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SUSTAINABLE E-WASTE MANAGEMENT THROUGH INDUSTRY 5.0

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Original Article

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Abstract

Rapid technological advancements have led to a substantial demand for electronics products, resulting in the significant expansion of the electronics and hardware industry. Shifts in the characteristics of electronic devices and the presence of enhanced products compel consumers to quickly discard their electronic products. This has led to the generation of e-waste in huge quantities. E-waste poses a health risk because it contains harmful materials such as lead (Pb), hexavalent chromium (Cr^{6+}), mercury (Hg), cadmium (Cd), and flame retardants like polybrominated biphenyls and polybrominated diphenyl ethers, among others. The management of electronic waste (E-waste) is a major issue in numerous developing nations. Disposing of e-waste with regular municipal trash poses a considerable threat to the environment in developing countries, where there is a deficiency of proper recycling methods and unregulated individuals resort to crude techniques to extract valuable metals for quick profits. To lessen detrimental environmental and public health effects, e-waste must be treated appropriately. The world is now moving towards Industry 5.0 and this industrial revolution focuses on human process integration with social and sustainability aspects. It highlights the human-machine interfaces in the value-creation aspect of business activities to eliminate social constraints. This article explores sustainable management of electronic waste in the context of Industry 5.0.

Keywords: e-waste, e-waste Management; Industry 5.0, Sustainable e-waste Management

Introduction

The trends of digitization, computerization, robotization, and automation are creating new routes for the development of industrial businesses. As lifestyle and technology continue to progress, the demand for electronic and electrical devices is growing rapidly. These devices have infiltrated all areas of our daily lives, and we often overlook the fate of these appliances once they are discarded, as they bring both benefits and drawbacks. The negative impacts on health and the environment due to waste generated from human consumption have been acknowledged for a long time. However, a relatively newly identified hazardous waste results from discarded Electrical and Electronic Devices (EEE).

Operating in a clean, pollution-free environment is undoubtedly essential for contemporary societies. While Industry 5.0 is distinctly focused on sustainability and protecting the environment, it still encounters challenges related to waste produced by industrial operations. The aim of this article is to outline strategies for waste management techniques and to recognize opportunities for minimizing waste levels through Industry 5.0 solutions. To do so, both technological and policy initiatives should be a part of this strategy. Examples of technological measures include developing innovative technologies for recycling e-waste and enhancing the current recycling infrastructure. Policy measures encompass

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actions such as establishing regulations to guarantee the safe disposal of e-waste, as well as backing public awareness initiatives to inform individuals about the significance of recycling electronic waste.

Literature Review

e-Waste

E-waste is mainly defined as the discarded components and devices of Electronic and Electrical Equipment (EEE) that are thrown away with no plan for reuse [1]. It is commonly referred to as Waste Electrical and Electronic Equipment (WEEE) and e-scrap in various regions around the globe [2]. E-waste includes a wide array of electronic devices, such as telecommunications and information technology devices, large domestic appliances, lighting fixtures, automatic dispensers, medical instruments, and monitoring and control systems, including consumer electronics such as electrical and electronic tools, sports and leisure gear, toys, mobile gadgets, and computers [3, 4].

e-waste production

The manufacturing and use of Electrical and Electronic Equipment (EEE) product categories have significantly expanded, resulting in a rise in the amount of money that consumers are ready to invest in electronic products [5]. The amount of e-waste increased from 41.8 million metric tonnes in 2014 to 53.6 million metric tonnes in 2019, indicating a notable rise [6]. This trend persists on a per capita basis, as depicted in global per capita e-waste production, which rose from 6.4 kg/person in 2014 to 7.8 kg/person in 2023 indicating widespread and massive growth [6, 7].

e-waste recycling

In contrast to typical solid waste like domestic refuse, electronic waste possesses both hazardous and valuable characteristics [8, 9]. When considering resource recovery, the metal and non-metal components found in e-waste are amenable to extensive recycling [10]. E-waste encompasses as many as 60 distinct metals, including copper, gold, silver, palladium, aluminium, and iron [11]. According to estimates from 2017, the worth and stock of materials found in e-waste are as follows: Iron/steel totalling 16,500 kt (9 billion Euros); copper amounting to 1900 kt (10.6 billion Euros); aluminium of 220 kt (3.2 billion Euros); gold of 0.3 kt (10.4 billion Euros); silver of 1.0 kt (0.58 billion Euros); and plastics of 8600 kt (12.3 billion Euros) [12].

Heavy metals like lead, mercury, and cadmium, along with persistent organic pollutants such as polychlorinated biphenyls and brominated flame retardants, are prevalent. When these hazardous materials are dealt with unlawfully, they can inflict significant damage on both the global ecosystem and human health. If e-waste is disposed of in landfills or burnt, harmful substances may seep into soil, water, and air, leading to environmental destruction and healthcare threats. The growing pollution and environmental deterioration are the consequences of upgrading electronic devices. E-waste from wealthier nations, where disposal costs are significant and environmental regulations are stringent, is frequently illegally transferred to countries with lower and middle incomes, such as China, India, Ghana, and Nigeria, for the purpose of recycling. The industrial infrastructure and e-waste recycling technology in these countries are often informal, leading workers to use rudimentary techniques to extract valuable materials from electronic waste, which causes detrimental and lasting effects on the local, regional, and even global ecological environment.

Given the ongoing challenges, many nations have implemented regulations and initiatives aimed at promoting responsible management of e-waste. The key elements of effective e-waste management include recycling and proper disposal techniques. Recycling processes for electronic devices focus on recovering valuable metals such as gold, silver, and copper, along with polymers and glass. These initiatives are essential for minimising environmental impacts and promoting sustainable practices in e-waste management. By recycling these materials for the production of new electronic products, the necessity for extracting and processing new raw materials can be diminished.

Moreover, various organisations and manufacturers have established e-waste collection programs and take-back initiatives to ensure the responsible disposal of electronic devices. These efforts seek to prevent e-waste from being deposited in landfills or illegally shipped to developing nations with less stringent environmental regulations. In addition to these initiatives, there is a growing focus on educating the public about the importance of e-waste recycling, coupled with promoting the creation of more durable and easily recyclable electronic products. This includes urging manufacturers to embrace environmentally sustainable practices, such as reducing the use of harmful materials, designing products for straightforward disassembly and recycling, and providing repair options to prolong the life of electronic devices.

Industry 5.0

Industry 5.0 is considered the forthcoming industrial revolution, aiming to harness the ingenuity of human specialists in conjunction with proficient, intelligent, and precise machines to achieve manufacturing solutions that are efficient in resources and aligned with user preferences, compared to Industry 4.0. A range of promising technologies and applications are anticipated to facilitate Industry 5.0, thereby enhancing production and enabling the on-demand delivery of customised products. This phase emphasises the human-machine interfaces in the business activities related to value creation, with the goal of overcoming social limitations. The synergy between humans and machines is expected to yield greater productivity and resource efficiency through industrial upcycling, and the fundamental components of Industry 5.0 include:

1. A human-centred approach that prioritises the needs of individuals within the production process, focusing on what technology can offer workers and its utility.
2. Sustainability, which emphasises the reuse, repurposing, and recycling of natural resources while minimising waste and environmental effects.
3. Resilience, which entails embedding robustness in industrial manufacturing. This robustness provides a foundation for flexible processes and adjustable production capabilities, especially in times of crisis [13].

Methodology

This study employs a qualitative research approach using secondary data sources. A thorough review of scholarly articles, industry reports, and governmental policy documents was performed to pinpoint trends, challenges, and technological solutions pertinent to e-waste management within the context of Industry 5.0. Content analysis was utilised to draw out insights concerning human-machine collaboration, intelligent technologies, and policy structures.

Result and Discussion

Sustainable E-Waste Management through Industry 5.0

Sustainable e-waste management through Industry 5.0 represents a progressive approach that leverages advanced technologies to improve efficiency, reduce environmental impact, and create new business models for managing electronic waste (e-waste). Industry 5.0 is centred around human-centric, sustainable, and intelligent technologies, which can significantly improve how e-waste is handled, recycled, and repurposed. The strategies include:

- **Embracing a Human-Centric Perspective in E-Waste Recycling**

  Industry 5.0 emphasizes collaboration between humans and machines, where human expertise complements advanced technologies. In e-waste recycling, workers with specialized skills could collaborate with robots or AI-driven systems to disassemble electronic devices more effectively, ensuring that valuable materials like precious metals (gold, silver, copper) and rare earth elements are efficiently extracted.

  Industry 5.0 is distinguished by highlighting the importance of collaboration between humans and machines, connecting technology with human creativity. It recognizes that attaining sustainable progress requires a harmonious balance between automation and human understanding, particularly when faced with complex and ethical decisions [14].

  Industry 5.0 will come into being when its three key components—smart devices, intelligent systems, and automated intelligence—fully integrate with the physical realm in partnership with human intellect. The term "automation" refers to autonomous robots acting as intelligent agents that work alongside humans in the same environment. A robust foundation of trust and reliability between these two parties will lead to improved efficiency, flawless production, minimized waste, and customized manufacturing. This strategy will motivate more people to return to the workplace and improve process effectiveness.

- **Cutting-Edge Robotics and Sophisticated Automated Systems to Improve the Recycling of Electronic Waste**
  Automated systems, including robotics and AI, have the potential to significantly improve the e-waste recycling process. Robots equipped with AI-powered vision systems can help with sorting e-waste by type, material, and value, ensuring higher efficiency in recycling. They can also perform tasks like dismantling devices, removing hazardous materials, or separating recyclable components. Advanced machines can extract valuable materials more precisely, improving recovery rates and reducing waste [15].

- **Utilization of Artificial Intelligence and Machine Learning Algorithms**
  The application of AI and machine learning algorithms helps forecast trends in electronic waste, streamline recycling procedures, and recognize and sort materials from mixed e-waste. Machine learning techniques can anticipate trends in waste production, categorize waste management approaches based on their environmental and economic impacts, and enhance operational processes to boost overall efficiency. Predictive models have demonstrated considerable promise in supporting proactive waste management strategies, enabling timely and effective responses to fluctuations in waste generation. Classification models have yielded deeper insights into the effectiveness and sustainability of different waste management approaches, assisting decision-makers in selecting the most suitable strategies for their unique situations. Furthermore, optimization models have underscored the capability of machine learning to improve resource allocation and operational efficiency, leading to reduced costs and a diminished environmental footprint [16].

- **The Internet of Things (IoT)**
  The IoT enables better monitoring and management of e-waste. Sensors can be embedded in electronic devices to track device lifecycle. By tracking the usage, condition, and age of electronic products, IoT systems can help predict when devices are likely to be discarded, making it easier to implement take-back programs and extend product lifecycles.

  IoT-enabled bins and waste management systems can help track and optimize e-waste collection routes, ensuring that recycling facilities receive a steady and consistent supply of materials [17].

  The IoT offers a transformative approach to managing electronic waste (e-waste) by allowing for immediate monitoring and data collection that enhances tracking of accumulation, optimizes collection routes, and supports data-driven decisions regarding resource allocation. IoT devices enable continuous monitoring and data collection for the collection and recycling of e-waste through a Smart Bin System. Implementing a Smart Bin system that incentivizes users for their participation is essential and promotes user engagement, fundamentally changing e-waste management through IoT-based technologies and smart bin methodologies [18].

- **Blockchain Technology**
  Blockchain technology provides a clear and secure method for tracking and controlling the movement of electronic waste materials. It can solve problems such as illegal dumping, improper handling of hazardous materials, and unethical recycling practices by creating a verified, unalterable record of the e-waste processing journey, from collection to recycling, while ensuring adherence to environmental regulations. Blockchain could be utilized to follow the entire lifecycle of materials, from the collection of e-waste to recycling and resale, offering consumers, businesses, and regulatory agencies enhanced visibility into the management of resources. Blockchain technology promotes transparent transactions among all the stakeholders involved and effectively monitors the product lifecycle. The impact of blockchain on improving the traceability of waste streams demonstrates that transparency is not only conceptually attractive but also practically advantageous. The implementation of digital product passports within a blockchain framework provides detailed information on appropriate disposal methods, establishing the foundation for a cohesive supply chain that carefully tracks a product's path from production to reuse or recycling [19].

- **Circular Economy and Design for Reuse & Design with Recycled Materials**
  Industry 5.0 emphasizes sustainability by promoting a circular economy, where products are designed for longevity, repairability, and recyclability. Manufacturers can be incentivized to design electronic products that are easier to disassemble, repair, and recycle. By embedding sustainability into product design, less e-waste is generated over time. Adopting sustainable product design and a circular economy may greatly prolong the life of electronic devices and reduce waste production [19].

  The proposition of designing with recycled materials enables a straightforward and objective evaluation of their technical, economic, and environmental benefits. A unified scoring system is proposed to simplify the decision-making process. This approach facilitates a connection between designers and the stakeholders involved in the end-of-life management of products. Additionally, this relationship can be strengthened by incorporating a complementary method that integrates recycling tools into the design process [20]. The databases used should be customized (i) to the recovery chain responsible for processing the selected product (in line with the design-for-recycling approach) and (ii) to the recovery chain that produces the chosen recycled material (associated with the design-from-recycling approach) [21].

  Companies might shift from traditional product ownership to leasing or subscription-based models for electronics (Product-as-a-Service Models). Here, the companies take responsibility for the lifecycle of their products, encouraging repair, reuse, and refurbishment instead of disposal.

- **Innovations in the Field of Material Science**
  Industry 5.0 facilitates innovations in material science that can help reduce the environmental impact of e-waste as eco-friendly materials are used, which consist of biodegradable components and non-toxic plastics, offering safer alternatives compared to rare earth metals. Additionally, new chemical processes can be deployed to reduce the use of hazardous substances in electronics, making recycling processes less harmful to the environment and human health.

- **Creating Consumer Awareness and Engagement through Education and Reward Programs**
  Industry 5.0 enables smarter and more personalized consumer engagement, encouraging sustainable behaviours through incentive programs and educating regarding recycling and repair education. AI and mobile apps can provide consumers with personalized information on where and how to recycle e-waste or offer incentives for returning old devices, thereby closing the loop on e-waste. Advanced technologies can help consumers understand the environmental impact of improper e-waste disposal and educate them about repair and recycling options through interactive apps, online platforms, or even Augmented Reality (AR) interfaces.

- **Policy and Regulatory Initiatives for the Management of Electronic Waste**
  At the global level, treaties and agreements act as crucial foundations for international cooperation and collaboration in tackling worldwide waste issues [22]. Various treaties such as the Basel Convention, which deals with the control of transboundary movements of hazardous waste and its disposal, and the Stockholm Convention concerning persistent organic pollutants, set forth standards and norms for managing and disposing of hazardous materials, facilitating cross-border collaboration and regulatory alignment. Initiatives like the Sustainable Development Goals (SDGs) and the Paris Agreement highlight the significance of waste management in achieving larger environmental and societal aims, nurturing a collective commitment to sustainable development and climate action. National waste management strategies and programs provide frameworks for governments to outline their priorities, set objectives, and allocate resources for local waste management efforts. These policies include an array of strategies, such as waste reduction, recycling and recovery efforts, diverting waste from landfills, and managing hazardous waste, all customized to the unique needs and circumstances of each nation. Through regulatory frameworks like waste management plans, permits, and enforcement actions, governments aim to ensure adherence to environmental standards, safeguard public

health, and reduce negative effects on ecosystems and natural resources. Regulations enacted by governments are crucial in fostering sustainable waste practices by creating legal obligations, incentives, and penalties that promote responsible waste management behaviours. These regulations cover various aspects, including waste collection and transportation, recycling targets, operation and closure standards for landfills, and producer responsibility initiatives. By establishing clear regulations and incentives, governments can foster an environment conducive to innovation, investment, and public-private partnerships in waste management, propelling the transition towards a circular economy and a more sustainable future [23, 24].

Suggestions

- Encourage collaboration between humans and machines in recycling by training skilled workers to assist intelligent machines (robots and AI systems) in the disassembly and sorting of electronic devices. Emphasise tasks that require ethical decision-making, accuracy, and flexibility, highlighting how human intelligence enhances automated processes.
- Implement robotics and AI technology in the processing of e-waste to improve the precision and safety of identifying, sorting, and dismantling electronic waste. Automate dangerous operations to reduce human exposure and enhance the recovery rates of valuable materials.
- Incorporate predictive analytics and machine learning techniques to forecast trends in e-waste generation and streamline collection and recycling operations. Use classification and optimisation models to assess sustainability impacts and inform decisions related to policies and operations based on data.
- Use IoT technology for monitoring product lifecycles and establishing smart collection systems by integrating sensors into electronic devices to track usage and estimate end-of-life.
- Deploy IoT-enabled smart bins for real-time data gathering, route optimisation, and better consumer interaction.
- Create a blockchain system to guarantee transparency and traceability throughout the e-waste lifecycle, from production to disposal, ensuring adherence to regulations. Implement digital product passports to educate consumers about responsible disposal alternatives and monitor circularity metrics.
- Promote practices aligned with the circular economy by adopting Design-for-Recycling and Design-from-Recycling approaches to simplify the repair, disassembly, and recycling of electronics. Encourage Product-as-a-Service models (leasing, subscription) to ensure producers take responsibility throughout the product's lifecycle.
- Allocate resources towards eco-friendly materials and green chemistry initiatives to drive advancements in materials science that lessen hazardous elements in electronics. Promote the adoption of biodegradable and non-toxic materials to facilitate safer disposal and easier recycling.
  Raise public awareness and motivate sustainable behaviours by initiating consumer education campaigns that emphasise the significance of recycling and repair. Utilise mobile applications and augmented reality tools to direct users to recycling centres and offer incentives for responsible disposal practices.
- Enhance policy frameworks and foster international collaboration by synchronising national policies with global treaties like the Basel and Stockholm Conventions. Advocate for Extended Producer Responsibility (EPR) and public-private partnerships to advance sustainable e-waste infrastructure.
- Promote research and capacity building by supporting academic and industry studies focused on innovative recycling technologies, sustainable product design, and policy development.
- Develop local capabilities through training initiatives and infrastructure investments, particularly in developing regions.

Conclusion

Sustainable e-waste management through Industry 5.0 is about leveraging cutting-edge technologies like Artificial Intelligence, Machine Learning, Deep Learning, the Internet of Things, and Blockchain Technology while fostering a collaborative approach between humans, machines, and businesses. The goal is to reduce the negative impacts of e-waste by improving recycling rates, reducing hazardous waste, and creating a circular economy for electronic and electrical equipment. Industry 5.0's focus on human-centred solutions, automation, AI, IoT, and blockchain provides a transformative opportunity to address the growing e-waste crisis and create a more sustainable, efficient, and transparent recycling ecosystem.

Conflict of Interest
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