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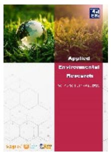

Research Article

Mapping E-Waste Distribution to Form a Circular Supply Chain – An Investigation on E-Waste Towards Circular Economy in Taiwan

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Abstract

While there has been a growing number of studies utilizing material flow analysis (MFA) to examine the flow of e-waste, there remains a lack of studies on industrial e-waste circularity in Taiwan. This study employs MFA to examine the annual generation of e-waste by Taiwanese industries, the domestic flow of this waste, the utilization of secondary materials recovered from e-waste, and the spatial distribution of e-waste and its secondary materials. The results reveal that Taiwan generates approximately 50,000 tons of e-waste per year, with waste code E-0221 and the "manufacture of other electronic parts and components" industry being the primary contributors. About 24.46% of the secondary materials derived from e-waste are utilized by e-waste-generated industries. However, the overall cyclical use rate is only 0.07%. This does not imply that the majority of industrial e-waste is not properly recycled. Rather, it suggests that more secondary materials obtained through downcycling, entering other industries. Besides, some manufacturers process its industrial e-waste in-house, which is not reflected by the cyclical use rate calculated in the study.

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Introduction

E-waste consists of various materials, including plastics, glass, and metals, some of which can be reclaimed and transformed into secondary materials [1]. Printed circuit boards (PCBs) found in e-waste, for example, contain valuable precious metals like gold and silver, which are significant drivers for e-waste recycling [1–3]. In certain cases, the recovered metals are even purer than those extracted from conventional minerals [4–5]. Recycling e-waste has the potential to reduce the global demand for new metal production and subsequently decrease greenhouse gas emissions [6].

In recent years, there has been a growing number of studies utilizing material flow analysis (MFA) to examine the flow of e-waste. Kahhat et al. [7] employed MFA to analyze the computer flow in the United States, including the exportation of used computers. Cordova-Pizarro et al. [8] utilized MFA to evaluate the technical and economic status of cell-phone e-waste in Mexico. Gautam et al. [9] developed a circular supply chain and employed MFA to estimate the stocks and flows of end-of-life solar photovoltaic e-waste. However, there is still a scarcity of source-specific MFA studies that could be valuable in formulating sustainable e-waste management strategies at the industry level [10].

The cyclical use rate is a measure of the proportion of recovered material that is reintegrated into the economy in overall material use [11]. To calculate the cyclical use rate for e-waste, it is crucial to have data on the utilization of secondary materials. De Meester et al. [12] determined the total material recovery in Belgium by aggregating the quantities of material allocated to high-end and low-end applications, which were obtained from various literature sources. In a similar vein, Horta Arduin et al. [13] focused on screen e-waste in France as a case study to enhance the precision of performance indicators used in the EU Waste Electrical and Electronic Equipment Directive. The authors computed the weight collection rate and recovery rate for this specific type of e-waste. The computation of the collection rate considers the loss of element content resulting from missing parts, while the calculation of the recovery rate incorporates limitations imposed by treatment technologies. This means that only the actual attainable element content, capable of achieving the same grade or similar characteristics as the original material, is taken into account.

Taiwan's electronic components manufacturing sector has earned a reputation for its excellence, particularly in the semiconductor industry, where it commanded a substantial market share of nearly 30% in the global semiconductor market in 2021 [14]. This achievement highlights Taiwan's significant contribution to the industry and its technological prowess. However, Taiwan's success in electronic components manufacturing is accompanied by a reliance on imports for raw materials due to limited natural resources within the country. Consequently, the recovery and utilization of secondary materials from industrial e-waste have become paramount for sustaining the industry's growth and resource efficiency.

With this backdrop, the study aims to delve into the dynamics of industrial e-waste generated by industries in Taiwan. It focuses on analyzing the annual volume of different types of industrial e-waste generated by industries in Taiwan, the domestic flow of industrial e-waste, the status of cyclical use of secondary materials recovered from industrial e-waste, and the spatial distribution of industrial e-waste and its secondary materials. The research collects data on the categories and source industries of industrial e-waste, as well as the associated processing methods. Utilizing this data and the domestic interindustry transactions table, the study estimates the secondary materials use for each industry. Finally, the study calculates the cyclical use rate of industrial e-waste by materials and industries.

Materials and methods

The methodology employed in this study is based on the general concept of MFA. According to Bringezu and Moriguchi [15], MFA involves examining the flow of materials throughout the entire process chain, encompassing extraction or harvesting, chemical transformation, manufacturing, consumption, recycling, and disposal.

1) MFA for Industrial e-waste

An MFA was conducted for industrial e-waste in Taiwan, which involved analyzing the generation, disposal, and cyclical use of materials. The study incorporated data from three sources: the "Sustainable Materials Management Database (SMMD)" [16], the "Industrial Waste Report and Management System (IWPMS)" [17], and the domestic interindustry transactions table. The focus was on material flow in 2020, which is the latest available data.

While the data on industrial e-waste generation and disposal were readily available from open data sources, the information regarding secondary materials use was not accessible. In order to address this gap, this study employed an innovative method by combining transaction data from the "waste collection, treatment, and disposal" sector with data on the material utilization of the top three industrial e-waste source industries, as well as international raw material prices, in order to estimate the secondary materials use. This method was based on two key assumptions: (1) industrial e-waste generated by each industry contains materials in proportion to the raw materials used, and (2) secondary materials recovered from industrial e-waste by each industry contain materials in proportion to the raw materials used. The secondary materials use for each industry was then calculated accordingly:

$$R_{ij} = \left(S_i \times \frac{E_i}{W_i} \times 10^6\right) \times \frac{U_{ij}}{\sum_{j=1}^{n} U_{ij} \cdot P_j} \qquad \text{(Eq. 1)}$$

In this equation, R_{ij} represents the amount of secondary material j used by industry i, measured in tons. S_i represents the price at which "waste collection, treatment and disposal" sold to industry i, measured in million NT dollars. E_i represents the amount of industrial e-waste generated by industry i, measured in tons. W_i represents the total amount of industrial waste generated by industry i, measured in tons. U_{ij} represents the amount of raw material j used by industry i, measured in tons. P_j represents the unit price of raw material j, measured in NT dollars per ton.

1.1) Price for which "waste collection, treatment and disposal" sold to industry *i* (S_i)

In order to ensure consistency between the industry classification and the data utilized in this study, the original domestic interindustry transactions table (also known as input-output table), which initially consisted of 164 sectors, underwent a simplification process. The study specifically focused on selecting and combining industries that were directly associated with industrial e-waste generation. As a result, a revised table was created, encompassing three distinct industries: "manufacture of computers, electronic and optical products," "manufacture of other electronic parts and components," and "electricity and gas supply." This refined classification allowed for a more targeted analysis of the industries directly involved in the generation of industrial e-waste.

1.2) Proportion of industrial e-waste in whole industrial waste in industry *i* (E_i / W_i)

The industrial waste data for each industry were acquired from SMMD. The objective of calculating this proportion was to convert the price at which the "waste collection, treatment, and disposal" sector sells to each industry into the price at which secondary materials from industrial e-waste are sold to each industry. This proportion also reflects the level of association between each industry and industrial e-waste, providing insight into their respective relationships.

1.3) Amount of raw material *j* used by industry *i* (U_{ij})

The study collected raw material data from two different sources: metals data from SMMD and non-metals data from the domestic interindustry transactions table consisting of 164 sectors. Based on the assumption that the proportion of materials contained in industrial e-waste and secondary materials is equivalent to that of raw materials, the utilization of raw materials becomes the key factor influencing the results of MFA.

1.4) Unit price of raw material *j* (P_j)

The unit price of each raw material (P_j) was determined by calculating the average prices during Q4 2021, considering recent price movements within a specific range centered around the midpoint. This approach helps ensure a more stable and dependable calculation, considering the inherent fluctuations in international prices. To accurately reflect the local currency, the original US dollar data was converted into NT dollars using appropriate conversion rates.

2) Cyclical use rate of industrial e-waste materials

After obtaining the secondary materials use for each industry, the study calculates the cyclical use rate further. The cyclical use rate (Eq. 2) which can be expressed in terms of materials and industries means the percentage of secondary materials used in the overall industrial production, based on a report published by EU [11].

3) Circular supply chain of industrial e-waste

The distribution of industrial e-waste correlates to that of electronic components industry, while the distribution of secondary materials recovered from industrial e-waste correlates to that of disposal organizations. Thus, the study mapped the industrial e-waste generation of each county, and then pinned the sites of electronic components industry and disposal organizations on the maps. These data are from IWPMS, “approved factory list” and “clearance and disposal organization database”.

Results

1) Generation of industrial e-waste

In Taiwan, industrial e-waste is considered hazardous waste and its flow, including recycling, self-processing, entrusted or co-processed, and overseas processing, must be reported to the local competent authority. The flow of entrusted or co-processed industrial e-waste has two stages: clearance and disposal. During the clearance stage, industrial e-waste must be transported by licensed clearance vehicles that are tracked in real-time to ensure that the industrial e-waste is delivered to disposal organizations. During the disposal stage, industrial e-waste can only be processed by licensed Grade A disposal organizations. As of February 2022, there were a total of 65 licensed Grade A disposal organizations in Taiwan.

1.1) Classification of Industrial e-waste

The industrial e-waste generated in Taiwan can be classified into 13 categories based on the official information of industrial waste defined in the "Waste Disposal Act" (see Table 1). Of all the industrial e-waste generated in 2020, "E-0221 Scrapped metal-containing PCBs and their scrapped powder" accounted for more than half (55.96%), followed by "E-0217 Scrapped electronic parts and components, leftover scrap, and defective goods" (20.1%) and "E-0207 scrapped transformers and capacitors containing grease in which the weight of PCB is lower than 0.0005%" (15.5%). These three categories are generated by different industries, with 75.24% of PCBs containing scrapped metal (E-0221) coming from the manufacture of other electronic parts and components.

1.2) Source industries of industrial e-waste

Table 1 depicts the amount of industrial e-waste generated by industries in 2020, as per the EPA statistics . The data highlights a total of 26 industrial e-waste source industries, with the top two contributing to nearly 70% of the total industrial e-waste generated. Interestingly, the distribution of industrial e-waste categories generated by the leading industries, namely "manufacture of other electronic parts and components" and "clectricity and gas supply," is dissimilar. The former is primarily responsible for generating scrapped electronic parts and components (E-0217) and PCBs containing scrapped metal (E-0221), while the latter is responsible for scrapped transformers and capacitors (E-0207).

$$Cyclical\ use\ rate\ (\%) = \frac{Secondary\ materials\ use\ (tons)}{Raw\ materials\ use\ (tons) + Secondary\ materials\ use\ (tons)} \quad \text{(Eq. 2)}$$

The study conducted a comparison of the average output of factories in the top four industries that generate industrial e-waste (as shown in Table 2). Among these industries, "manufacture of other electronic parts and components" has the highest number of factories, with 2,785, while "electricity and gas supply" has the lowest number, with only 667 factories. As a result, the study estimate that each factory in the "clectricity and gas supply" industry has the highest average output of 16.66 tons. This can be attributed to the fact that utilities typically consume more resources per factory than other industries.

2) MFA for Industrial e-waste

Figure 1 illustrates the source industries, processing methods, and cyclical use of industrial e-waste in Taiwan. The data on source industries and processing methods are obtained from the "sustainable materials management database" [16] and the "industrial waste report and management system" [17], respectively. Meanwhile, the data on cyclical use are based on the estimates made in this study.

2.1) Generation of Industrial e-waste

According to the data from the "sustainable materials management database" [16], a total of 55,180 tons of industrial e-waste were generated in Taiwan in 2020, with 26 source industries (the industries after the 10th are merged into other). The top four industries were "manufacture of other electronic parts and components" (27,511 tons), "electricity and gas supply" (11,114 tons), "manufacture of computers, electronic and optical products" (3,421 tons), and "manufacture of semi-conductors" (2,892 tons), which accounted for 81.44% of the total industrial e-waste generated. This indicates that industrial e-waste sources are concentrated in specific industries.

Table 1 Generation of industrial e-waste by industry in Taiwan, 2020

Industry code	E-0201	E-0202	E-0207	E-0213	E-0214	E-0215	E-0217	E-0218	E-0220	E-0221	E-0222	E-0229	E-0301
	Weight (tons)												
S1	0.1	-	-	0.8	-	-	4,130.9	47.9	-	23,233.8	96.8	0.5	0.2
S2	-	108.5	10,956.9	-	8.1	29.8	-	-	7.1	-	4.1	-	-
S3	-	-	-	977.7	-	16.4	290.9	25.1	7.5	2,033.0	70.7	-	-
S4	-	-	-	0.0	-	-	2,546.8	-	-	326.4	15.0	-	3.4
S5	0.8	431.7	133.8	6.3	0.9	11.4	1,587.1	466.2	0.1	5,285.9	2,306.5	-	12.1

Note: S1 denotes "manufacture of other electronic parts and components", S2 denotes "electricity and gas supply", S3 denotes "manufacture of computers, electronic and optical products", S4 denotes "manufacture of semi-conductors", and S5 denotes "others"; each waste type is denoted by waste code, as shown in Supplementary Material 1.
Source: Sustainable Materials Management Database [16]

Table 2 Average generation of each factory of the top four industrial e-waste-generated industries in Taiwan, 2020

Industry	Output (tons)	Factory	Average generation (tons)
Manufacture of other electronic parts and components	27,510.82	2,785	9.88
Electricity and gas supply	11,114.48	667	16.66
Manufacture of computers, electronic and optical products	3,421.35	2,641	1.30
Manufacture of semi-conductors	2,891.64	446	6.48

Source: Factory Operation Cencus [18]

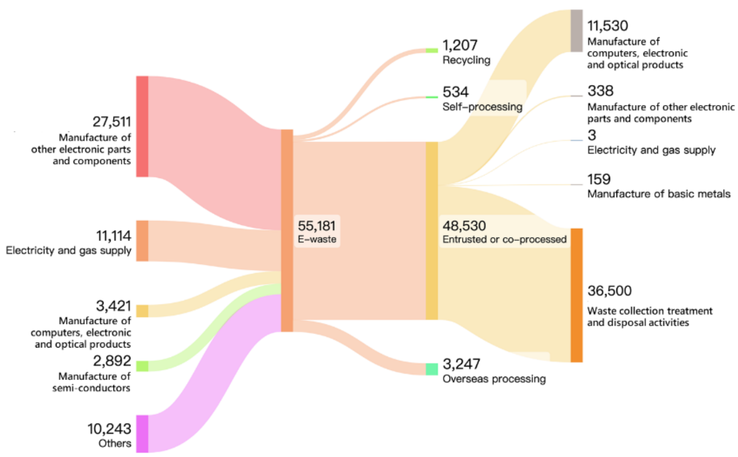


Figure 1 Source industries, processing methods and cyclical use of industrial e-waste in Taiwan, 2020.

2.2) Disposal of industrial e-waste

There are four industrial e-waste processing methods: "recycling," "self-processing," "entrusted or co-processed," and "overseas processing." The main flow is "entrusted or co-processed," with 48,530 tons, accounting for 90.68%. A comparison of the changes in recent years shows that from 2017 to 2020, the output of industrial e-waste remained relatively stable, with approximately 50,000 tons each year. However, the highest output was recorded in 2020, with a total of 53,518 tons (Figure 2). Additionally, the data shows that the amount of "overseas processing" decreased year by year, with a reduction of 2,038 tons from 2017 to 2020, while that of "entrusted or co-processed" increased by 3,908 tons. These changes indicate a shift towards domestic industrial e-waste treatment, reducing the reliance on foreign countries for disposal. This approach enables the generation of recycled materials and their value to remain within Taiwan.

2.3) Cyclical use of industrial e-waste

The study found that the main industrial e-waste processing method in Taiwan is "entrusted or co-processed," and thus focused on the cyclical use of materials in this flow (Figure 1). After treatment, some of the industrial e-waste is recycled into secondary materials that can be used in the industries, while the rest is disposed of. The results showed that 24.46% of industrial e-waste in the "entrusted or co-processed" flow was recycled into secondary materials and used by the original industries that generated the industrial e-waste. Among these industries, "manufacture of computers, electronic and optical products" used the most recycled materials (11,530 tons), while "manufacture of computers, electronic and optical products" and "manufacture of other electronic parts and components" were both sources of industrial e-waste and potential demand industries for secondary materials. However, only the former used a large amount of recycled materials (11,530 tons).

3) Cyclical use rate of industrial e-waste materials

The cyclical use rate measures the proportion of recycled materials used in production, so a higher cyclical use rate indicates greater purity and suitability for use in industries.

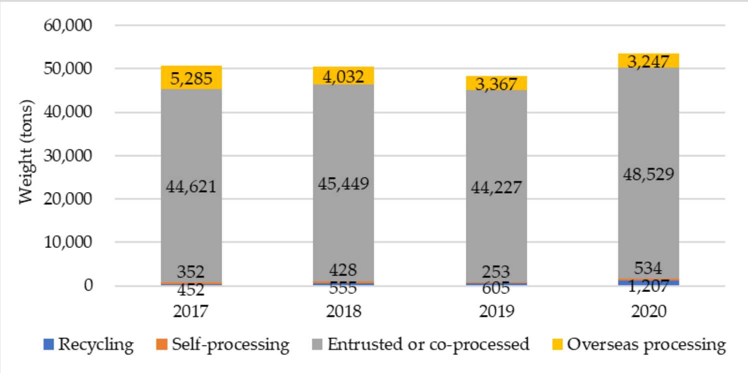


Figure 2 Processing methods of industrial e-waste in Taiwan from 2017 to 2020.
Source: Industrial Waste Report and Management System [17]

Table 3 Cyclical use rate of industrial e-waste materials by material type

Material	Raw material use (tons)	Secondary material use (tons)	Cyclical use rate
Plastics	15,353,750	11,689	0.08%
Glass	542,125	107	0.02%
Iron	114,282	52	0.05%
Copper	61,345	15	0.03%
Aluminum	11,775	5	0.04%
Zinc	956	1	0.08%
Lead	2,631	1	0.02%
Nickel	1,036	0.30	0.03%
Tin	331	0.08	0.02%
Gold, Silver and Platinum	1	0.00	0.04%
Total	16,088,232	11,870	0.07%

Table 4 Cyclical use rate of industrial e-waste materials by industry

Industry	Raw Material Use (tons)	Secondary Material Use (tons)	Cyclical Use Rate
Manufacture of computers, electronic and optical products	13,908,010	11,530	0.08%
Manufacture of other electronic parts and components	2,172,139	338	0.02%
Electricity and gas supply	8,083	3	0.04%
Manufacture of semi-conductors	2,151,836	0	0%

3.1) Cyclical use rate by material

While some industrial e-waste is being processed into secondary materials, the current cyclical use rate is still relatively low at 0.07% overall (Table 3), equivalent to 0.0007 tons of recycled materials used per ton of material used in production. Zinc has the highest cyclical use rate at 0.083% among individual materials. Despite this progress, the industrial e-waste-generated industry continues to heavily rely on raw material imports, as evident from the low cyclical use rate of secondary materials. The varying quality of recycled materials produced by different disposal organizations is also highlighted, with higher technology disposal organizations producing high-purity recycled materials that can be directly supplied to the industrial e-waste-generated industries. Conversely, lower purity recycled materials produced by other organizations may not be able to replace raw materials effectively.

3.2) Cyclical use rate by industry

Table 4 shows the cyclical use rate of industrial e-waste materials by industry. It reveals that the utilization of secondary materials in each industry is low, and even the industry with the highest cyclical use rate, "manufacture of computers, electronic and optical products," only reaches 0.08%. It seems that a significant portion of secondary materials are not being effectively recycled in the industrial e-waste stream.

Moreover, despite "Manufacture of semi-conductors" being the fourth-largest contributor to the industrial e-waste stream, it has a zero transaction value with "waste collection, treatment," according to the Domestic Interindustry Transactions table for 2016. This indicates that the semiconductor industry does not use any secondary materials at all. The study further discusses the potential reason in section 4.3.

4) Circular supply chain of industrial e-waste

Figure 3 illustrates the capacity and actual disposal volume of industrial e-waste in different counties. It is observed that most counties possess sufficient capacity to recycle industrial e-waste produced in their respective areas. However, some counties with insufficient capacity transport their industrial e-waste to disposal organizations in neighboring counties. Taoyuan and Kaohsiung have the highest capacity and actual disposal volume of industrial e-waste, indicating that a significant amount of secondary materials recovered from industrial e-waste is concentrated in these two counties.

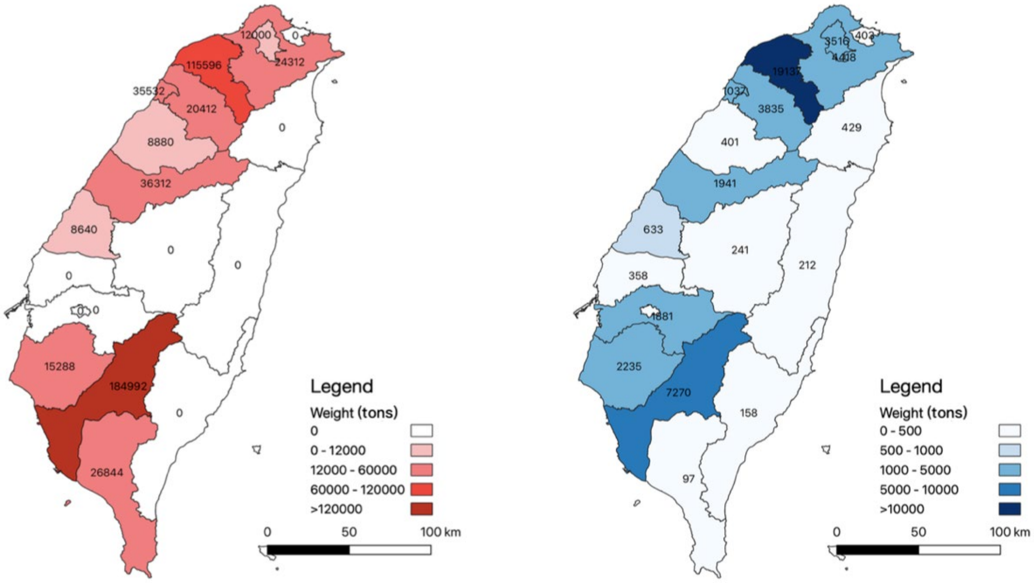
The study compared the distribution of industrial e-waste-generated industries with the distribution of industrial e-waste disposal organizations in Taoyuan and Kaohsiung (Figure 4). Taoyuan has 1,368 factories of industrial e-waste-generated industries and 15 industrial e-waste disposal organizations, while Kaohsiung has 419 factories of industrial e-waste-generated industries and 28 industrial e-waste disposal organizations.

From the volume of waste processed and the spatial distribution of waste treatment facilities, it can be observed that Taiwan has established a stable foundation for a circular supply chain. Sufficient processing capacity indicates that existing facilities are adequate. The proximity of waste generation sources to treatment locations ensures reasonable transportation costs. With this robust foundation in place, it is foreseeable that Taiwan will continue to develop its circular supply chain in the future.

Discussion

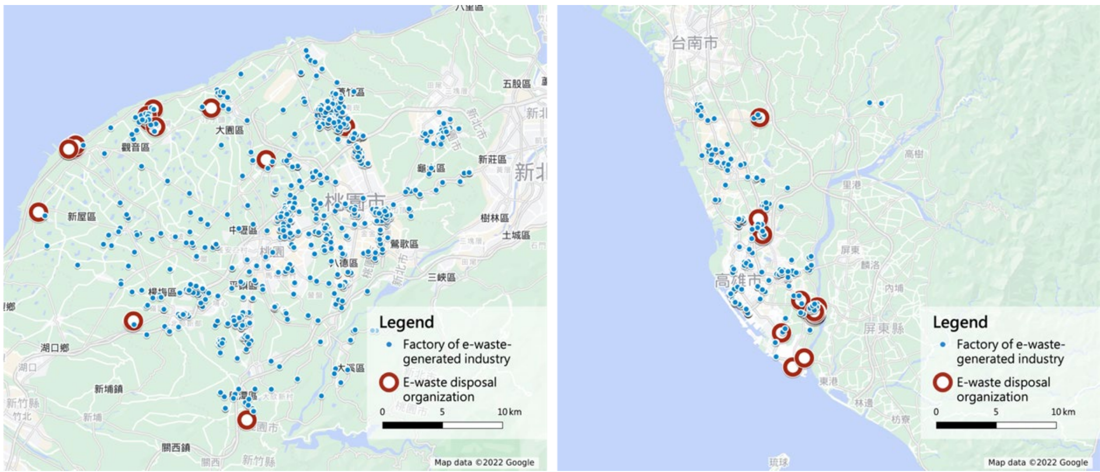
1) Generation of Industrial e-waste

E-waste, which is experiencing rapid growth globally, has shown a different trend in Taiwan's industrial sector. Approximately 50,000 tons of industrial e-waste generated per year from 2017 to 2020. This stability suggests that the generation of industrial e-waste in Taiwan has potentially peaked. Additionally, the export of industrial e-waste from Taiwan has been consistently decreasing, with only 6% being exported in 2020, which is lower than the average for Asia at 10% [19]. By reducing the export of industrial e-waste, Taiwan is taking responsibility for the proper handling and disposal of its own electronic waste, which aligns with sustainable waste management practices and environmental protection goals.



(a) **(b)**

Figure 3 Industrial e-waste disposal volume comparison in each county of Taiwan, 2020. (a) Approved maximum amount of the industrial e-waste disposal volume and (b) amount of the actual industrial e-waste disposal volume.



(a) **(b)**

Figure 4 The distribution of industrial e-waste-generated industries and industrial e-waste disposal organizations in (a) Taoyuan and (b) Kaohsiung.

2) MFA for Industrial e-waste

The MFA results indicate that the "manufacture of other electronic parts and components" industry generates the most industrial e-waste, which is not surprising given that it produces essential electronic components such as PCBs. Since most of the precious metals are concentrated within PCBs, the majority of the industrial e-waste value lies within this industry [2, 20]. However, only 24.46% of industrial e-waste is directly recycled and sold for use in industrial e-waste-generated industries, highlighting the need for more effort to build a circular supply chain.

The findings from the material flow analysis (MFA) reveal that the "manufacture of other electronic parts and components" industry is the primary contributor to the generation of industrial e-waste. This industry's involvement in producing crucial electronic components, particularly PCBs, explains its significant industrial e-waste generation [2, 17]. PCBs contain a substantial amount of valuable precious metals, making this industry a key player in terms of the overall value of industrial e-waste.

Despite the potential value and recyclability of industrial e-waste, the study highlights that only 24.46% of this waste is directly recycled and reintegrated into industries that utilize industrial e-waste as a resource. This indicates a considerable gap in establishing a fully functional circular supply chain for industrial e-waste. Efforts should be directed towards improving the recycling and recovery processes, as well as promoting the adoption of sustainable practices throughout the industrial e-waste management lifecycle. Enhancing collaboration among stakeholders, such as manufacturers, recyclers, and policymakers, can play a crucial role in fostering a more efficient and sustainable circular economy for industrial e-waste.

3) Cyclical use rate of industrial e-waste materials

The analysis of the cyclical use rate for industrial e-waste materials reveals a concerning trend, as the utilization of secondary materials for each element and industry remains below 1%. It seems to be a significant gap in achieving a circular economy for industrial e-waste materials, where many of these valuable resources are not being effectively reintegrated into the production of new electronic products.

On the other hand, however, explaining solely based on the cyclical use rate may overlook other factors. For example, the semiconductor industry in Taiwan has the capability to recycle electronic-grade materials. Since much of this recycling occurs within the facilities themselves [21], transfer information regarding these materials between semiconductor manufacturers and waste treatment facilities is not publicly available. Furthermore, the proportion of high-value recycled materials is inherently lower in the overall electronic waste, as in the case of PCBs where the main component is plastic. Therefore, the majority of components are recycled through downgrading processes.

4) Circular supply chain of industrial e-waste

In order to establish a robust and efficient circular supply chain for industrial e-waste, the availability of high-quality secondary materials becomes paramount. However, the challenge lies in the fact that disposal organizations employ diverse technologies and processes for the recovery of industrial e-waste, leading to significant variations in the quality of secondary materials obtained [22]. This variability introduces uncertainty in the supply of secondary materials, making it difficult for manufacturers to rely on consistent and standardized inputs.

To address this issue, it is crucial to implement measures that ensure the grading and certification of secondary materials based on their purity and quality. By implementing standardized grading systems, secondary materials can be categorized according to their composition and characteristics, providing manufacturers with a clear understanding of the suitability and potential applications of these materials. This grading system can help establish a transparent market for secondary materials, enabling manufacturers to identify reliable sources that meet their specific requirements.

Furthermore, mapping the distribution of secondary materials can facilitate the identification of potential sources and establish efficient material supply chains. By creating a comprehensive database or platform that documents the availability and quality of secondary materials, manufacturers can easily locate suitable sources and evaluate the feasibility of substituting primary raw materials with recovered materials. This information can assist manufacturers in making informed decisions regarding material sourcing, optimizing resource utilization, and reducing their dependence on virgin resources.

Conclusions

Taiwan's heavy reliance on imported raw materials, coupled with its thriving electronic industry, underscores the importance of maximizing the use of secondary materials. This study evaluates the current utilization of secondary materials in the electronic industry to offer insights into resource efficiency, reducing reliance on imports, and promoting sustainability.

MFA indicates that 90.68% of industrial e-waste is handled by disposal organizations, with a declining trend in exports suggesting reduced reliance on foreign disposal. Approximately a quarter of industrial e-waste is transformed into secondary materials, mainly utilized by the "manufacture of computers, electronic and optical products" industry.

The cyclical use rate of secondary materials in industrial e-waste is only 0.07%, with zinc being the most widely used secondary material by industrial e-waste-generated industries, and the "manufacture of computers, electronic and optical products" using the most secondary materials. However, the cyclical use rate for both perspectives is lower than 1%. This does not imply that the majority of industrial e-waste is not properly recycled. Rather, it suggests that the proportion of high-value secondary materials is relatively low, with more secondary materials obtained through downcycling, and most of them enter other industries. Besides, some manufacturers process its industrial e-waste in-house, especially in semiconductor industry, which results in the inability to observe the transactional relationship between industrial e-waste sources and waste disposal facilities from public data.

The limitation of this study is the inability to directly obtain data on the use of secondary materials, requiring the use of estimation methods. The estimation method employed in this study can serve as a reference for future studies. Future research could delve deeper into the utilization of secondary materials in the semiconductor industry, as well as the flow of the low-value portion of industrial e-waste.

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