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RESEARCH ARTICLE

Environmental and Technological Aspects of Electronic Waste Management

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ABSTRACT

This article examines e-waste flows and the associated environmental risks at the accumulation, co-storage, and recycling stages. According to the Global E-Waste Monitor 2024, e-waste generation is expected to grow by 3–4% annually: 53.6 million tons in 2022, with a forecast of over 74 million tons by 2030. The article highlights the combination of valuable (copper, aluminum, and precious metals) and hazardous components (lead, mercury, cadmium, and brominated flame retardants). Particular attention is paid to the consequences of co-storage with municipal solid waste, including the formation of toxic leachate and the migration of pollutants into water, soil, and the atmosphere. The article also examines the technological challenges of recycling and extended producer responsibility models in various countries. It concludes that it is necessary to develop separate collection infrastructure, strengthen regulations, and implement consumer education programs.

INTRODUCTION

1. The growth rate of the amount of electronic waste

Electronic waste is quickly becoming one of the most pressing issues in global waste management. With the advancement of technology and consumer culture, the accumulation of discarded electronics has increased dramatically, creating significant environmental, health, and economic challenges. This article examines the growth rate of electronic waste, its composition, and the consequences of improper storage and recycling. Particular attention is given to the challenges posed by co-storage with other waste types, the difficulties associated with recycling electronic waste, and the state of the global legal framework aimed at addressing this issue. Through a holistic approach, this study highlights the urgent need for sustainable practices and strengthened regulation to minimize the negative impact of electronic waste on the environment.

According to the Global E-Waste Monitor 2024, the total volume of e-waste globally reached 53.6 million tons in 2022. Experts predict that by 2030, if current trends continue, this figure will exceed 74 million tons [1]. This growth raises serious environmental and socioeconomic concerns: firstly, due to the toxic components (lead, mercury, cadmium, brominated flame retardants) in the waste, and secondly, due to the loss of valuable secondary resources (copper, aluminum, precious metals).

Figure 1 shows data on e-waste production in the world's largest countries. According to statistics, in 2022, Russia took the leading position in Europe, with a waste volume reaching 1.9 million tons. This is higher than the figures for Germany (1.8 million tons) and the United Kingdom (1.7 million tons). These figures are explained by the country's large territory, high population, and growing consumer electronics consumption. However, absolute figures alone do not provide a complete picture: they do not reflect differences in consumption levels and population sizes across countries.

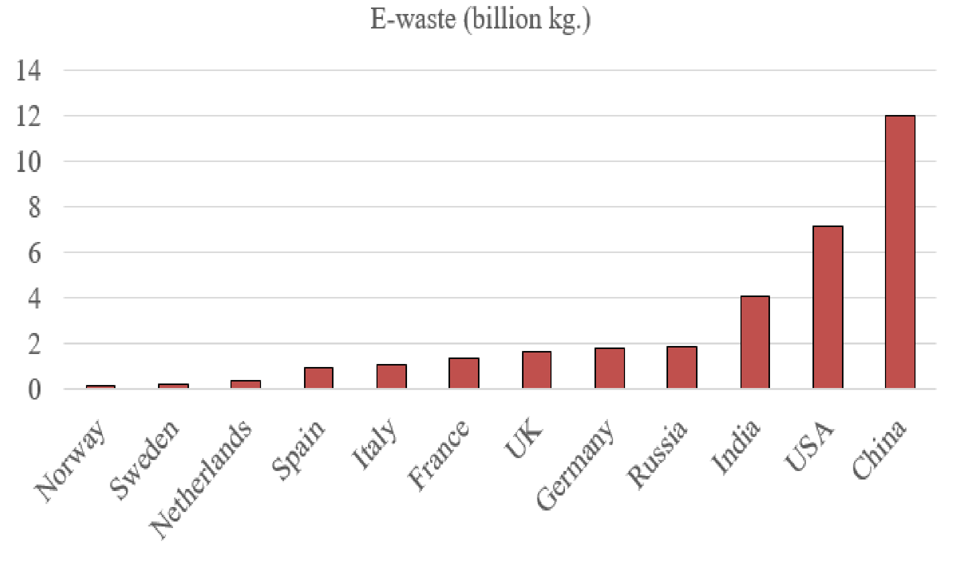

Figure 1. GEWM-2024 statistics on the volume of generated electronic waste in 2022 in major world powers

Russian statistics correlate with global trends. According to Rosprirodnadzor (Form 2-TP), from 2019 to 2023, the volume of e-waste generated in the Russian Federation increased from 89.8 thousand tons to 133.7 thousand tons, an increase of approximately 49%. However, some fluctuations were observed in this trend. For example, a peak of 154 thousand tons was recorded in 2021, which can be explained by the widespread upgrading of equipment, accelerated generational changes in electronics, and increased consumer demand. [2] In 2022, the volume decreased to 113.4 thousand tons, likely due to economic fluctuations and a decline in equipment imports. However, a new increase is observed by 2023. This trajectory indicates that e-waste generation in Russia is steadily increasing, despite short-term declines.

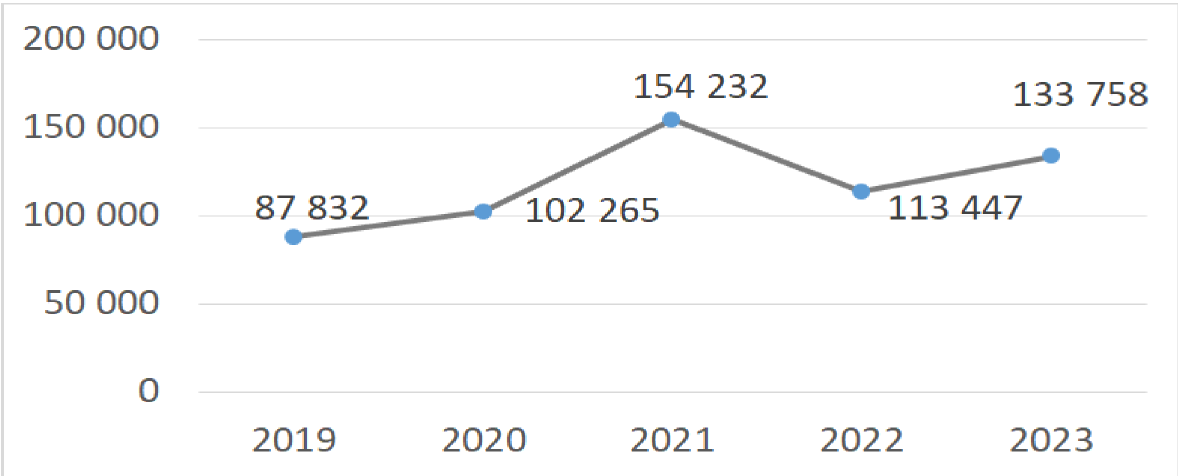

Figure 2. Dynamics of electronic waste generation in the Russian federation in 2019–2023

It's important to note that, despite the high absolute figures, e-waste generation per capita in Russia remains relatively low. In 2022, this figure was only 7.6 kg per capita, significantly lower than in most European countries and the United States, where the specific figures reach 20–30 kg. Thus, Russia is characterized by a contradiction: large total waste volumes with a low per capita accumulation rate.

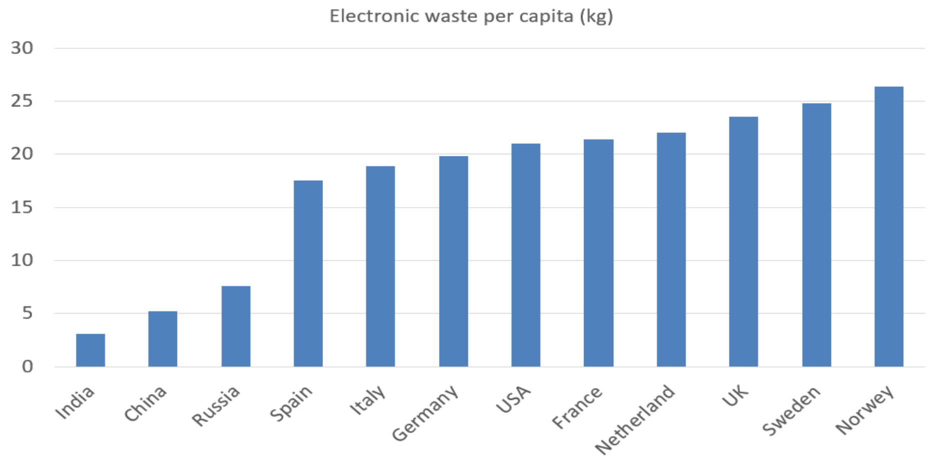

Figure 3. Volume of e-waste per capita in 2022 by country

When analyzing growth rates, it is important to consider the limitations of the statistical base. The Russian waste accounting system, based on Rosprirodnadzor's Form 2-TP, has a number of problems:

- Data is overly aggregated, with different types of waste often lumped into a single category;
- Identical materials may fall into different classification groups, distorting the overall picture;
- There is no complete traceability of waste flows from generation to processing;
- Some data is populated with assumptions due to the lack of uniform measurement standards.

This leads to actual volumes of e-waste differing significantly from official data. For example, computer and server cases containing aluminum, plastic, and copper are sometimes mistakenly counted as aluminum scrap or scrap metal, making it difficult for them to reach specialized recycling facilities.

Similar problems are common in international statistics. Some e-waste from developed countries is exported to countries in Africa and Asia, where recycling is either nonexistent or occurs informally without proper oversight. However, in the statistics of exporting countries, such waste is counted as "recycled," which formally inflates recycling rates. This creates a paradoxical situation: official reports record high recycling rates, but in reality, a significant portion of the waste ends up in uncontrolled landfills, posing a threat to health and ecosystems.

From 2019 to 2023, the volume of e-waste in the Russian Federation increased by 49%, driven by the increased use of electronics and household appliances. Although Russia became the leader in Europe in terms of the total volume of e-waste (1.9 million tons) in 2022, the amount generated per capita is only 7.6 kg, which is significantly lower than the average for most European countries.

2. Composition of electronic waste

Electronic waste (E-waste) is a group of waste that includes electrical and electronic devices (EEDs), including their component parts, that are no longer suitable for their intended purpose and require disposal, recycling, or safe storage. E-waste can be divided into several categories:

1. Large household appliances: Among the heaviest sources of environmental pollution are devices such as air conditioners and refrigerators, which contain freon, for example.

2. Small household appliances: This category includes small appliances such as vacuum cleaners and electric kettles.

3. Information and communications technology (ICT) equipment: This group includes computers, laptops, mobile phones, and routers.

4. Consumer electronics: Televisions, cameras, and audio devices.

5. Lighting equipment: Fluorescent and LED lamps.

6. Specialized equipment: Medical instruments and scientific equipment.

E-waste consists of a complex combination of various materials. They contain valuable elements, including precious metals (gold, silver, palladium) and base metals (copper, aluminum), along with hazardous substances such as mercury, lead, and cadmium [3]. To better understand the complexity of this process, Figure 4 shows a flow chart illustrating just some of the components of e-waste:

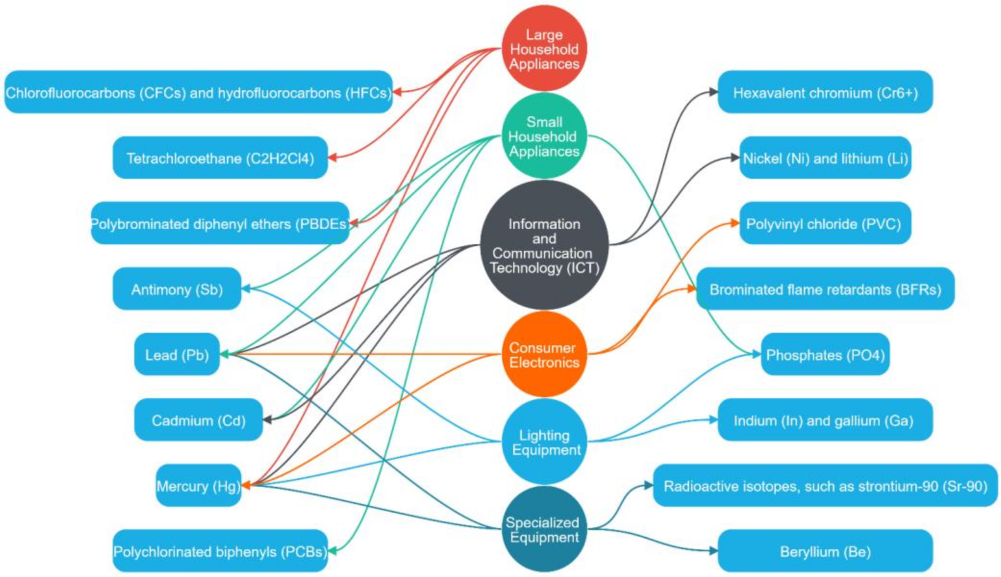

Figure 4. Categories of electronic waste and associated hazardous substances

It should be emphasized that the specific composition of e-waste complicates its recycling. A single device may contain precious and non-ferrous metals, petrochemical-based plastics, glass, ceramics, and toxic elements. This combination makes it impossible to apply a single, universal recycling method. For example, mechanical crushing and subsequent fraction separation are sufficient to extract copper and aluminum, whereas the removal of mercury or lead requires specialized chemical or thermal treatment. As a result, e-waste recycling requires a multi-stage process, increasing costs and requiring a developed infrastructure.

Furthermore, so-called "hidden" components must not be forgotten. Many plastic parts contain brominated flame retardants, which prevent devices from igniting but, if improperly disposed of, release persistent organic pollutants. Housings and cable insulation often contain chlorine-containing additives, which can form dioxins when burned. All of this reinforces the environmental significance of the proper management of e-waste and explains the need for accurate compositional analysis at the early stages of recycling. While valuable materials offer opportunities for recycling and resource recovery, hazardous components pose a significant risk if not properly managed.

3. Economic potential of E-Waste recycling

The problem of electronic waste management is traditionally considered in an environmental context, but its economic dimension is no less important. Under current practices, a significant portion of this waste is disposed of in landfills or ends up as municipal solid waste. As a result, society not only bears environmental costs but also loses colossal amounts of resources that could otherwise be recycled.

A distinctive feature of electronic waste is its high concentration of base and precious metals. For example, printed circuit boards in personal computers and mobile phones contain an average gold content of 200–300 grams per ton, silver – approximately 1 kg, and significant amounts of palladium and platinum. By comparison, the gold content of most gold-bearing ores does not exceed 5–10 grams per ton. Therefore, failure to recycle printed circuit boards and their disposal entails direct economic losses comparable to the underutilization of mineral deposits.

Data on cable waste is no less revealing. Cable cores are primarily made of copper or aluminum, and one ton of cable can contain up to 600–700 kg of copper. Copper is a scarce metal on the global market, and its price has been steadily rising in recent years. However, when cable waste is buried, a significant portion of these resources is irretrievably lost. Moreover, the decomposition of insulating materials in landfills releases dioxins and other toxic compounds, increasing the cost of subsequent remediation efforts.

Large household appliances (refrigerators, air conditioners, washing machines) also contain significant amounts of recycled materials. According to the European Commission, recycling one ton of such appliances can recover up to 700–800 kg of ferrous metals and approximately 50–60 kg of non-ferrous metals. When buried, this mass becomes a lost raw material, and the release of freons and similar refrigerants exacerbates climate and ozone problems.

Particular attention should be paid to battery waste, particularly lithium-ion batteries. They contain strategically important elements such as cobalt, nickel, lithium, and manganese. One ton of batteries contains up to 3-5 kg of cobalt and 1-2 kg of lithium, with the market price of cobalt reaching $33,000-35,000 per ton in 2024. The lack of systematic recycling leads not only to economic losses but also to significant environmental threats: electrolytes and heavy metals migrate into the soil and groundwater, creating long-term sources of pollution. [4]

Cathode Ray Tubes (CRTs) form a separate category; despite their gradual phase-out, they are still found in waste. They contain up to 20% lead oxide, as well as barium and strontium. The economic viability of recycling these components may be lower than that of printed circuit boards or batteries, but their disposal leads to long-term contamination of soils and groundwater. Consequently, in this case, we are talking about a combination of economic and environmental damage, which is subsequently compensated for by budgetary funds.

According to the Global E-Waste Monitor 2024, annual global losses from the disposal of e-waste and the loss of the resources it contains exceed $55 billion. For Russia, where hundreds of thousands of tons of this type of waste are generated annually, this means not only lost economic opportunities but also increased dependence on imported strategic materials. Thus, an analysis of the economic potential of e-waste recycling suggests that landfilling is unsustainable from both an environmental and economic perspective. Developing an effective system for the separate collection and recycling of e-waste could significantly reduce the environmental impact while simultaneously providing the economy with additional sources of strategically important materials.

4. Legal regulation

The problem of e-waste has prompted many countries to develop new legislative frameworks. Some of these systems have proven effective, demonstrating how regulation can transform a potential environmental crisis into a sustainable solution.

In the European Union, e-waste disposal is managed within a robust and well-coordinated legislative framework. These systems are based on the principle of extended producer responsibility (EPR). Manufacturers are responsible for the entire lifecycle of their products, including their proper disposal and recycling. Along with EPR, the availability of modern recycling facilities and extensive public awareness campaigns create a cycle of responsibility and efficiency. People are educated about the importance of recycling electronics, and the infrastructure for the effective recycling of these items is created.

Some Asian countries exemplify how timely legislative action can transform the e-waste situation. In 1998, Japan passed the Household Appliances Recycling Act, shifting responsibility for the disposal of electrical appliances to manufacturers. This legislation created a direct incentive for companies to develop devices that are easier and cheaper to recycle, spurring innovation in product design and sustainability. Over time, this law has significantly reduced the environmental footprint of discarded electrical appliances through the creation of efficient and organized recycling systems.

South Korea also took proactive measures to manage e-waste, beginning with the 1992 Resource Conservation and Recycling Promotion Act. This law introduced a deposit-refund system, requiring manufacturers to pay a fee based on the volume of goods they supplied. Refunds were tied to the quality of waste collection and recycling, which encouraged proper waste management. By 2003, the system was further enhanced by the introduction of a mechanism requiring manufacturers to be responsible for e-waste disposal. Companies were given the option to choose from several approaches: establishing their own recycling facilities, collaborating with existing facilities, or joining specialized producer responsibility organizations. By 2006, more than 40% of e-waste in South Korea was collected and recycled under these systems, with manufacturers playing a leading role [5].

Russia has a practice similar to the system used in South Korea. The primary instrument regulating waste management, including electronic waste, is the Extended Producer Responsibility (EPR) mechanism. Under this system, manufacturers are required to ensure the collection, recycling, and disposal of waste generated after the use of their products. Companies can fulfill these obligations independently, establish or partner with recycling facilities, or join specialized organizations, similar to the system in place in South Korea [6].

However, despite the existence of this mechanism, a number of unresolved issues remain in Russia. One of the main challenges is the lack of clear classification of waste received for primary processing [7]. This leads to the mixing of e-waste with other types of waste, significantly complicating its recycling and increasing environmental risks. There is also a need to improve the regulatory framework to specifically regulate the handling of e-waste.

5. The problem of mixed storage and landfills

One of the most important problems in managing e-waste is its improper storage and disposal. When e-waste is mixed with Municipal Solid Waste (MSW), the risks increase exponentially [8].

Landfill leachate is a highly contaminated liquid that forms when rainwater percolates through layers of waste in a landfill. This water interacts with decomposing materials and absorbs toxic chemicals, resulting in a complex mixture of dissolved organic matter, heavy metals, and other contaminants. Since e-waste contains significant amounts of hazardous substances such as lead, cadmium, and brominated flame retardants, their presence increases the toxicity of landfill leachate.

Landfill leachate containing hazardous components of e-waste can disrupt the integrity of ecosystems if not properly disposed of. Environmental impacts include:

• Groundwater Pollution: Heavy metals such as mercury and lead can leach into groundwater, making it unsafe for human consumption and agricultural use.

• Soil Pollution: The presence of high concentrations of metals such as zinc and chromium disrupts soil microbial activity and reduces soil fertility.

• Bioaccumulation in Food Chains: Toxic elements from leachate can enter local waterways, affecting aquatic life and subsequently bioaccumulating in larger organisms, including humans.

• Air Pollution: Volatile substances from leachate, such as mercury vapor and organic compounds, can evaporate into the atmosphere, degrading air quality. These toxins can accumulate in the atmosphere and travel long distances, which is especially dangerous for cities located near landfills. Managing leachate-related risks requires reliable landfill engineering, such as the installation of impermeable liners and leachate collection systems. However, improper sorting of e-waste prior to disposal remains a serious problem. To mitigate these issues, targeted policies promoting separate e-waste collection and dedicated recycling infrastructure are needed.

6. Recycling and disposal of electronic waste

Recycling and recycling electronic waste is a complex task due to the complex structure of electronic devices and the inconsistency of recycling capacities across the globe. Another challenge is that the waste consists of various types of materials, including toxic substances and valuable precious metals. Safe recycling requires expensive equipment and appropriate technologies, including chemical stabilization and high-temperature incineration. Let's consider some recycling methods.

Small electronics (laptops, phones, etc.) consist of tightly integrated components, such as housings, printed circuit boards, batteries, and screen components. Effective recovery and recycling require mechanical recycling, and in this case, manual disassembly. Mechanical recycling also allows for the separation of less complex electronic waste, such as large household appliances and system units, into different chemical compositions.

One of the key challenges of this method is the difficulty of working with devices containing toxic substances, which creates certain risks for the environment and the health of workers. Although automation of processes could reduce such risks, the complexity and heterogeneity of the designs of modern electronic devices makes this impossible at the present time, and most operations must be performed manually.

Various thermal methods, such as incineration, drying, flame oxidation, gasification, and pyrolysis, are widely used in the recycling and disposal of electronic components. Incineration is considered one of the most common and simplest recycling methods. The primary goal of thermal waste treatment is to extract its energy potential with minimal negative impact on the environment, so incineration of certain types of waste is often the most feasible and effective method. The advantage is that waste volume can be significantly reduced, and the resulting ash can be used, for example, as a concrete filler. A disadvantage is the emission of harmful gases into the atmosphere. To minimize the impact, purification filters are used, but their use significantly increases the cost of the recycling process [9].

In practice, pyrolysis is often used. This process is a combination of thermal and chemical treatment. It relies on the complete decomposition of the starting materials in specialized furnaces without exposure to oxygen, and a catalyst is used to accelerate the reaction. It is effective when organic contaminants on the material need to be removed. There are three types of pyrolysis: low-temperature, medium-temperature, and high-temperature. It is used in the recycling of medical waste, PET plastic, and rubber products.

There is a lack of global standardization of recycling approaches, making it difficult to develop unified, effective systems. Specialized facilities equipped to process hazardous or composite materials remain rare, especially in developing countries where such centers are desperately needed. Meanwhile, e-waste recycling is carried out informally, using methods such as acid baths and open burning, exposing workers and the environment to harmful and hazardous substances, creating serious environmental and social risks.

7. Innovative technologies and prospects for handling electronic waste

The current situation with electronic waste shows that traditional recycling methods are no longer adequate to cope with the growing volume and complexity of its composition. Mechanical sorting, incineration, and hydrometallurgical processes have long been considered the basis for recycling, but today they are increasingly giving way to new approaches. These approaches are aimed not simply at reducing the volume of waste, but at maximizing the extraction of valuable resources and reducing the negative impact on the environment.

Particular attention is being paid to automated sorting systems. While just ten years ago, fraction separation was primarily performed manually, today, lines operating using machine vision and artificial intelligence algorithms are gradually becoming the standard. Scanners recognize materials by their spectral characteristics, separating printed circuit boards from plastic or copper from aluminum. This not only speeds up the process but also reduces human error, which is critical for hazardous components. Experience from European countries shows that the introduction of automated lines increases the purity of the separated fractions, and therefore the economic return on their subsequent processing [10]. Another area that has been rapidly developing in recent years is bioprocessing. This method uses microorganisms to release organic acids and other substances that can gradually dissolve metals from printed circuit boards and batteries. Compared to traditional chemical methods, this solution appears more gentle: it does not require the use of aggressive reagents, and the process can be conducted under conditions close to natural ones. This approach is particularly valuable when working with low-grade waste that would typically be sent to landfill. Researchers believe that bioleaching has the potential to become a key tool in the sustainable recycling of e-waste [11].

A third approach involves the use of plasma technologies. Their unique feature is their ability to operate at extremely high temperatures, which leads to the complete decomposition of organic matter and the conversion of metal residues into inert slag. Such installations are seen as a solution to the problem of composite materials—multilayer plastics, laminates, and cable insulation. Such waste is practically unsuitable for traditional processing, but plasma processing allows it to be converted into a relatively safe product that can then be used, for example, in the construction industry. [12]

Digital tools for tracking and monitoring e-waste flows have become a significant element of the innovation agenda. Electronic product passports, which record information about a device's life cycle, have been implemented in Europe for several years. Developers propose supplementing these systems with blockchain technologies, which will enable tracking of every waste shipment and eliminate the practice of illegal export to countries with weak environmental regulations. These initiatives are still in the testing phase, but their importance is difficult to overstate: transparent flows create the basis for trust between the state, producers, and recyclers. [13]

Among the innovations, hybrid approaches are also worth mentioning. Combining pyrolysis with subsequent chemical processing allows for increased recovery of non-ferrous metals, while the use of electrometallurgy makes it possible to separate complex mixtures with high precision. Such solutions require significant energy inputs, but their effectiveness will only increase with the development of renewable energy, which can offset the high cost of electricity.

All these areas share a common goal: the creation of a multi-level recycling system. This isn't about replacing old methods with new ones, but rather distributing tasks between them. Automated sorting improves the quality of stream separation, biotechnology enables the recycling of residual fractions, and plasma processing addresses the problem of "non-recyclable" materials. Together, they form a technological loop that can reduce the burden on landfills and return a significant portion of resources to the recycling cycle.

In the long term, innovative technologies will determine which countries will emerge as leaders in e-waste recycling. With e-waste generation growing annually, countries will need to not only increase recycling capacity but also invest in research and development that will improve the efficiency and safety of existing processes. Such a strategy will simultaneously address environmental challenges and create new economic niches associated with the return of valuable materials to the economy.

CONCLUSION

The problem of e-waste is becoming increasingly pressing amid the accelerated growth of its volumes, driven by technological advances, changing consumer habits, and the rapid obsolescence of devices. An analysis of this topic reveals several key findings that highlight the need for a systems-based approach to e-waste management globally.

First, the rate of growth of e-waste is exponential. According to the Global E-Waste Monitor, its volume reached 53.6 million tons in 2022, and is projected to increase to 74 million tons by 2030. This growth is driven not only by the growing number of electronic devices but also by the disposable culture that encourages frequent replacement.

Second, e-waste consists of a complex mixture of materials, combining valuable resources with hazardous substances. Valuable metals have high recycling potential, while toxic components pose a serious risk to ecosystems and human health. This requires a specialized approach to the disposal and recycling of each component. South Korea's experience demonstrates that the implementation of a deposit-return mechanism and extended producer responsibility (EPR) enables the effective collection and recycling of e-waste. Key factors for success include clear legal regulations, producer involvement in the recycling process, and the ability to choose from various approaches to fulfilling obligations. Russia, which has a similar EPR system, faces challenges in its implementation, including the lack of clear waste classification and the mixing of e-waste with other types of waste during the initial stages of recycling.

One key issue is the mixed storage of e-waste with other types of municipal solid waste. Such storage increases the toxicity of landfill leachate, polluting groundwater, soil, and air, and bioaccumulating in the food chain. These environmental risks highlight the need for separate collection and the use of modern recycling technologies.

Thus, solving the e-waste problem requires a global approach combining technological innovation, robust legislation, and public awareness. Stricter measures are needed, such as mandatory producer responsibility, the development of recycling infrastructure, and the promotion of eco-friendly habits among consumers. Only a comprehensive effort at all levels will reduce the impact of e-waste on the environment and human health, while opening up new opportunities.

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