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Research Article

A comprehensive analysis of e-waste recycling and metal recovery solutions in Turkey

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ABSTRACT

E-waste, despite its significant potential for metal recovery, continues to have low recycling rates globally, including in Turkey. With the growing demand for metals driven by the large-scale production of electrical and electronic devices, the efficient management and recovery of e-waste have become increasingly critical. Compared to traditional ores, e-waste contains substantially higher concentrations of valuable metals, making it a promising secondary resource.This study investigates the generation of electrical and electronic waste in Turkey and evaluates current recycling practices. Alternative scenarios for metal recovery were developed and assessed based on process efficiency, environmental impact, operational feasibility, and cost. The findings reveal that a hybrid system is the most effective approach. Specifically, pyrometallurgical methods are best suited for low-value metal-containing e-waste, while bio- or hydrometallurgical processes are recommended for high-value metal-containing e-waste after separation. This approach offers a comprehensive and sustainable solution for improving e-waste management and metal recovery efficiency.

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INTRODUCTION

In recent years, the rapid advancement of electronic device technologies has significantly contributed to the proliferation of electronic waste. As the reliance on electronic devices for communication and daily activities has increased, the quantity and usage duration of these devices has also escalated. While the integration of sophisticated electronic infrastructures into everyday products provides numerous advantages, it simultaneously leads to higher levels of consumption [1] and the resulting demand for high-capacity production [2]. Additionally, the swift pace of technological innovation often promotes the frequent replacement of existing devices, even when they have not reached the end of their functional lifespan. This trend results in the premature disposal of electronic products, thereby contributing to a concerning rise in electronic waste generation.

The management and recovery of this growing volume of electronic waste are crucial for two primary reasons:

•Electronic waste contains a variety of hazardous heavy metals (such as Co, Hg, Ba, Cd, etc.). Therefore, it can be classified as hazardous waste, posing significant risks to the environment if not managed properly.

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•A substantial portion of the metals found in electronic waste is valuable and has limited availability. Consequently, the recovery of these metals during the management of electronic waste is crucial from both an economic and resource management perspective.

Electronic waste poses significant threats to both the environment and human health if not disposed of properly. The leachate generated from electronic waste can lead to the spread of hazardous components such as polychlorinated biphenyls (PCBs), mercury, polybrominated biphenyls (PBBs), brominated flame retardants (BFRs), polybrominated diphenyl ethers (PBDEs), and lead [3]. Research conducted at electronic waste recycling facilities in China has detected known carcinogenic polycyclic aromatic hydrocarbons (PAHs) and heavy metals in ambient air samples. It has been reported that the primary cause of this contamination is the open burning of plastics and metals contained in electronic waste during the recovery process [4]. Another study conducted at the same facility indicated that toxic heavy metals pose severe risks, leading to neurological and mental health issues, kidney disorders, and even fatalities. This situation highlights the dangers associated with persistent toxic substances (PTS), which has resulted in the prohibition of the production and use of 12 persistent organic pollutants (POPs) under the decisions of the Stockholm Convention [5].

According to the data from The Ministry of Environment, Urbanization and Climate Change of Turkey 2021 bulletin, the production of waste electrical and electronic equipment (WEEE) amounted to 52,129 tons in 2021. Additionally, based on the 2022 Turkish Statistical Institute (TUIK) data, waste management accounted for the highest expenditure category in environmental protection spending, representing 60.9% of the total. Reducing the high costs associated with disposal and recovery or generating economic benefits from these wastes in specific areas, is crucial not only for environmental protection but also for human health. Electronic waste contains significant quantities of valuable metals such as gold, silver, and platinum. When these metals are extracted from mining sites, they yield much lower quantities compared to the equivalent amounts found in electronic waste. On average, electronic waste contains between 10 to 10,000 grams of gold per ton, while gold mines yield only 0.5 to 13.5 grams of gold per ton of ore [6]. Another study found that printed circuit boards (PCBs) contain, on average, 1,000 grams of silver, 250 grams of gold, and 10 grams of palladium per ton of electronic waste, whereas these quantities in mining ores are each below 10 grams per ton [7].

The increase in electronic waste and its management is not only an environmental issue that needs to be addressed in Turkey but also worldwide. Therefore, this study evaluates the current situation in Turkey and develops alternative solutions for the recovery of electronic waste by creating various scenarios.

MATERIAL AND METHODS

In this study, the production quantities, recovery rates, and existing technologies related to electronic waste examined for both globally and in Turkey. By conducting a comparative analysis of the current situation, various scenarios and alternatives for the recovery of electronic waste are evaluated. The current e-waste production and recovery facilities were analyzed using data from the Turkish Statistical Institute. The production of total waste, e-waste, and the percentage of e-waste in total waste were compared with other countries.

Due to the insufficient recovery of e-waste, alternative metal recovery scenarios were created based on the separation of impurities and the recovery processes. The scenarios were compared with each other in terms of process efficiency, energy consumption, environmental impacts, investment costs, process duration, application areas, byproduct production, and ease of operation. Application areas, process efficiency, recovery rates, and system costs were compared based on the separation of waste and the elimination of impurities. Additionally, the pyrometallurgical pyrolysis process, (bio) leaching processes, and combinations of these processes were compared.

It is known that pyrometallurgical processes are much simpler than other methods; however, their recovery rates and metal separation efficiency are not as high as those of (bio) leaching processes. On the other hand, pyrometallurgical methods are more costly than biological or chemical processes because (bio)leaching processes are cost-effective and predictable. During the pyrolysis process, hazardous gases and substances are also released. Therefore, Dutta et al. [8], stated that (bio)leaching processes are more environmentally friendly, which was also considered when comparing the processes.

Types of Electronic Waste and Their Contents

Electronic waste comprises a wide variety of components. The devices that constitute this waste include information and communication technologies such as mobile phones, computers, music players, and motherboards, as well as larger appliances used in residential applications, such as electric heaters, microwave ovens, and fans. The extensive diversity of electronic devices increases both the variety and quantity of materials contained within them. Generally, electronic waste consists of various materials, including plastics, metals, ceramics, wood, glass, and rubber (Table 1).

Table 1. Component distribution in electronic waste

Type of Electronic Waste	Components	Content (%)	References
Monitor	Metal	43.7	[9]
	Plastic	23.3	
	Glass	15	
	Printed Circuit Boards (PCBs)	17.3	
Mixed Electronic Waste	Metal	61	[10]
	Plastic	20	
	Rubber	1	
	Glass	5	
	Ceramic	2	
	Wood	3	
	Printed Circuit Boards (PCBs)	3	
	Other	5	
Mixed Electronic Waste	Iron and Steel	47	[11]
	Copper	7	
	Plastic	21	
	Glass	5	
	Valuable Metals	20	
Mixed Electronic Waste	Metal	60.2	[12]
	Plastic	15.3	
	Metal-Plastic Mixture	5	
	Glass	12	
	Cables	2	
	Contaminants	3	
	Printed Circuit Boards (PCBs)	1.7	
	Other	1.4	

Recovery and Disposal Methods for Electronic Waste

The recovery of electronic waste necessitates the initial classification of the waste, followed by its collection and the selection of suitable recovery methods. Accordingly, electronic waste has been divided into seven categories, as depicted in Figure 1.

In the recovery of electronic waste, it is important to first separate components containing plastic, glass, rubber, and wood to increase recovery efficiency and prevent the formation of harmful by-products. For this purpose, the collected electronic waste should be sorted and processed according to their respective categories. However, before the separation process, potential hazardous components should be examined, and necessary precautions should be taken. Various methods are used for separating plastic and metal components. The recovery processes of electronic waste can generally be approached in three main ways:

- Physical Recovery Processes
- Chemical Recovery Processes
- Biochemical Recovery Processes

Physical recovery processes are typically used for separating metallic and non-metallic materials. Additionally, processes such as pyrolysis, where waste is subjected to thermal treatment, are also involved. In chemical recovery processes, after a partial physical separation or pre-treatment, metals are dissolved in a solution in the presence of an oxidizer (lixiviant). The recovery process is then completed through chemical purification. Biochemical recovery processes, like chemical processes, occur in the presence of a lixiviant, but in addition to the necessary ions for oxidation, microorganisms also play a role in the process. Furthermore, the reuse of lixiviants can contribute to the process by reducing wastewater production in some cases. However, biochemical methods may not always have the same efficiency as chemical methods.

When considering the recovery scenarios for electronic waste, the evaluation takes into account existing facilities, waste characteristics, and recovery methods, while also considering criteria such as cost, feasibility, and recovery efficiency.

RESULTS AND DISCUSSIONS

Generation of Electronic Waste in Turkey

According to the reports published by the United Nations Environment Programme and the International Solid Waste Association [14], Table 2 presents global waste production quantities and per capita waste generation. Additionally, "The Global E-waste Monitor 2020" [15] provides further insights into electronic waste metrics on a global scale.

Not only in Turkey, but globally, e-waste recycling rates are very low compared to other types of waste. For instance, China had a 16% recovery rate, the USA 15%, India 1%, Japan 22%, Germany 52%, the United Kingdom 57%, and France 56% in 2024 [16]. According to the report by the International Telecommunication Union (ITU) [17], the statistics for Special Waste and Medical Waste indicate that the quantity of Waste Electrical and Electronic Equipment (WEEE) reported in 2015 was 32,029 tons, which increased to 67,153 tons by 2020. This reflects nearly a twofold increase in electronic waste within a five-year period. However, when this amount is compared to the total waste generated in 2020, it is found that electronic waste constitutes only 0.2% of the total municipal waste. In comparison to the global average, this figure suggests that the production of electronic waste in Turkey is ten times lower. From this data, two conclusions can be drawn:

i)There is an insufficient number of electronic waste recovery and/or disposal facilities, and

ii)Electronic waste is not being properly separated.

Both of these conclusions indicate that adequate operational infrastructure for the recovery or disposal of electronic waste has not been established. Nevertheless, another report from the Republic of Turkey, Ministery of Environment, Urbanisation and Climate Change (2022) [18] shows that electrical and electronic waste amounts increases till 2020 and started to decrease after 2021 and 2022 22.4% and 21.5% from previous years.

According to TUIK data [19], when considering the retail sales volumes in Turkey for the years between 2020 and 2023 (Fig 2), it is evident that the category of computers, books, and communication devices exhibited the highest growth for the average of last 4 years. This trend can also be interpreted as an indicator of the increasing consumption rate of electronic devices. The rising consumption rate of electronic devices results in older devices rapidly becoming waste in the face of advancing technology.

Figure 1. Classifications of electronic waste [13]

Scenarios for Electronic Waste Recovery

Commonly preferred methods for electronic waste recovery can be categorized into three main approaches: pyrometallurgical methods, hydrometallurgical methods, and bio-hydrometallurgical methods. Each of these methods has distinct advantages and disadvantages. While pyrometallurgical methods typically yield lower metal recovery efficiency compared to hydro- and bio-hydrometallurgical methods, they are generally easier to manage and have lower operational costs [8]. However, in pyrometallurgical methods, pyrolysis is often favoured as a process, although it poses environmental challenges due to the release of toxic gases, necessitating an advanced gas treatment system to mitigate harmful emissions [20].

Before applying these recovery methods, certain preprocessing steps are essential. These steps involve removing protective materials in electronic waste, such as plastic, glass, wood, and rubber. Additionally, to enhance process efficiency, impurities are separated, and the waste undergoes crushing and grinding to increase contact surface area, which subsequently boosts recovery efficiency. Within this framework, three distinct scenarios for electronic waste recovery have been developed, and these scenarios are compared based on various evaluation criteria. The scenarios created are presented in Figure. 3.

When recovering metals from electronic waste, economically valuable metals are particularly of interest. In pyrometallurgical methods, materials such as ceramics and glass within the waste contribute to an increase in slag volume, resulting in a corresponding increase in metal loss. Moreover, this method allows only partial metal separation, leading to limited improvements. For valuable metal recovery, hydrometallurgical and bio-hydrometallurgical methods present more appealing alternatives, as they enable more effective metal separation and recovery. Compared to pyrometallurgical processes, hydrometallurgical methods offer greater precision, predictability, and ease of control, making them a more viable choice in certain applications [21].

Table 2. Total and per capita quantities of municipal and electronic waste in Turkey and Worldwide (WEEE: Waste Electronic and Electrical Equipment, N/A: Not Available)

Regions*	Total Waste Amount (Million Tons)	Waste per Capita (kg/person/day)	Regions***	WEEE (Million Tons)	WEEE per individual (kg/inh/year)	Collected and Properly Recycled (%)
North America	320	2.25	Global	53.6	7.3	N/A
South America	150	0.8	Europe	12	16.2	42.5
Northern Europe	50	1.25	Africa	2.9	2.5	0.9
Western Europe	100	1.6	Asia	24.9	5.9	11.7
Eastern Europe	110	0.9	Americas	13.1	13.3	9.4
Southern Europe	70	1.2	Oceania	0.7	16.1	8.8
Central and South Asia	280	0.5	Turkey	0.847	10.2	6
Western Asia and North Africa	150	0.7				
Australia and New Zealand	20	1.5				
Turkey **	30	1.03				

*The values are approximate, derived from the United Nations Environment Programme and the International Solid Waste Association report graph (2024).
** The most recent data available from the Turkish Statistical Institute (TUIK) report (2022) has been processed.
*** According to The Global E-waste Monitor 2020 report, the data for 2019

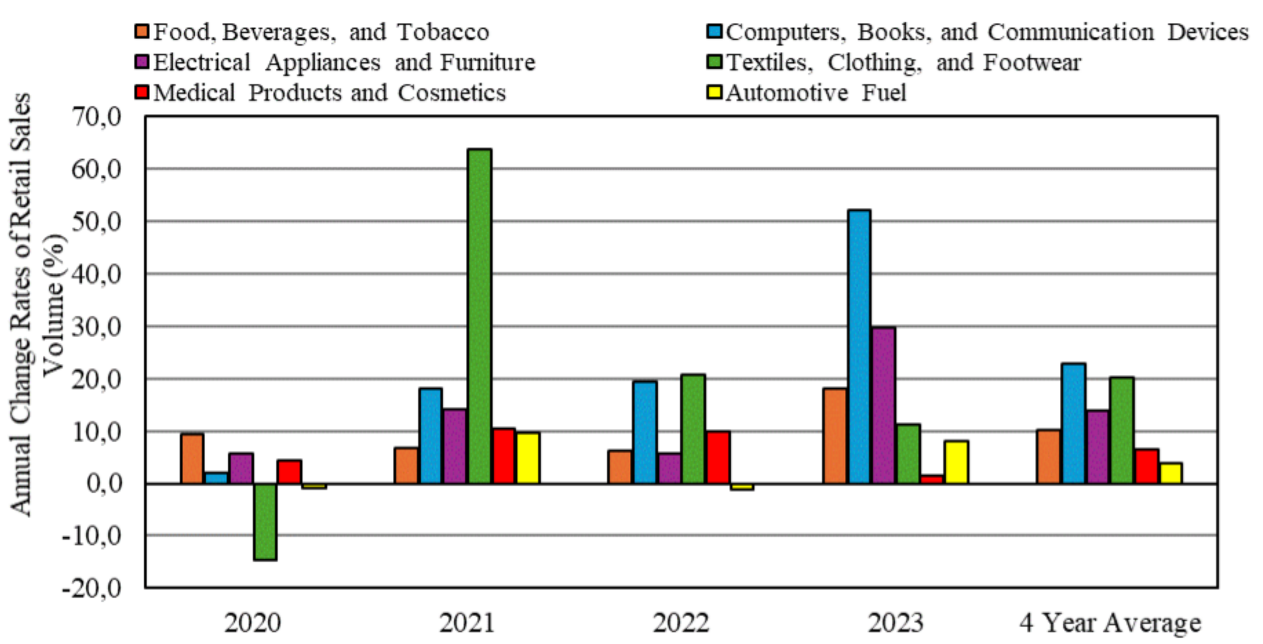

Figure 2. Retail sales volume change rates for years

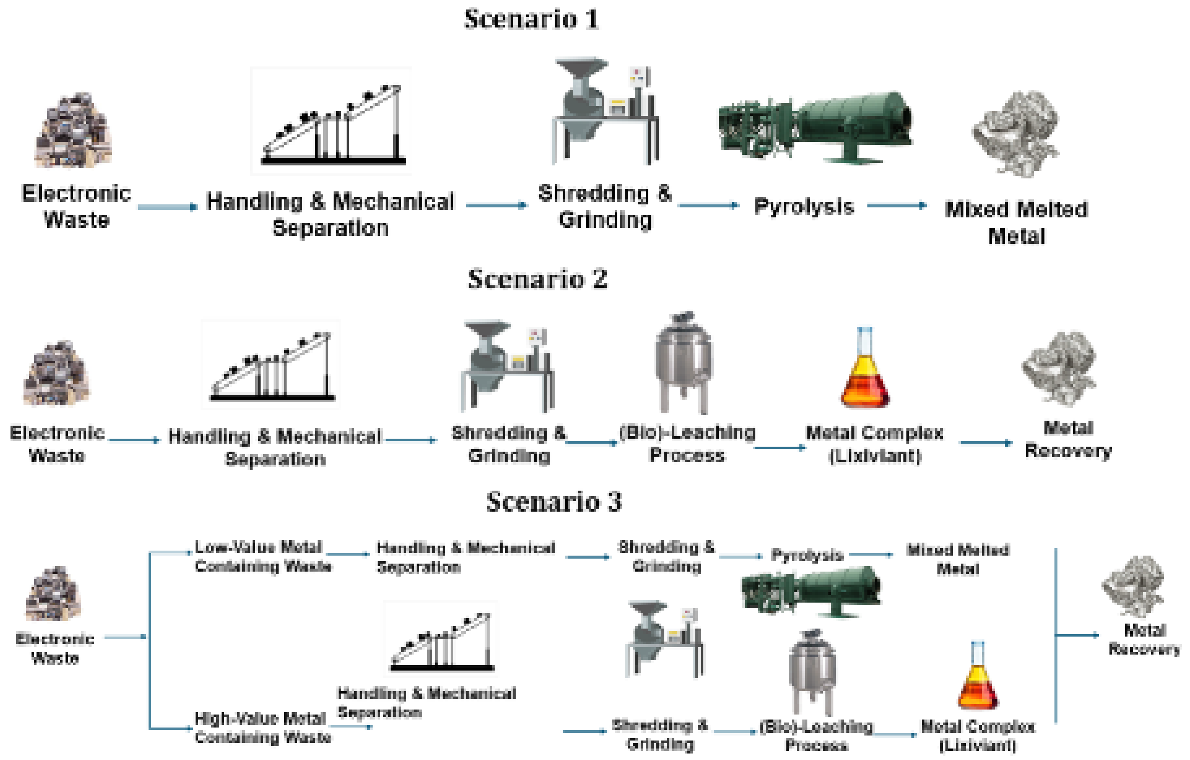

Figure 3. Electronic waste recovery scenarios

The first and most crucial step in all recovery scenarios is the proper separation and collection of electronic waste at the source. If waste is not sorted correctly, it will significantly reduce the efficiency and effectiveness of the facilities established for recovery operations. Unlike other types of waste, electronic waste contains a much higher concentration of toxic and hazardous materials, posing significant environmental risks. Therefore, even the act of collecting these wastes separately from other waste and preventing them from being sent to general storage facilities holds considerable environmental importance.

Additionally, in all processes and scenarios, it is essential to remove the collected waste from its packaging or protective materials (such as plastic, glass, wood, and rubber). Before the primary metal recovery process, various technologies and methods are available to separate metallic and non-metallic waste. These separation processes are categorized as disassembly or dismantling, desoldering or solder removal, size reduction or shredding, and fractionation or sorting [13]. These methods vary depending on the type of collected electronic waste.

In the first recovery scenario, after removing non-metallic parts, shredding and grinding equipment is used to increase the contact surface area of the waste, making the bulky waste easier to process by reducing it to manageable sizes. Subsequently, pyrolysis is applied, which can vary depending on the types of waste targeted for recovery. For example, in Liu et al.'s study [22], over 90% of copper, tin, and lead were recovered from printed circuit boards using pyrolysis at 700 °C for 60 minutes. Similarly, Jadhao et al [23], examined the extraction of valuable metals from discarded printed circuit boards using a combination of ultrasonication (a sustainable method) and low-temperature pyrolysis (at 400 °C). The results of their study showed an almost complete recovery of precious metals such as gold (Au), silver (Ag), palladium (Pd), and platinum (Pt) from the metallic fraction of the e-waste. The authors concluded that the integration of pyrolysis and ultrasonication offers a highly effective approach for managing electronic waste, recovering both base and valuable metals, and generating value-added gases that can be utilized as an energy source.

For this reason, conducting feasibility studies before establishing facilities is essential. Not only will the types of metals recovered vary, but the by-products generated will also differ in composition. Proper treatment and disposal of these by-products require specialized treatment methods.

Although there are potential risks, it may be feasible to integrate the process into existing pyrolysis or incineration facilities. However, it is essential to establish an appropriate waste gas treatment system specifically designed for the pyrolysis of electronic waste. In this scenario, it would be possible to bring the process into operation more quickly by incorporating it into an existing system. The primary risk in this system is the formation of by-products. While this approach has lower operational costs compared [24] to other recovery methods, its metal recovery efficiency has been found to be lower than that of other processes [25].

In the secondary scenario, hydrometallurgical or bio-hydrometallurgical methods can be used for e-waste recovery. The process performance depends on many factors such as lixiviant concentration (acidic or caustic media). The most significant advantage of hydrometallurgical systems is cost effective, efficient and predictable. However, the use of hazardous substances such as acidic, caustic, and inflammable solvents remains the primary challenge in hydrometallurgical methods [24]. This issue has led to the acceptance of bio-hydrometallurgy as a green technology for e-waste management. Microorganisms can oxidize both organic and inorganic substances under extreme conditions, making them suitable for metal recovery. Bio-hydrometallurgy systems reduce or enable the recovery of lixiviants in the system for use in metal oxidation.

The final scenario presents a hybrid solution for e-waste recovery based on the metals present in the e-waste. E-waste consists of a variety of rare and different metals. Therefore, before selecting the appropriate recovery process, it would be more appropriate to separate e-waste with high and low economic value and direct them to the suitable recovery processes. Sending low-value waste to incineration or pyrolysis facilities, while recovering waste containing valuable metals through bio-hydrometallurgical methods for more precise treatment, is a better option.

The melting points of metals cover a broad range, varying from approximately 200°C to 1500–2000°C. (Figure 4). This requires the process to be suitable for operation at different temperatures, leading to a more complex operational process. Therefore, categorizing electronic waste and evaluating it in different facilities will also facilitate ease of operation.

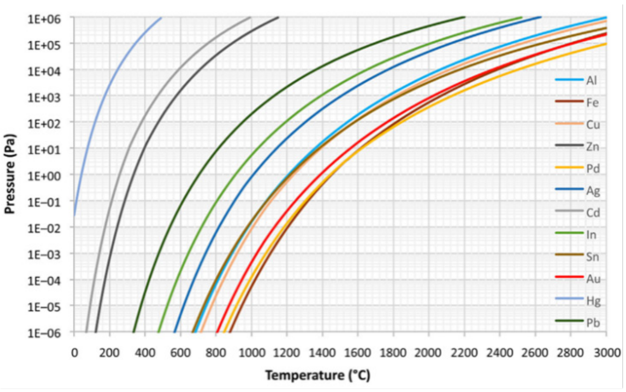

Figure 4. Relationship between the saturation pressure and temperature for different metals [20]

This approach also supports the rationale for separating e-waste based on its material composition.

Based on the given criteria, all three scenarios were ranked among themselves.Within the given criteria, the most successful scenario was scored 3, while the weakest scenario was scored 1, and the evaluation was conducted based on the total score.

All scenarios were compared based on process efficiency, environmental impacts, cost, and applicability. The recovery of all e-waste through pyrometallurgical processes received the lowest score due to its poor recovery performance, significant environmental impacts caused by the production of toxic gases, and the high costs associated with controlling these emissions. However, the pyrometallurgical process demonstrated a higher ease of operation and process duration scores compared to hydrometallurgical or bio-hydrometallurgical methods. In contrast, a hybrid operation combining both pyro- and (bio-)hydrometallurgical systems offers better control over waste management due to the separation of e-waste into categories. Low-value metals can be recovered through pyrolysis, but despite the operational challenges and long process durations, achieving higher efficiency in the separation of valuable metals would be a better solution. Separating waste materials before feeding them into the process also provides better control over the system. This is because, in the pyrolysis process, the presence of molten mixed metals makes separation more difficult. Similarly, in (bio)-leaching processes, steps such as precipitation, adsorption, or ion exchange become more complex as the diversity of metals increases, potentially requiring different operating conditions or more intricate process management.

Table 3. Performance assessment for different electronic waste recovery scenarios

Scenarios	Process Efficiency	Energy Consumption	Environmental Impacts	Cost	Process Duration	Application Areas	Recovery Rate	Waste/Wastewater Management	Ease of Operation	Total
Scenario 1	1	1	1	1	3	1	1	3	2	14
Scenario 2	3	3	3	2	1	2	3	1	1	19
Scenario 3	2	2	2	3	2	3	2	2	3	21

CONCLUSIONS

E-waste recycling rates are low not only in Turkey but globally, and a comprehensive solution for their management has not yet been achieved. However, the demand for metals continues to rise due to the large-scale production of electrical and electronic devices. Compared to the metal content in ores per ton, e-waste contains significantly higher amounts of metals, presenting a considerable potential for recovery. This study examines the production of electrical and electronic waste in Turkey and the current recycling rates. It explores alternative scenarios to identify the most suitable solution for metal recovery. The scenarios were compared based on process efficiency, environmental impact, operational feasibility, and cost. The findings suggest that a hybrid system would be the optimal alternative. Specifically, pyrometallurgical methods for e-waste with low-value metal content, and bio- or hydrometallurgical processes for e-waste with high-value metal content, were determined to be the most effective management approach.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

1. G. Bekaroo, R. Sungkur, P. Ramsamy, A. Okolo, and W. Moedeen, "Enhancing awareness on green consumption of electronic devices: The application of Augmented Reality," Sustainable Energy Technologies and Assessments, vol. 30, pp. 279–291, 2018, doi: https://doi.org/10.1016/j.seta.2018.10.016.
2. B. H. Robinson, "E-waste: An assessment of global production and environmental impacts," Science of The Total Environment, vol. 408, no. 2, pp. 183–191, 2009, doi: https://doi.org/10.1016/j.scitotenv.2009.09.044.
3. Ankit, Saha, L., Kumar, V., Tiwari, J., Sweta, Rawat, S., Singh, J., & Bauddh, K. "Electronic waste and their leachates impact on human health and environment: Global ecological threat and management," Environmental Technology & Innovation, vol. 24, no. 102049, 2021, doi: https://doi.org/https://doi.org/10.1016/j.eti.2021.102049
4. W. J. Deng, P. K. K. Louie, W. K. Liu, X. H. Bi, J. M. Fu, and M. H. Wong, "Atmospheric levels and cytotoxicity of PAHs and heavy metals in TSP and PM2.5 at an electronic waste recycling site in southeast China," Atmos Environ, vol. 40, no. 36, pp. 6945–6955, 2006, doi: https://doi.org/10.1016/j.atmosenv.2006.06.032.
5. A. Leung, Z. W. Cai, and M. H. Wong, "Environmental contamination from electronic waste recycling at Guiyu, southeast China," J Mater Cycles Waste Manag, vol. 8, no. 1, pp. 21–33, 2006, doi: 10.1007/s10163-005-0141-6.
6. S. Manigandan, K. S. Rajmohan, and S. Varjani, "Chapter 16 - Current trends in gold recovery from electronic wastes," in Current Developments in Biotechnology and Bioengineering, S. Varjani, A. Pandey, E. Gnansounou, S. K. Khanal, and S. Raveendran, Eds., Elsevier, 2020, pp. 307–325. doi: https://doi.org/10.1016/B978-0-444-64321-6.00016-1.
7. R. Cayumil, R. Khanna, R. Rajarao, P. S. Mukherjee, and V. Sahajwalla, "Concentration of precious metals during their recovery from electronic waste," Waste Management, vol. 57, pp. 121–130, 2016, doi: https://doi.org/10.1016/j.wasman.2015.12.004.
8. Dutta, D., Rautela, R., Gujjala, L. K. S., Kundu, D., Sharma, P., Tembhare, M., & Kumar, S., "A review on recovery processes of metals from E-waste: A green perspective. Science of The Total Environment," vol. 859, no. 160391, 2023, doi: https://doi.org/https://doi.org/10.1016/j.scitotenv.2022.160391
9. Ankit, Saha, L., Kumar, V., Tiwari, J., Sweta, Rawat, S., Singh, J., & Bauddh, K. "Electronic waste and their leachates impact on human health and environment: Global ecological threat and management," Environmental Technology & Innovation, vol. 24, no. 102049, 2021, doi: https://doi.org/https://doi.org/10.1016/j.eti.2021.102049
10. J. Van Yken, N. J. Boxall, K. Y. Cheng, A. N. Nikoloski, N. R. Moheimani, and A. H. Kaksonen, "E-waste recycling and resource recovery: A review on technologies, barriers and enablers with a focus on oceania," Aug. 01, 2021, MDPI AG. doi: 10.3390/met11081313.
11. K. Liu, Q. Tan, J. Yu, and M. Wang, "A global perspective on e-waste recycling," Mar. 01, 2023, Elsevier B.V. doi: 10.1016/j.cec.2023.100028.
12. S. M. Abdelbasir, C. T. El-Sheltawy, and D. M. Abdo, "Green Processes for Electronic Waste Recycling: A Review," Jun. 01, 2018, Springer Science and Business Media Deutschland GmbH. doi: 10.1007/s40831-018-0175-3.
13. R. Nithya, C. Sivasankari, and A. Thirunavukkarasu, "Electronic waste generation, regulation and metal recovery: a review," Apr. 01, 2021, Springer Science and Business Media Deutschland GmbH. doi: 10.1007/s10311-020-01111-9.
14. United Nations Environment Programme and International Solid Waste Association, "Global Waste Management Outlook 2024 - Beyond an age of waste: Turning Rubbish into a Resource," 2024. doi: 10.59117/20.500.11822/44939.
15. V. Forti, C. P. Balde, R. Kuehr, and G. Bel, "The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential," 2020.
16. S. Suin, "REVISITING E-WASTE MANAGEMENT: GLOBAL SCENARIO, STRATEGIES, AND SUSTAINABLE DEVELOPMENT," Environmental Research and Technology, Dec. 2024, doi: 10.35208/ert.1468546.
17. International Telecommunication Union (ITU), "The Global E-waste Monitor 2024," https://www.itu.int/en/ITU-D/Environment/Pages/Publications/The-Global-E-waste-Monitor-2024.aspx#:~:text=The%20Global%20E-waste%20Monitor%202024%20was%20launched%2020%20March%202024.
18. M. of E. U. and C. C. Republic of Turkey, "ATIK İSTATİSTİKLERİ BÜLTENİ (2022)," Dec. 2022.
19. Turkish Statistical Institute, "TÜİK Statistical Data Portal." Accessed: Jan. 07, 2025. [Online]. Available: https://data.tuik.gov.tr/

20. B. Ebin and M. I. Isik, “Pyrometallurgical Processes for the Recovery of Metals from WEEE,” in WEEE Recycling: Research, Development, and Policies, Elsevier, 2016, pp. 107–137. doi: 10.1016/B978-0-12-803363-0.00005-5.
21. J. Cui and L. Zhang, “Metallurgical recovery of metals from electronic waste: A review,” Oct. 30, 2008. doi: 10.1016/j.jhazmat.2008.02.001.
22. Y. Liu, J. Zhang, X. Yang, W. Yang, Y. Chen, and C. Wang, “Efficient recovery of valuable metals from waste printed circuit boards by microwave pyrolysis,” Chin J Chem Eng, vol. 40, pp. 262–268, 2021, doi: https://doi.org/10.1016/j.cjche.2020.11.008.
23. P. R. Jadhao, E. Ahmad, K. K. Pant, and K. D. P. Nigam, “Environmentally friendly approach for the recovery of metallic fraction from waste printed circuit boards using pyrolysis and ultrasonication,” Waste Management, vol. 118, pp. 150–160, 2020, doi: https://doi.org/10.1016/j.wasman.2020.08.028.
24. L. A. Diaz and T. E. Lister, “Economic evaluation of an electrochemical process for the recovery of metals from electronic waste,” Waste Management, vol. 74, pp. 384–392, Apr. 2018, doi: 10.1016/j.wasman.2017.11.050.