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Recycling Methods for e-Waste

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Abstract: Every year, more than thousands of consumers consume electronic devices such as computers, laptops, mobile, earbuds, printers, televisions, headphones, watches and other portable devices that become outdated or old and they are mainly dumped into landfills which causes many harmful effects on the environment by the toxic and harmful substances present in it. E-waste is one of the fastest-growing wastes globally and possesses many hazardous materials, for example, halogenated compounds, heavy metals, radioactive substances, and micro and nano-size dust all of which require proper handling during the collection, storage, recycling, and disposal stages otherwise causes harmful environmental consequences. This study focuses on the best practices used and innovations in e-waste recycling through sustainable end-to-life solutions. A comprehensive literature review and the recent developments in recycling technologies have been considered in mechanical, chemical, thermal, or biological treatment. The research further discusses the socio-economic effects of e-waste recycling and how policy frameworks are key from a global perspective. These results highlight the need for an integrated approach to e-waste management taking into account a combination of technological, economic, and regulatory aspects to reduce environmental risks and support circular economy principles. The 3R principle – Reduce, Reuse, and Recycle is an efficient way to tackle the growing e-waste and maintain a healthy environment.

***Keywords*: E-waste, Recycle, Reuse, Environmental impacts, E-waste management, Sustainability.**

1. Introduction

Electronic wastes are abandoned electronic gadgets that are no longer in use or have become technologically outdated. The materials used went from small household appliances, like mobile phones, laptops, smartwatches, washing machines, and computers, to huge industrial machines and even medical devices. Today, with rapid advancement in technology, consumer electronics last only for a limited number of years, leaving behind a staggering pile of e-waste in the world. E-waste is believed to hold useful materials like gold, silver, copper, and platinum that can be recovered as by-products in the recycling process. However, others are poisonous substances, lead, mercury, and cadmium. If they find their way to the land where they can get into water-soluble ground waters; it might pose environmental effects and affect the health of several people. In low-income regions, where e-waste is often transferred for informal recycling, workers-excepting children-con are exposed to these toxic materials, leading to respiratory, neurological, and other health problems. The growth in e-waste also speaks to economic issues, because such disposal can be very resource-intensive, and many economies lack the infrastructure for adequate recycling [1].

Fig 1. e-waste [2]

Fig. 2: e-waste [3]

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The problem is met head-on through initiatives like the circular economy, in which products, after being reused and refurbished, get recycled and returned to nature in a natural form. E-waste was also beginning to draw attention because of the growing awareness about its impacts. Now, through EPR laws implemented by several countries, manufacturers must take back used electronic products. E-waste, therefore, is of significance in the preservation of human health and the environment, but also of great value in saving valuable resources, since used materials reduce new raw material demand. E-waste management, therefore, becomes one of the critical focus areas for policymakers, industries, and environmental organizations to realize development sustainability.

E-waste Recycling is in line with the zero-waste concept and is a circular economy, which is an economic system that starts with the reuse of resources and is followed by circular make, repair, and remanufacture to keep the products and materials high in business and use them as long as possible [7]. In reverse logistics management, recycled materials such as REEs by this recycling method are given a new life by the application of that technique that looks at a new life cycle and reduction of mining, thus natural ecosystems are preserved too. Resources are recycled, and they pass through the processing line to produce new production, which in turn circulates among the materials with which the production cycle has been made, which means that the resource supply chain becomes more sustainable, and the security of the supply chain is checked if we look at the ongoing energy transition.

The recycling process of e-waste is mainly recovering and recycling valuable substances like metals, plastics, and rare earth elements in the proper way and safely treating and disposing of the hazardous components. This study aims to investigate various recycling procedures of collection, dismantling, separation, and refining and create best practices that will make high materials recovery and lower environmental footprints possible. The new technology and methods to be used in this study will have a tool that will specifically tackle the main constraint of e-waste, the quantity, by looking at alternatives that sustain the ecosystem as well as improve the health of the people. In the end, the research on the creation of a sustainable e-waste management model that is effective for a circular economy promotes responsible consumption, and supports environmental stewardship will be the goal although technological development continuously changes the landscape [7].

2. Sources and Generation

The disposal of electronic waste, or e-waste, has become a major problem worldwide, especially due to enhanced technological levels, changes in customer behavior, and increased economic activity. According to 2024 estimates, the world is set to generate around 74 million metric tons of e-waste annually, which is starkly more than the 48 million metric tons it was in 2012. This strong uptick in volumes underscores the acute need for proper disposal and recycling strategies to handle the situation of trash electronic devices, which is becoming more critical.

Consumer electronics are the premier sources of e-waste. Gadgets like smartphones, laptops, tablets, and TV sets are most often changed or replaced within only a few years after their purchase. Every hour consumer choices change and hence due to this more e-waste is generated. A classic example of the average life span of a smartphone is seen to have been reduced to the level of two to three years, as the majority of the users are taken by the new models that have better features, performance, and technology. This "upgrade culture" is even more intensified by marketing strategies that highlight the latest gadgets, compelling customers to believe that their current functioning devices are obsolete already though they are still working [4].

Table 1: Sources of Various Kind of Waste [17] [18] [19] [20].

SL NO.	HOUSEHOLD APPLIANCES	MEDICAL EQUIPMENT'S	IT EQUIPMENT'S	COMMUNICATION DEVICES	INDUSTRIAL EQUIPMENT'S	SPACE DEBRIS
1	Fan	Ventilators	Monitors	Mobile Phones	Excavators	Satellites
2	AC	MRI Machines	CPU	Telephones	Generators	Solar Panels
3	Cooler	Dialysis Machines	Mouse	Laptops	Turbines	Batteries
4	Refrigerator	X-Ray Machines	Data Cables	Routers	Transformers	Rocket Bodies
5	Grinder	CT Scanner	Printers	Smartwatch	Large Scale Heater	Rocket Engines
6	Oven	Imaging Equipment	Hard Drives	Tablets	Milling Machine	Electronic Control System
7	LED/LCD/TV	Defibrillator	Circuits Boards	Fax Machines	Industrial printer	Spacecraft Parts
8	Washing Machine	Ultrasound Machines	Chips	Pager	Conditioning Units	Antennas
9	Electric Stove	Cords and Cables	Motherboard	Telegram	Forklifts	Heat Sheild
10	Home Theatres	Radiotherapy Equipment	Server Systems	Radio	Cranes	Sensors
11	Iron	IT Servers	Stabilizer	Walkie-Talkie	Analysers	Control Systems
12	Hair Dryer	ECG Machine	AC	Headphones	Spectrometer	Telescope

Fig. 3: Space debris [5]

Fig. 4: E-waste Generation [8]

Fig. 5: Sorting of E-waste [6]

Besides this, technology applications in various sectors such as education and healthcare have greatly contributed to an upsurge in e-waste. The school scenario includes the shift to digital learning tools that, in turn, lead to the retrieval of laptops and tablets as schools and students look for the latest technologies. About the healthcare industry, the advancements in medical equipment, namely, diagnostic machines and monitoring devices, are the cause for e-waste as the facilities switch to the newest technology to improve patient care. In the company's case, they are also going through a digitization process, which means that they need to replace the old office machinery; thus, e-waste is increasing.

The increase in economic activity, especially in the developing world, is also an important element that influences e-waste production. With the rise in related disposable incomes, more people are getting access to electronic devices, thus causing more device consumption in those areas. New markets are on the road of accelerated technological adoption and this trend is associated with the increase in e-waste production too. Followed by the rise in urban population, more people are moving to cities and they are more likely to lead an urban digital lifestyle; hence, higher electronic consumption and the consequent discarding of older devices due to the shift.

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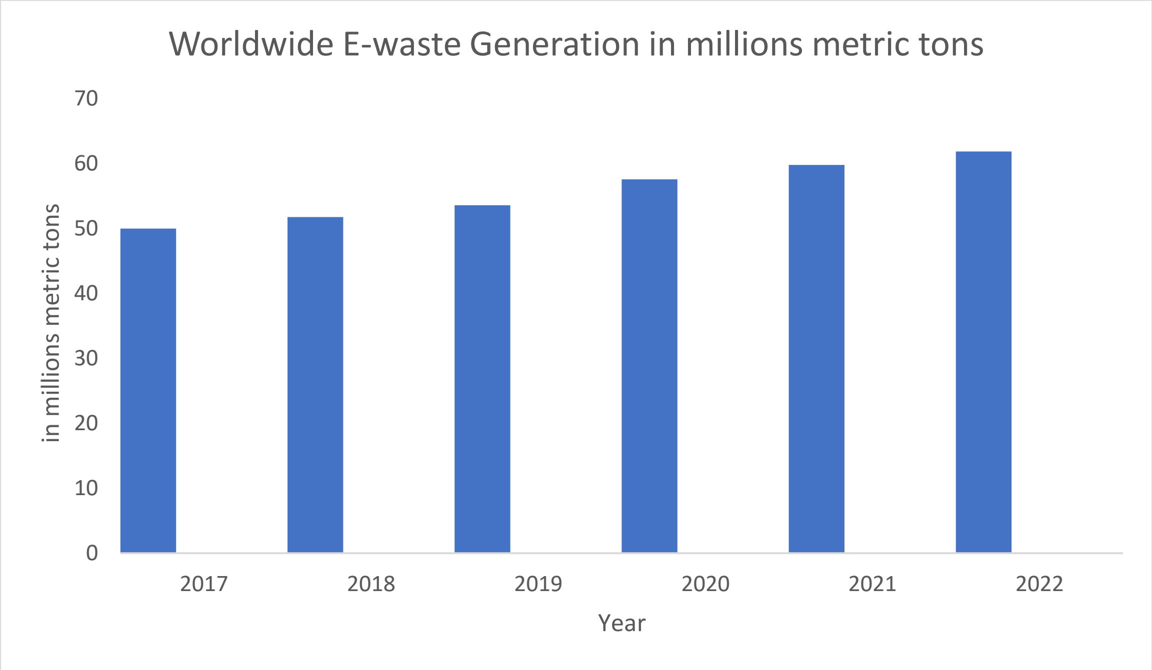

Fig. 6: Worldwide E-waste Generation from 2017 to 2022 [14]

One of the major problems regarding this topic is improper waste management practices in the world [4]. The Lack of recycling capacities, especially in developing regions, causes a larger part of e-waste to be either disposed of improperly in landfills or informally channeled. Depending on semi-formal recycling methods can endanger the workforce and the earth, often leading to the waste of valuable materials that should be recovered. Furthermore, a huge number of consumers are still unfamiliar with the proper techniques of waste disposal, causing e-waste to be merged with regular waste streams which declines the issues.

The problem of planned obsolescence is also a huge problem that makes e-waste even worse. Sometimes, manufacturers design products to have a short lifespan, or they can be hardly repaired thus encouraging consumers to buy new products rather than keep their old ones. This policy not only increases the amount of junk but also the materials that were initially inside the discarded electronics are lost.

During any space mission when the rocket is launched, it goes through several separating stages where after the burning of the fuel from the first booster it gets separated from the rocket, and then the second engine or the booster starts, and after the burning of fuel from the second booster it also gets separated from the rocket. After reaching the desired orbit the payload carrier also gets separated from the rocket, just the satellite or a spacecraft works after that and the rest of the components either re-enter into Earth's atmosphere in which some of them get burned due to Earth's atmosphere and few of them fall in oceans or land creating e-waste others remain in earth orbit creating space debris.

3. Recycling Methods

Electronic waste is becoming a global concern for everyone, pushing for innovative and sustainable results. Recent technological advancements are opening up new ideas for perfecting waste recycling processes. This paper explores innovative results like automated disassembly systems, artificial intelligence (AI) for sorting, and advanced recycling ways. It examines how these ways can Improve the effectiveness of recycling styles, boost resource recovery, and

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reduce environmental impacts. This paper also includes the challenges and possible results of applying these developments to Capture further sustainable waste operation processes.

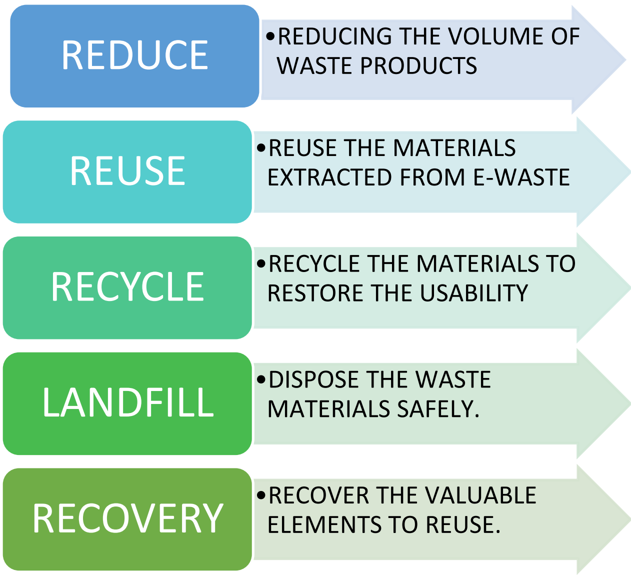

Fig 7. Cycle of E-waste [10]

3.1 Automated Disassembly Systems:

Robotic systems that can disassemble electronic appliances like mobile phones, laptops, and TVs are becoming more advanced. Robotic systems and automated smart dismantling are perfect prototypes of automated technologies that have transformed how e-waste is recovered. These automated systems use a combination of AI/ ML and robotics and honor and remove factors like safeguards, circuit boards, and batteries [10].

3.2 Artificial Intelligence For Waste Sorting:

The primary issue of e-waste is that it contains different sorts of particulars, which are exceptionally extreme to isolated from each other. These machine-learning calculations also break down each of the collected basics to draw up a list of electronic items that can be created by reusing this locale. AI-ground strategies are the spine squander sorting frameworks that guarantee an exact and viable arrangement to the issue. The application of AI squander sorting ways is likely to create from over one-tenth to forty percent of the recyclable handle sum [10].

Major Advantages:

- Fields of Sort accuracy reaches even 99% level.
- Improved efficacy by making it faster and more efficient a procedure by 50%.
- Ability to detect and discriminate precious and unique rare earth elements.

Using an AI-based sorting system is capable of classifying different types of waste for example metals, plastic, and other materials which allows more efficient resource recovery and recycling.

3.3 Hydrometallurgical Recycling:

Hydrometallurgical recycling is recovering essence from e-waste by applying waterless chemistry. The procedure includes exercising the detergents (substantially acids or bases) to dissolve essence from the solid waste stuff, and also the ways of rush, solvent birth, and electrolysis are used to produce the essence in a purer form.

Hydrometallurgical processes are generally characterized by advanced selectivity and environment kindliness; therefore, even though they may prove to be less dynamically consuming, the GPS of the temperature is low.

3.3.1 Filtering: Filtering is the first stage of virtually all hydrometallurgical procedures. It's a process of dissolving precious essence from solid accoutrements by the waterless result which is generally an acid or base, besides other chemicals.

- Acid filtering for this case, sulfuric acid is a typical chemical employed to prize essence, bobby, zinc, and nickel from ores or electronic scrap.
- Cyanidation the process of gold recovery is altogether done using the cyanide result, in which gold is filtered out to be precise.
- Alkaline filtering for essences similar to lithium that is used in lithium-grounded chemical and lithium-ion battery recycling.

3.3.2 Separation and cleansing: After the filtering process is completed, the essence-containing result are contaminations, thus the cleansing process is needed. Either, this can be achieved through different styles similar as solvent birth (SX) the solvent birth process is the process of the operation of organic liquid to successfully gain a named essence from the alloy.
Ion exchange is the process where ions are replaced between the result with the resin, which aids in the disposal of undesirable impurities rush. A particular way of carrying these essences includes their redundant rush from a result by manipulating pH or temperature by adding certain chemicals (similar to reducing agents).

3.4 Bioleaching of Metals from E-Waste

Bioleaching also known as biological leaching is an eco-friendly way that is used to extract precious metals from the e-waste. Micro-organisms play an important role in this extraction of precious metals from the e-waste micro-organisms like iron & sulphur-oxidizing bacteria and fungi are involved in this method. for example, the bacteria like Acid thiobacillus Ferro-oxidants and Aspergillus Niger secrete the acids that dissolve the metals from e-waste

These dissolved metals are then collected and purified for reuse and recycling This method is more eco-friendly than traditional methods like hydrometallurgy which uses higher energy consumption and hazardous chemicals [13].

Advantages:

- Cost-efficient: operational cost is lower as compared to traditional methods.
- Sustainable: It allows the reuse and recycling of valuable metals, minimizing the impact of e-waste on the environment.
- eco-friendly: It minimizes energy consumption and the need for harmful chemicals.

3.5 Plasma Arc Recycling:
In this process, the plasma is used to create a temperature of more than 10,000°C to break down the e-waste into fundamental components. In this process, the waste is heated at high temperatures so that it gets melted and vaporized without the involvement of combustion.

Advantages:

- Environmentally friendly: It decreases the impact of e-waste on the environment by minimizing the emission of waste.
- Energy Efficiency: Plasma arc recycling is much more energy efficient than traditional methods.
- Resource recovery: Precious metals are recovered efficiently.

3.6 Electrochemical Recycling:

Electrical current is used in this process to break down the substance into its fundamental components For recovering valuable metals this method is used during this process the electrochemical cell, which consists of the positive electrode and the negative electrode is submerged in an electrolyte solution and when the current is supplied it causes a chemical reaction at the electrodes resulting oxidation at anode and reduction at the cathode occurs simultaneously, the electric current helps metals to dissolve from the waste material into an electrolyte solution. then the dissolved materials can then be collected and purified for reuse.

Advantages: -

- Efficiency: Various ranges of metals can recover, including expensive metals like palladium, gold & silver as well as basic metals like nickel, copper & zinc.
- Sustainability: Environmental impact is reduced by promoting the recycling and reuse of precious material.

3.7 Pyrolysis:

Pyrolysis is the thermal decomposition of materials in an oxygen-free environment at high temperatures of 300°C to 900°C. Pyrolysis decomposes organic materials, including plastic and rubber, into gases, liquid bio-oil, and solid residues known as char. This process is utilized in the recycling of e-waste to retrieve valuable metals and materials from electronic devices, like circuit boards, cables, and plastics.

3.7.1 Preparation: E-wastes are collected, crushed, and shredded so that a large surface area is exposed and metals and non-metals are separated.

3.7.2 Optional Pre-Treatment: Hazardous materials such as mercury and lead are removed to avoid contamination during the pyrolysis process.

3.7.3 Pyrolysis Process: The shredded e-waste is heated in the pyrolysis reactor 400°C-900°C. This thermal decomposition of plastics and organic materials at those temperatures break down the following products into gaseous, liquid oils, and carbon-rich solid residues.

3.7.4 Product Separation:

- Gaseous Products: These can be upgraded into liquid fuels or energy.
- Liquid Products (Bio-oil): This includes organic compounds that are further broken down into other products or are used as substitution fuels.
- Solid Residue (Char): It is carbon-rich, and it also holds other metals in the form of copper, gold, and silver.

3.7.5 Post-pyrolysis Processing: The solid metal residue is separated, for example through gravity, magnetic separation, and then purified again to be reused in the production of new products.

3.8 Magnetic Nanoparticle Technology:

Magnetic Nanoparticle Technology is used in e-waste management to upgrade the capability and effectivity of the recycling process.

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In this process, the magnetic nanoparticles are added to the e-waste and when the external magnetic field is applied the magnetic metals get attached to the nanoparticles making it easy to separate the magnetic and non-magnetic substances.
Magnetic nanoparticles can is also used to remove toxic substances from the e-waste, such as heavy metals and other hazardous chemicals which makes the process of recycling much safer and eco-friendly.

Advantages:

- Magnetic nanoparticle upgrades the capability of metal recovery, it increases the recovery of valuable material by reducing the amount of waste.
- This method reduces the use of toxic chemicals and minimizes the e-waste.
- This method recovers valuable metals by recycling hence it is very cost-efficient.
- It is very versatile as it applies to various electronic components such as circuit boards, batteries, etc.

3.9 Active Debris Removal System:

In this method, we can use the spacecraft equipped with nets or a robotic hand or arm that can capture the debris and remove it from orbit companies like Astro scale and ESA are working on this method to capture and deorbit debris safely [15].

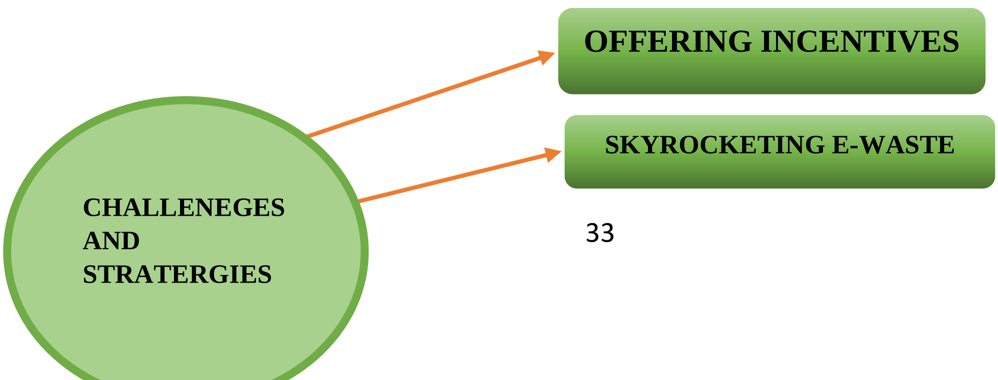
3.10 Passive Debris Removal:

This method operates with the designing of the satellites and rockets with the features that they deorbit the debris safely [15].

3.11 Reusable Technologies:

Develop and use technologies which is reusable the company SpaceX has developed the technology that their rockets come back and land safely and it is reusable [16].

These new upcoming recycling techniques are important for sustainable advancement and development. Bio-leaching, advanced mechanical recycling, hydrometallurgical recycling, active debris removal systems, passive debris removal, reusable technologies, and electrochemical recycling help to regain valuable resources and decrease environmental effects. Pyrolysis and magnetic nanoparticle technology improve recycling efficiency by recycling waste like plastic and creating some useful products out of it. these techniques are much more sustainable and productive for management of e-waste and to recover the resources.



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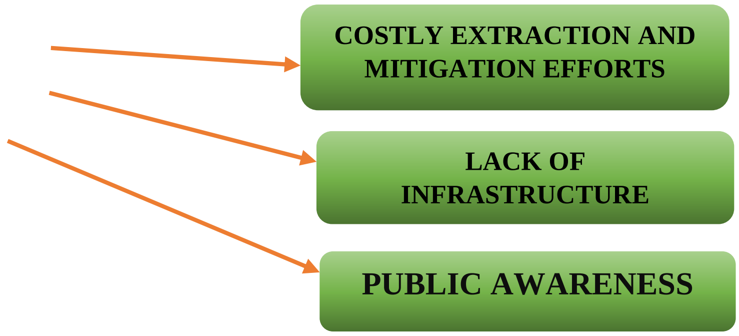

Fig (8): Crucial Challenges [9]

4 Challenges of E-Waste Recycling:

4.1 Problems Connected with E-Waste Disposal:

E-waste is made up of many materials that also contain plastics, metals, and toxic materials which would take a long time and immense energy to disassemble and recycle [11].

4.2 Destructive Chemicals:

E-waste comprises materials like cadmium, mercury, and lead, which, when transported improperly, create epidemic-scale damage to the environment and cause human health problems [11].

4.3 Informal Recycling Sector:

In most locations, there is adequate e-waste recycling in bulk; however, this is mainly done without proper safety measures that contribute to hazardous environmental pollution and exposure to toxins [12].

4.4 Lack of Infrastructure:

Many regions lack the necessary infrastructure for the collection and transportation of waste. there are less amount of advanced recycling facilities that can handle the complex e-waste material this limits the ability to recover valuable metals and management of harmful substances resulting in improper disposal of practices like burning or landfilling them which exposes the harmful substances in nature [12].

4.5 Legislation and Enforcement:

Every country has different e-waste regulations, due to which confusion is created and leads to inefficiency few countries have strict rules for import and export while few countries do not make any laws for e-waste import & export even with this existing regulation the enforcement is not that capable due to the lack of awareness, limited resources, and monitoring system this led to improper disposal like illegal dumping of e-waste [12].

4.6 Public Awareness:

Most people are unaware of the dangerous effects of improper waste disposal regarding human health and environmental impact this avoidance can further lead to improper disposal of e-waste. There is even a lack of availability of information about how to handle and dispose of e-waste majority of the people are unaware of the local recycling programs thus then for many of them e-waste is not the priority. Few of them would have known the importance of e-waste management but still, they ignore the concept of proper disposal convenience or daily habits as the concept of recycling and proper waste management in not in a daily habit which challenges the behaviour [10].

5 Result & Discussions

The constant growth of electronic equipment has led to a dramatic increase in electronic waste (e-waste), better recycling methods that help to protect the environment, and public health issues arising due to hazardous chemicals released from e-waste. This paper focuses on the different e-waste recycling methods, recognizing corresponding challenges, and sustainable future. There are several sources and categories of e-waste like consumer electronics, medical e-waste, and ICT devices, driven by technological advances and decreased product lifespan. Recycling methods such as hydrometallurgical recycling, pyrolysis, and AI waste sorting have shown promise in reclaiming valuable materials while addressing unique aspects of electronic waste. However, challenges such as the complexity of e-waste, destructive substances, inadequate infrastructure, and lack of awareness restrict and block recycling efforts. Overcoming these issues via challenges requires a comprehensive approach.

6 Conclusions

In summary, these newly developed, very efficient, and environmentally friendly processes of resource recovery such as hydrometallurgical recycling, mechanical recycling, biological leaching, electrochemical recycling, magnetic nanoparticles technology, and pyrolysis are uncovering new capabilities of extraction of precious metals. This method in conjunction with the 3R principles of REDUCE-REUSE-RECYCLE develops overall plans for the management of e-waste. AI technologies can also be employed in the waste management system for they do not allow the foremost challenges related to e-waste such as its composition heterogeneity, incorporation of toxic materials, rudimentary processing facilities, etc. The WHO with its unique position is also working on the issues related to children and elderly people with a particular focus on the health impacts of e-waste and related literature. WHO is also strengthening health systems to mitigate the impact of e-waste. Suffice it to say, that there should be an investment in education and information on the need for and the use of e-waste management, the development of appropriate and effective e-waste management technologies, the promotion of sustainable e-waste management policies and strategies, and finally implementation of e-waste management in a way that promotes public health and environmental protection.

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