesia. It shows that stabilization and solidification are the most used by the company to manage hazardous waste, amounting to 252,000.00 tonnes, while the least used is utilization as fuel, which is equal to 36,000.00 tonnes.

3. Results and Discussion

3.1 Hazardous Waste Generation in the Industrial Sector

The ISCBF classified 9 (nine) types of business that can produce hazardous waste. Hazardous waste producing industries in each business is based on the attachment of Governmental Decree Number 101 of 2014. At least 30 (thirty) industries can produce hazardous waste, as shown in Table 8 as reported by Indonesia Central Bureau of Statistics [12]. Based on the 2016 economic census from the government data portal, the numbers of MSEs in Indonesia reached 4,397,349 while MLEs reached 82,364 industries, amounting to 4,479,713 industries in Indonesia. Based on the Law of Republic Indonesia Number 20 of 2008, a micro business is a productive business owned by the

individuals and/or individual business entities that meet the criteria for Micro Business in Law of Republic Indonesia Number 20 of 2008. Small Business is a productive business that stands alone, which is carried out by an individual or business entity that is not a subsidiary or branch of a company that is owned, controlled, or is part of either directly or indirectly from a Medium or Large Business that meets the criteria of a Small Business as explained in the Law of Republic Indonesia Number 20 of 2008. Medium Business is a productive economic business that stands alone, which is carried out by an individual or business entity that is not a subsidiary or branch of a company that is owned, controlled, or is part of, either directly or indirectly, with a Small or Large Business with a total net worth or annual sales proceeds as regulated in the Law of Republic Indonesia Number 20 of 2008. Meanwhile, Large Businesses are productive economic enterprises carried out by business entities with a net worth, or annual sales proceeds greater than Medium Business, which include state-owned or private national businesses, joint ventures, and foreign businesses carrying out economic activities in Indonesia.

In Indonesia alone, there are significantly more MSEs than MLEs. The results showed that the average number of Micro, Small, and Medium Enterprises (MSME) workers was 112,709,244 or 97.03%. Micro enterprises absorb 92% of the workforce, 5% of small and medium enterprises, and 3% of the MSMEs' total workforce. The average contribution of MSMEs to Indonesia's GDP during the 2012 - 2017 period was IDR5,928,934.98 or 59.74%. Micro enterprises gave the largest contribution, namely 6.05%, small businesses with 16.20%, and medium enterprises contribute to 22.75% of MSMEs' total GDP as reported by Suhaili M & Sugiharsono S [13].

In determining the total hazardous waste generation for the base year, data was obtained from various studies regarding management and hazardous waste generation in Indonesia's industrial sector. Those data are then used as a reference in determining the hazardous waste generation in the coming year. The data is then multiplied by the number of MLEs and MSEs for each type of industry that potentially produce hazardous waste. The percentage of waste generation by MLEs and MSEs will be different, thus coming to the assumption that the hazardous waste generated by MLEs is 85% while the hazardous waste generated by MSEs is 10% of the total waste. A more detailed hazardous waste generation can be seen in Table 9.

Based on the base year's calculation, namely 2019, the total hazardous waste generation of the MLEs sector was 521,228,941.25 tonnes yr^{-1} while the hazardous waste generation of the MSEs sector was 52,122,894.12 tonnes yr^{-1}. So, the total waste generation in the industrial sector reached approximately 573,351,835.37 tonnes yr^{-1}. The most hazardous waste generation comes from the processing business as it has more industries than others - processing business of MSEs and MLEs reached 2.724.351 industries. Meanwhile, the service business produces the least amount of hazardous waste with 53.903 industries.

Based on the distribution of hazardous waste generation in Indonesia’s industrial sector, Figure 2 shows that the industrial sector producing hazardous waste is concentrated in Java with West Java, Central Java, and East Java Province as the highest generator. This is due to the number of MLEs and MSEs in these provinces is more than the other provinces in Indonesia, with the processing industry, especially food and textile industry dominating the business in this region. Meanwhile, Kalimantan and Papua tends to generate smaller amount of hazardous waste, even though the number of mining businesses in these regions is quite a lot, the number of other types of businesses is smaller than in Java, so that the generation of hazardous waste generated in Kalimantan and Papua is still lower than in Java.

3.2 Validation of Hazardous Waste Generation Data

To validate the estimated hazardous waste generation from previous calculations, a comparison was made with the hazardous waste data obtained from the Ministry of Environment and Forestry (2019) and local governments in 10 (ten) provinces in Indonesia. In 2019, 15,455 potential hazardous waste producing businesses were reported and recorded by the Ministry of Environment and Forestry. Meanwhile, the 2016 Economic Census reported that 18,933,219 businesses MSEs and MLEs could produce hazardous waste based on Governmental Decree Number 101 of 2014. Thus, to determine the national hazardous waste generation from all hazardous waste producing businesses, a comparison was made based on the number of businesses, the national hazardous waste generation based on the Ministry of Environment and Forestry, and local governments. The results can be seen in Table 10.

From Table 10 concludes that the generated hazardous waste is still acceptable. Based on Table 9, the total hazardous waste generation in 2019 from the industrial sector is 573,351,835.37 tonnes. Meanwhile, the estimated hazardous waste generation from local government's data was 476,283,786.42 tonnes yr^{-1} and 162,352,845,213.20 tonnes yr^{-1} from the Ministry of Environment and Forestry data. The estimated hazardous waste generation used as a reference is taken from the local government as hazardous waste management permits are available in each province, making the local government's data more comprehensive and valid. However, it is unconfirmed whether all industries in Indonesia report their hazardous waste management to their respective local governments. Thus, the calculated hazardous waste generation is assumed to be the closest to the actual conditions.

3.3 Projection of Hazardous Waste Generation from the Industrial Sector

After determining the hazardous waste generation for the industrial sector in the base year, a projection of the hazardous waste generation was carried out until 2040 using the AGR method and the UGIOV method with the assumptions mentioned above. From these 2 (two) methods, the range of hazardous waste generation in the industrial sector in 2040 reached 1,066,603,307.02 tonnes yr^{-1} to 1,298,591,111.95 tonnes yr^{-1}. The difference in the hazardous waste generation's projection results in 2040 from the two methods was 231,987,804.93 tonnes yr^{-1} or 9.81% of the average hazardous waste generation of both methods in 2040. The increase in hazardous waste generation in the industrial sector each year can be seen in Figure 3.

This annual increase of hazardous waste from Indonesia's industrial sector requires a well-developed and integrated system in hazardous waste management, from the provision of hazardous waste management infrastructure, facilities, and hazardous waste management regulations. The impact of poor management of hazardous waste can affect the environment and human health. The projection of hazardous waste generation in the industrial sector until 2040 can help prepare a national plan and strategy for managing hazardous waste in Indonesia's industrial sector.

3.4 The Calculation of Industrial Sector's Hazardous Waste

Analyzing the hazardous waste material flow begins by calculating the source value derived from the previous calculation of the industrial sector's hazardous waste generation. It was known that the generation of hazardous waste in the industrial sector in Indonesia in 2019, both from MLEs and MSEs was 573,351,835.37 tonnes. The hazardous waste material flow can be seen in Table 4.

Based on the material flow, the percentage of unmanaged industrial hazardous waste was 31.34%, making the percentage of managed industrial hazardous waste with 68.66%. Further waste processing was based on the percentage of the Ministry's data and the hazardous waste treatment process of one of Indonesia's largest company that provides services for disposal, collection, and recycling of hazardous waste and non-hazardous waste. In addition, data for exported hazardous

waste were obtained from BPS (2019), totaling 105,803.80 tonnes. The most exported hazardous waste are waste, parings & scrap, polymers of ethylene, of rigid cellular products totaling 40,086.10 tonnes.

The generation of hazardous waste stored in hazardous waste transfer depots reached 123,492,199.22 tonnes yr^{-1}. The hazardous waste is divided into several treatments: exported waste, utilized, processed, disposed into the landfill, dumped into the sea, discarded and contaminated to the soil, and others. The utilized hazardous waste from industrial sectors is quite large, reaching 123,767,763.60 tonnes yr^{-1}. Hazardous waste that undergoes processing is still minimal, only reaching 4,881,425.79 tonnes yr^{-1}. Hazardous waste management consists of incinerators for medical waste, stabilization and solidification, physical, chemical, biological processing, and other treatments.

In 2018, an estimated 230,840 kg d^{-1} of medical waste resulted from approximately 2,820 hospitals in Indonesia, whereas the best waste treatment implemented was an incinerator as reported by Zulkarnain et al. [14]. Hazardous waste processing technology with an incinerator produces hazardous by-product in the form of fly ash and bottom ash (FABA). The chlorine content of fly ash from medical waste incinerators is higher than that of city waste incinerators as reported by Ni et al. [15]. There is approximately 5% of the residual ash from burning medical waste from the total weight of waste that will pollute the environment if it is not treated and disposed of poorly. Other impacts of incineration of medical waste that do not comply with standard procedures include dioxin gas emissions, which are carcinogenic and can cause cancer, and $PM_{2.5}$ pollutants that pose a risk to the respiratory and cardiovascular systems. The by-product generated from the incinerator needs special attention in its management following regulations to avoid negative impacts on the environment and human health.

In hazardous waste treatment, the term solidification/stabilization (S/S) is usually used to convert hazardous waste into harmless waste. S/S technology is based on the interaction of waste to form solids both physically and chemically. Cement, lime, dissolved silica are materials that are often used in S/S technology. The purposes of this process is to form solids that are easy to handle and will not leach contaminants into the environment. Product from S/S technology are safe products and can be used into other products such as paving blocks and concrete blocks. The use of this technology to treat hazardous waste is becoming more important due to regulations that limit the use of land to dispose of hazardous waste as reported by Silva MAR et al.[16].

Hazardous waste can also be processed through physical, chemical, and biological processes. Some of the chemical processing technologies are high temperature kilns such as cement kilns, coal fired power plant boilers, blast furnaces, etc. Hazardous waste that enters the cement kiln will be destroyed at a temperature of around 1,200 – 2,000degree Celcius. Certain types of hazardous waste can be used as fuel or alternative raw materials, thereby reducing the need for fossil fuels and natural raw materials as reported by Li X et al. [17]. Meanwhile, processing hazardous waste biologically involves a natural biological system and engineered living organisms to treat hazardous waste as reported by Zhang et al. [18]. The best-known biological treatment of hazardous waste is vitoremediation or bioremediation. Vitoremediation is the use of plants in the process of accumulation and absorption of various toxic and dangerous substances from the soil. Meanwhile, bioremediation is the use of types of microorganisms and bacteria as materials to degrade hazardous waste. With biological treatment methods, the costs incurred tend to be lower than other treatments, but for large amounts of hazardous waste the time required is longer. As well as the use of living organisms that are at risk of bringing various toxic compounds into the food chain.

Based on material flow analysis, the landfill's hazardous waste reached 43,302,970.72 tonnes yr^{-1}, while the hazardous waste dumped into the sea reached 91,881,030.60 tonnes yr^{-1}. The hazardous waste processing that needs to be highlighted is hazardous waste that contaminates the soil, hazardous waste treatment, and hazardous waste dumping. The hazardous waste generation contaminating the soil is divided into 2 (two) sources: industrial and non-industrial. The hazardous waste from the industrial sector that contaminated the soil was 5,849,656.49 tonnes, while the non-industrial sector produced 180,498.52 tonnes. The most hazardous waste came from the industrial sector, namely sludge from the production process and storage facilities for petroleum or natural gas with 1,923,506.34 tonnes. Meanwhile, the non-industrial sector, namely dust and/or sludge from air pollution control facilities and primary and/or secondary slag from the production process, produced 48,687.00 tonnes as reported by Indonesia Central Bureau of Statistics [6].

The material flow analysis in the industrial sector can be used as a reference for the government in making policies, plans, and strategies related to hazardous waste management, especially the industrial sector, which produced the most hazardous waste. The impact arising from untreated hazardous waste can be deadly for humans and the environment.

4. Conclusion

The calculated total hazardous waste generation from the industrial sector in Indonesia can be used as a reference in planning hazardous waste management regulations by the government. Based on calculations in 2019, the total hazardous waste generation from the MLEs reached 521,228,941.25 tonnes yr^{-1}, while the total waste generation from the MSEs reached 52,122,894.12 tonnes yr^{-1}. The total hazardous waste generation in the industrial sector throughout Indonesia reached approximately 573,351,835.37 tonnes yr^{-1}. The projection of hazardous waste in this study used 2 (two) methods namely AGR method and the UGIOV method. The projected range of hazardous waste generation in the industrial sector reached 1,066,603,307.02 tonnes yr^{-1} to 1,298,591,111.95 tonnes yr^{-1} in 2040 using both projection methods. Based on the Material Flow Analysis, 68.66% of the hazardous waste was managed by disposing 11% of the hazardous waste in landfill, and utilizing 31.44% of the waste, while 31.37% of the hazardous waste went to hazardous waste transfer depots, and only 1.24% of the hazardous waste was processed. Meanwhile, 31.34% of the hazardous waste was still considered to be unmanaged and pollute the land. So, it is necessary to have a reliable and integrated hazardous waste management system to reduce the negative impacts on the environment and human health.

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. Aurilia Ayuanda Mulyadi fulfilled the analysis, processed the data, wrote the draft, and performed proofreading. Suci Ameliya Tambunan performed proofreading. All authors read and approved the final manuscript.

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Table 1 Hazardous waste data from each sector

Sector	Processed Hazardous Waste (tonnes yr^{-1})			
	2016	2017	2018	2019
Mining, Energy, and Oil and Gas	531,101.38	45,802,660.27	43,188,826.46	55,289,028.53
Manufacture	15,832,731.80	7,060,942.59	12,124,515.81	15,290,521.47
Agroindustry	240,579.54	3,401,087.86	2,495,811.56	3,422,143.15
Infrastructure	108,071.54	7,797.17	60,946.91	260,318.58
Service	178,560.88	1,309,748.89	8,124,379.15	16,469,555.51
Total per year	16,891,045.14	57,582,236.79	65,994,479.89	90,731,567.25

Table 2 Results of the attenuation coefficient using emission from incinerated waste

Year	2016	2017	2018	2019
Emissions from CO	4,645.04	15,835.12	18,148.48	24,951.18
Emissions from CO_2 Eq CO	13,935.11	47,505.35	54,445.45	74,853.54
Emissions from NOx	230.39	785.42	900.16	1,237.58
Emissions from CO_2 Eq NOx	1,843.15	6,283.37	7,201.32	9,900.63
Total	15,778.26	53,788.72	61,646.76	84,754.17
CAGR % Emissions Change		0.791%		

Table 3 CAGR value based on industrial sector's GDP

Year	Value	CAGR
2019	6,291,720,700,000,000	
2018	6,020,825,500,000,000	
2017	5,744,788,600,000,000	
2016	5,498,235,000,000,000	
2015	5,281,218,100,000,000	0.047977 or 4.7977%
2014	5,116,811,500,000,000	
2013	4,883,548,200,000,000	
2012	4,666,558,300,000,000	
2011	4,426,036,800,000,000	
2010	4,126,707,300,000,000	

Table 4 GDP value of potentially producing hazardous waste [8]

GDP of Business Fields	Annual GDP in Constant Prices (Billion IDR)
B. Mining and Excavation	806,206.2
C. Processing Industry	2,276,682.8
D. Procurement of Electricity and Gas	111,436.7

GDP of Business Fields	Annual GDP in Constant Prices (Billion IDR)
E. Water Supply, Waste Management, Waste and Recycling	9,005.5
F. Construction	1,108,425.0
G. Wholesale and Retail Trade; Car and Motorcycle Repair	1,440,523.2
M,N. Service Company	206,936.2
Q. Health Services and Social Activities	127,506.6
R,S,T,U. Other services	204,998.5
Total Annual GDP Based on Constant Prices in 2019 (Billion IDR)	6,291,720.7

Table 5 Comparisons of the characteristics of India and Indonesia

Country	GDP (M$) (countryeconomy.com)	GDP per capita ($) (countryeconomy.com)	The Rate of GDP According to Constant Prices (BPS, 2019)	Hazardous Waste Growth Rate
Indonesia	1,022,454	3,871	4.80%	32.64% [6]
India	2,718,732	2,010	7.30%	2-5% [9]

Table 6 Treatment of hazardous waste management [6]

Treatment	Percentage
Managed	68.66%
Unmanaged	31.34%
Utilized	31.44%
Stored at the Hazardous Waste Transfer Depo	31.37%
Processed	1.24%
Disposed Into Hazardous Waste's Landfills	11.00%
Dumping	23.34%
Others	0.82%

Table 7 Hazardous waste managed by one of the largest hazardous waste management companies in Indonesia

Waste Processing	Total Amount (tonnes)
Incineration	69,298.90
Stabilization and Solidification	252,000.00
Physical, Chemical, and Biological Treatment	72,000.00

Waste Processing	Total Amount (tonnes)
Utilization (as fuel)	36,000.00

Table 8 Businesses and industries that can produce hazardous waste [12]

No	ISCBF Code	Types of Businesses and Industries	Industry
1	B	Mining and Excavation	Mining for Petroleum, Natural Gas, Geothermal, and Mining Supporting Service Activities Coal and Metal Ore Mining Mining and Excavation of Other Mining Materials
2	C	Processing Industry	Food Industry Textile Industry Apparel Industry Leather, Leather Goods, and Footwear Industry Paper and Paper Products Industry Recording, Media Printing, and Reproduction Industry Chemical and Products Made of Chemical Industry Pharmaceutical, Medicinal Products, and Traditional Medicines Industry Rubber, Products from Rubber and Plastic Industry Computer, Electronic Goods and Optical Industry Electrical Equipment Industry Base Metal Industry Motor Vehicle, Trailer, and Semi-Trailer Industry Repair and Installation Services for Machines and Equipment Coal Product and Petroleum Refinery Industry
3	D	Procurement of Gas / Steam, Hot Water, and Cold Air	Procurement of Gas / Steam, Hot Water, and Cold Air
4	E		Water Management

No	ISCBF Code	Types of Businesses and Industries	Industry
		Water Management, Wastewater Management, Waste Management, and Recycling, and Remediation Activities	Wastewater Management, Waste Management, and Recycling, and Remediation Activities
5	F	Construction	Building Construction Civil Building Construction Special Construction
6	G	Wholesale and Retail Trade; Car and Motorcycle Repair	Wholesale and Retail Trade; Car and Motorcycle Repair
7	M,N	Service Company	Animal Health Activities
8	Q	Health Services and Social Activities	Hospital Activities Doctor's and Dentist's Practice Activities Other Human Health Services Activities
9	R,S	Other Services	Computers, Personal Goods, and Household Items Repairs

Table 9 Hazardous waste generation from the industrial sector [8]

No	ISCBF Code	Hazardous Waste Producing Business	Hazardous Waste Generation of MLEs (tonnes yr^{-1})	Hazardous Waste Generation of MSEs (tonnes yr^{-1})
1	B	Mining and Excavation	979,564.21	97,956.42
2	C	Processing Industry	516,947,846.12	51,694,784.61
3	D	Procurement of Gas / Steam, Hot Water, and Cold Air	267,290.90	26,729.09
4	E	Water Management, Wastewater Management, Waste Management, and Recycling, and Remediation Activities	1,397,073.60	139,707.36
5	F	Construction	501,233.85	50,123.38

No	ISCBF Code	Hazardous Waste Producing Business	Hazardous Waste Generation of MLEs (tonnes yr^{-1})	Hazardous Waste Generation of MSEs (tonnes yr^{-1})
6	G	Wholesale and Retail Trade; Car and Motorcycle Repair	275,444.06	27,544.41
7	M,N	Service Company	1,263.46	126.35
8	Q	Health Services and Social Activities	57,849.30	5,784.93
9	R,S	Other Services	801,375.75	80,137.58
		Total	521,228,941.25	52,122,894.12

Table 10 Estimation of hazardous waste generation based on official government data

Types of Data	The Number of Industries	Hazardous Waste Generation (tonnes yr^{-1})
The Ministry's Official Data	15,455.00	132,527,026.85
The Ministry's Estimated Data	18,933,219.00	162,352,845,213.20
Local Government's Official Data	10 Province	140,083,466.59
Local Government's Estimated Data	34 Province	476,283,786.42

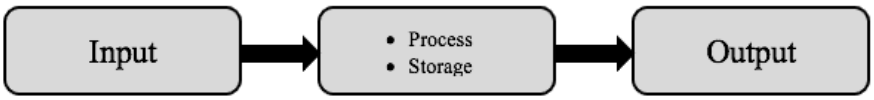

Figure 1 General process of material flow analysis [11]

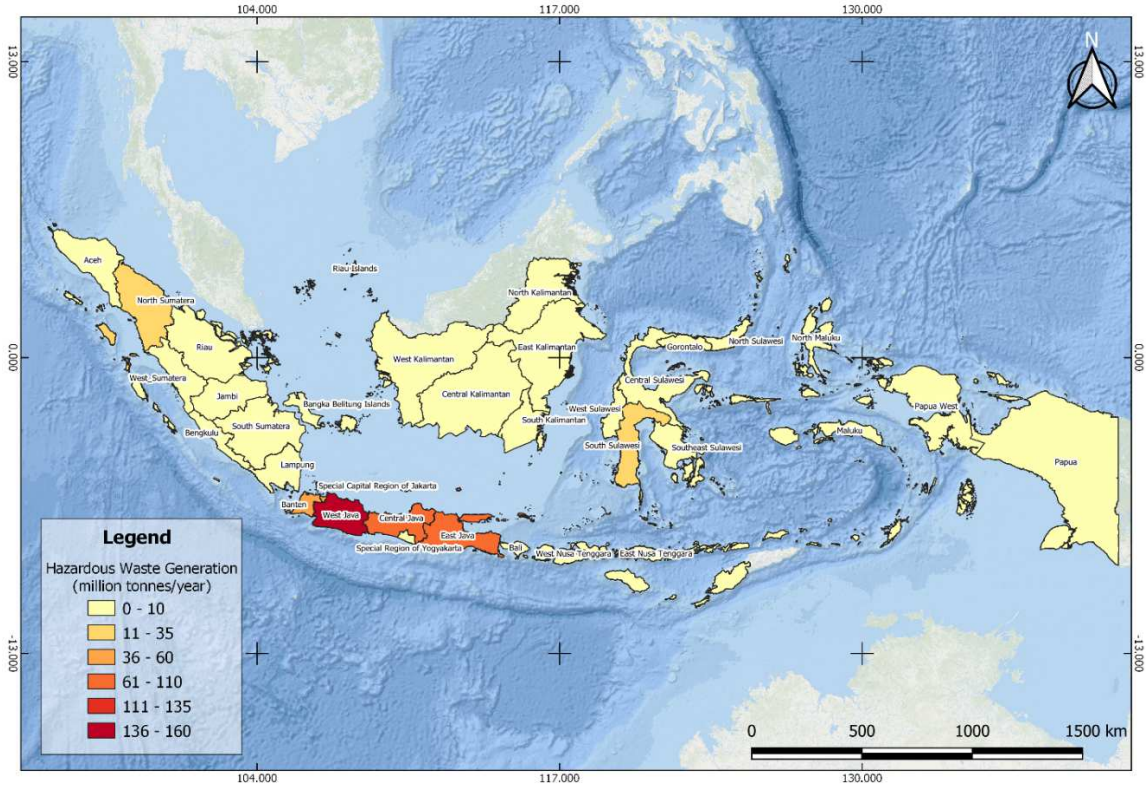

Figure 2 Estimated industrial hazardous waste generation maps in each province in Indonesia

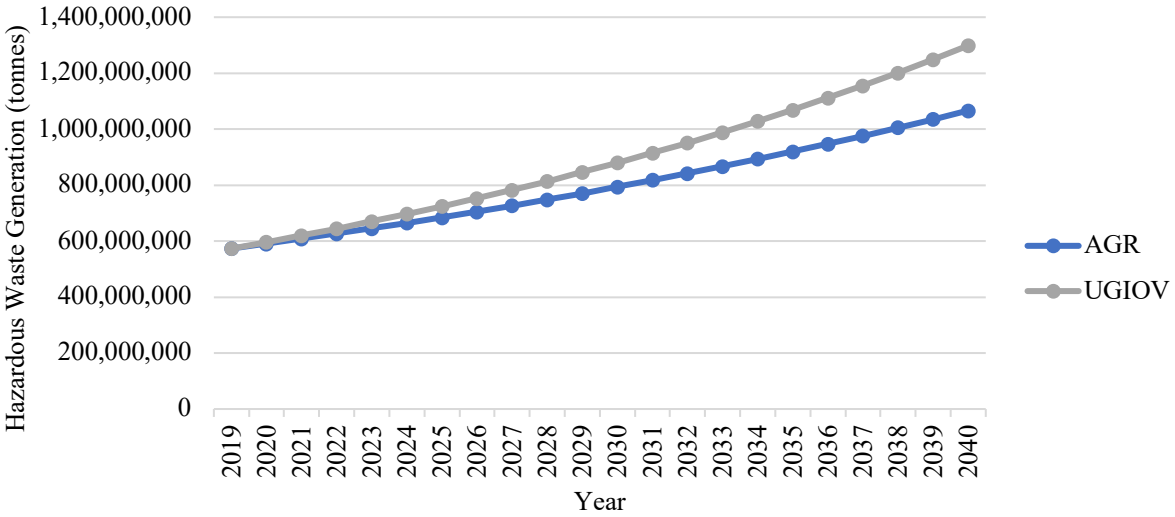

Figure 3 The projection graph of hazardous waste generation from industrial sector

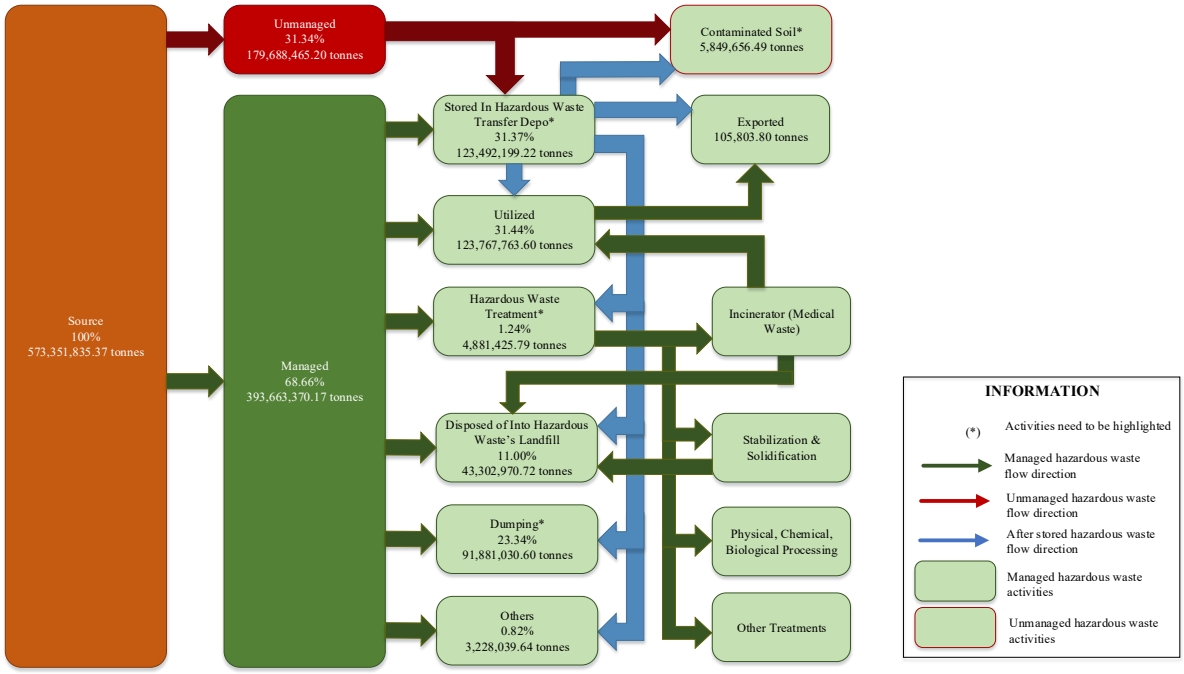

Figure 4 Material flow analysis of hazardous waste of Indonesia's industrial sectors

Figures

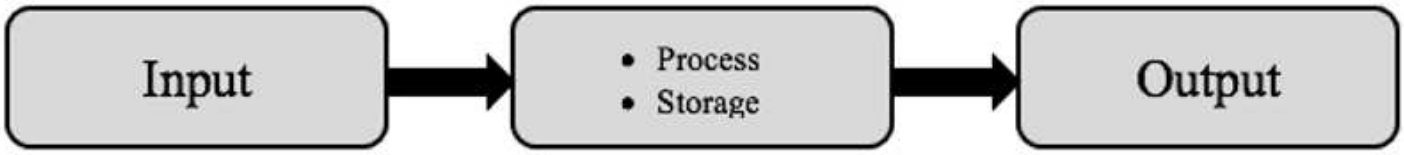

Figure 1

General process of material flow analysis [11]

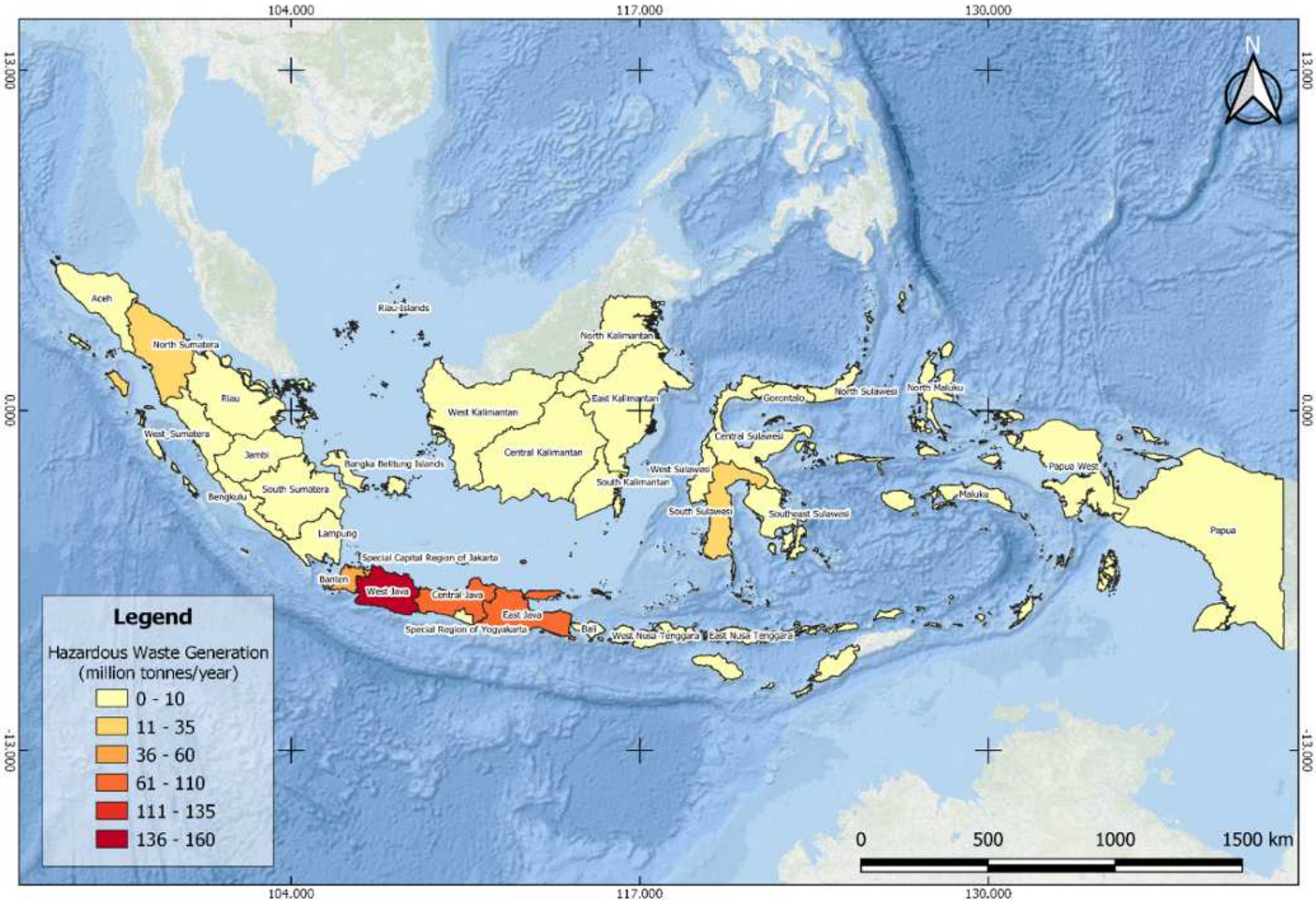

Figure 2

Estimated industrial hazardous waste generation maps in each province in Indonesia. 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.

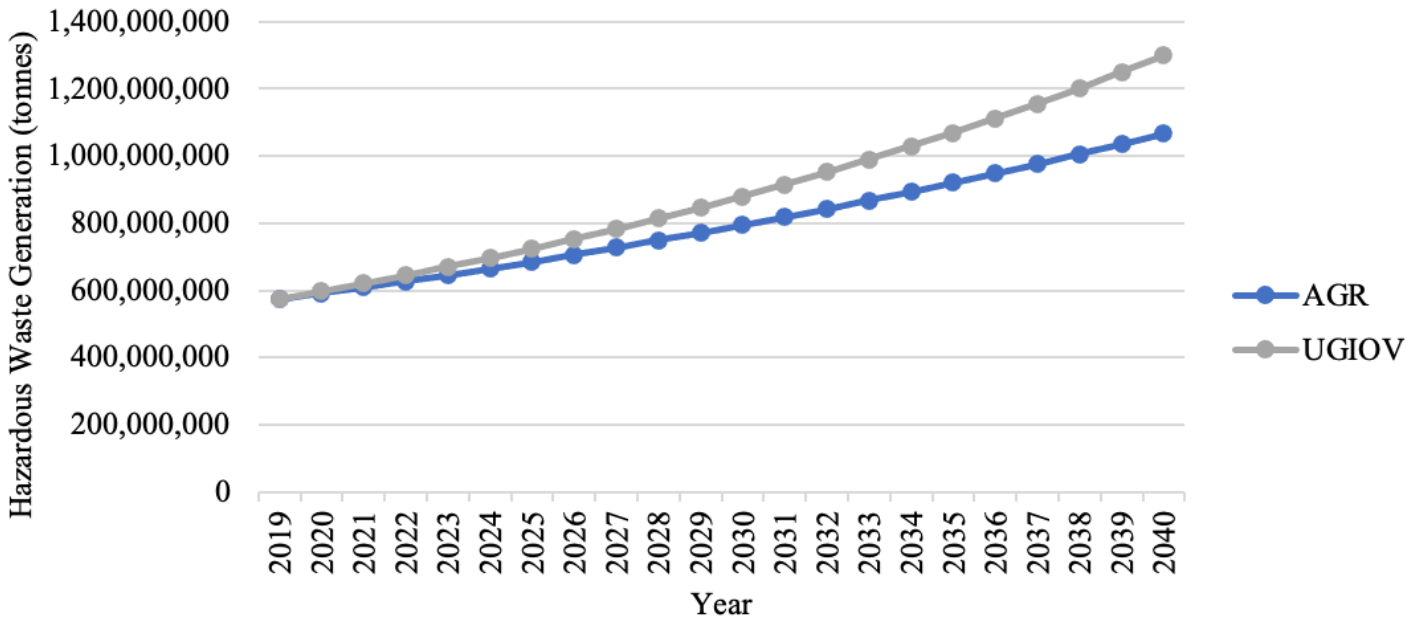

Figure 3

The projection graph of hazardous waste generation from industrial sector

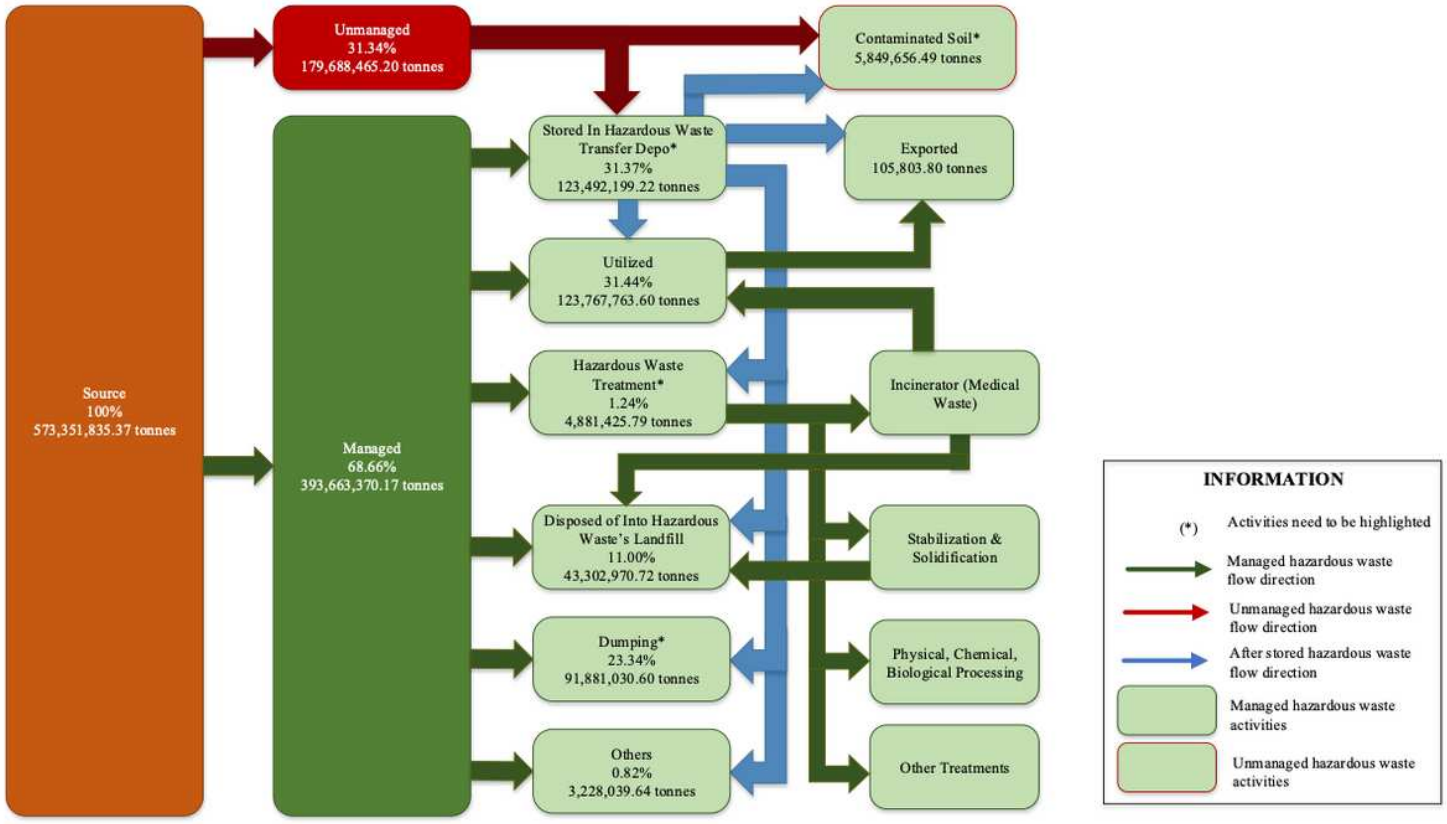

Figure 4

Material flow analysis of hazardous waste of Indonesia's industrial sectors