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# Sustainable E-Waste Management Through Industry 5.0: A Cambodian Context

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## Abstract

Cambodia, like many developing nations, faces an urgent need to address the growing e-waste challenge. With an influx of electronic devices and limited e-waste management infrastructure, the environmental and health implications are significant. A people-oriented and sustainable form of development like Industry 5.0 has the potential to revolutionise the management of e-waste. In this paper, the authors focus on the applicability of principles of Industry 5.0, namely the use of collaborative robots, Internet of Things (IoT) and blockchain, for the sustainable management of e-waste in Cambodia. Using data from secondary sources, this study analyses the existing practices of e-waste management in Cambodia, establishes certain deficiencies and proposes Industry 5.0 solutions that would help prevent environmental damage, practice sustainable waste management, and enhance recycling practices. It provides recommendations for policy and regulatory mechanisms to foster better uptake as the overall aim is to support Cambodia's sustainable development policies.

**Keywords**: *E-Waste Management, Industry 5.0, Sustainable Development, Circular Economy.*

## Introduction

One of the waste streams that is generally growing at the fastest rate in the world is electronic waste (e-waste), which refers to waste electrical and electronic equipment (WEEE). According to the Global E-Waste Monitor 2020 of the United Nations, in 2019, approximately 53.6 million metric tons of e-waste was generated around the globe and as people are consuming more electronics and the product life cycle is decreasing, this figure is expected to increase (Geneva Environment Network, 2024). Developing countries such as Cambodia which are growing economically as well as technologically face a considerable setback in the management of e-waste (Karin Lundgren, 2012). The absence of organized waste collection and disposal facilities, weak legal approaches, and low awareness among the citizens contribute to the risks faced by health and the environment due to improper management of e-waste.

The informal sector has also made the e-wasteproblem in Cambod ia more complex, as it plays an important role in the collection and processing of discarded electronic equipment using unsafe recycling practices that result in the exposure of workers to hazardous substances, like lead, cadmium, and mercury, which may cause serious health risks (Sothun, 2012) (Parvez et al., 2021). Moreover, these processes frequently result in the release of pollutants into the environment, contaminating soil and water sources.

Addressing this critical issue requires innovative and comprehensive solutions. Industry 5.0, a paradigm that builds upon Industry 4.0, offers an advanced approach that integrates human-centric and environmentally sustainable practices with state-of-the-art technologies (van Erp et al., 2024). Unlike Industry 4.0, which focused on automation and smart technology, Industry 5.0 emphasizes the collaboration between humans and machines to create sustainable and efficient processes (Rame et al., 2024). The principles of Industry 5.0—leveraging collaborative robots (cobots), the Internet of Things (IoT), and blockchain technology—can transform e-waste management by enhancing efficiency, safety, and transparency (Zafar et al., 2024).

The findings of this study are particularly relevant as Cambodia seeks to balance economic growth with environmental stewardship. By exploring the potential of Industry 5.0, the paper highlights a pathway for Cambodia to develop a modern e-waste management system that not only mitigates current challenges but also supports long-term sustainable development.

### *Objectives*

The objectives of this research are:

1. To assess the current state of e-waste management in Cambodia.
2. To identify the gaps and challenges in existing e-waste management practices.
3. To explore how Industry 5.0 technologies can be applied to enhance sustainable e-waste management.

### *Research Questions*

1. What is the current state of e-waste management in Cambodia?
2. What are the key challenges in the existing e-waste management system?
3. How can Industry 5.0 principles be applied to improve e-waste management in Cambodia?

## Literature Review

### *Global Overview of E-Waste Management*

E-waste management has emerged as a significant global challenge, driven by the rapid pace of technological advancement and the increasing obsolescence of electronic devices. According to the United Nations' Global E-Waste Monitor 2020, only 17.4% of e-waste generated globally is formally recycled, indicating a significant gap in effective waste management practices (Adrian et al., 2020). Studies by Baldé et al. (Adrian et al., 2020) and

Forti et al. (Adrian et al., 2020) highlight the environmental and health risks posed by the improper handling of e-waste, including the release of toxic substances such as lead, cadmium, and mercury, which have been linked to severe health outcomes like neurological damage and organ failure (Rautela et al., 2021). The research emphasizes that effective e-waste management practices require robust policy frameworks, advanced technological solutions, and public awareness campaigns.

### *E-Waste Management in Developing Countries*

Developing countries face unique challenges in managing e-waste due to limitations in infrastructure, regulatory oversight, and financial resources. Research by Kahhat and Williams (Kahhat & Williams, 2012) shows that developing nations often become destinations for e-waste from more developed countries due to lenient import regulations and weak enforcement mechanisms (Liu et al., 2023). These nations typically rely on informal sectors for e-waste processing, which, while economically beneficial for local workers, often involves rudimentary and hazardous methods of material recovery. Studies by Awasthi and Li (Awasthi & Li, 2017) emphasize that without effective regulation and infrastructure, the reliance on informal sectors perpetuates environmental pollution and health risks.

Cambodia's experience aligns with these findings, as noted in reports from NGOs and government bodies. The collection and recycling of e-waste are predominantly handled by informal workers who lack protective measures and appropriate technology, leading to high levels of exposure to hazardous substances and contributing to environmental degradation (PPCA, 2018).

### *Industry 5.0: A Human-Centric and Sustainable Approach*

Industry 5.0 builds on the advancements of Industry 4.0, integrating human collaboration and sustainability with high-tech automation. As opposed to Industry 4.0's focus on automation and cyber-physical systems, Industry 5.0 emphasizes human-machine synergy to create more adaptable and sustainable processes. According to Demartini et al. (Demartini et al., 2021), this shift allows for a more holistic approach to production and management, where sustainability and societal well-being are prioritized alongside efficiency and productivity (Puma-Flores & Rosa-Díaz, 2024).

Key components of Industry 5.0 relevant to e-waste management include collaborative robots (cobots), the Internet of Things (IoT), and blockchain technology. Research by Wang et al. (Wang et al., 2023) demonstrates that cobots can enhance efficiency and safety in e-waste dismantling by automating repetitive and dangerous tasks while allowing human operators to oversee complex decision-making processes (Bloss, 2016). This integration reduces the risk of exposure to hazardous substances and improves the recovery rates of valuable materials like precious metals and rare earth elements.

### *Role of the Internet of Things (IoT) in E-Waste Management*

IoT has been identified as a powerful tool in enhancing e-waste management through improved monitoring, data collection, and logistics. According to research by Perera et al. (Perera et al., 2014), IoT devices embedded in e-waste collection bins and recycling facilities can enable real-time tracking of waste flows, optimize collection schedules, and ensure efficient use of resources (Sosunova & Porras, 2022). This data-driven approach helps reduce operational costs and improves recycling rates by making processes more responsive to current demands.

In the context of Cambodia, IoT can address challenges related to waste collection and tracking, providing transparency and enabling better policy enforcement. Studies from countries with successful IoT implementations, such as South Korea and Japan, show significant improvements in recycling rates and resource efficiency when IoT-based systems are employed.

### *Blockchain Technology for Transparency and Traceability*

Blockchain technology has the potential to enhance transparency and accountability within e-waste management systems. As highlighted by Saberi et al. (Saberi et al., 2019), blockchain offers immutable record-keeping that can track the entire lifecycle of electronic devices, from production to disposal. This level of transparency is crucial for enforcing regulations, preventing illegal e-waste exports, and fostering trust among stakeholders. By using blockchain, authorities and consumers can verify that e-waste is being processed in an environmentally responsible manner, thus mitigating the risk of informal sector involvement and improper disposal (Mishra et al., 2022).

In developing countries, blockchain can be a game-changer by facilitating partnerships between government entities, recycling companies, and consumers. Case studies from pilot projects in developing regions, such as India and Nigeria, illustrate how blockchain can strengthen waste management systems by improving data accuracy and enabling cross-border cooperation.

### *Challenges and Limitations of Implementing Industry 5.0 Solutions*

Despite the potential benefits, the adoption of Industry 5.0 technologies in developing countries like Cambodia faces several hurdles. Research by Kumar and Dixit (Dixit & Kumar, 2023) points out that the initial costs of implementing advanced technologies such as cobots and IoT infrastructure can be prohibitive. Additionally, there is often a lack of technical expertise required to operate and maintain these systems. These barriers necessitate the development of public-private partnerships, international funding, and capacity-building initiatives to facilitate technology transfer and local adaptation.

## Research Methodology

This study employs a qualitative approach, leveraging secondary data to explore the potential of Industry 5.0 solutions in transforming e-waste management practices in Cambodia. The methodology includes a process for data collection, and analysis, ensuring a comprehensive examination of the current landscape, technological possibilities, and policy implications.

### *Data Collection Strategy*

The research relies on the systematic collection of secondary data from diverse sources to build a robust foundation for analysis. The main data sources include:

- Government Reports and Policy Documents
- Non-Governmental Organization (NGO) Reports
- Academic Journals and Peer-Reviewed Articles
- Industry White Papers and Technical Reports
- Conference Proceedings and Expert Panel Discussions

### *Selection Criteria for Data Sources*

To ensure the credibility and relevance of the data, the following criteria were used to select the sources:

- Publication Date from 2014 onwards
- Geographic Focus on South East Asia
- Source Credibility

### *Analytical Framework*

The analysis was conducted using a thematic approach, which involved the following steps:

- **Data Extraction and Categorization**: Extracted data were organized into thematic categories aligned with the research questions. These categories included current e-waste management practices, challenges in implementation, potential Industry 5.0 applications (collaborative robots, IoT, blockchain), and policy frameworks.
- **Comparative Analysis**: A cross-country comparison was employed, using data from countries with successful Industry 5.0-driven e-waste management systems (e.g., South Korea, India, and Vietnam). This comparison provided insights into potential best practices that could be adapted to Cambodia.
- **Gap Analysis**: The collected data were examined to identify gaps in Cambodia's existing e-waste management practices. This analysis focused on infrastructure, policy, and public awareness levels, highlighting areas where Industry 5.0 technologies could be most impactful.

### *Limitations and Mitigation Measures*

- **Data Availability**: One limitation was the availability of specific, recent data on Cambodia's e-waste management. To mitigate this, supplementary data from regional and comparable international contexts were utilized.
- **Reliability of Sources**: Secondary data may vary in reliability. To address this, only well-documented and peer-reviewed sources were included.
- **Generalizability**: While this study focuses on Cambodia, findings may not be universally applicable to other developing countries without adjustments for context. Comparative insights were balanced to highlight what is specific to Cambodia and what might apply more broadly.

### Data Analysis

This section delves into the findings from secondary data sources regarding the current state of e-waste management in Cambodia, the challenges faced, and the potential of integrating Industry 5.0 technologies to bridge these gaps. Data from Cambodia is compared with case studies and best practices from other countries that have successfully adopted Industry 5.0 solutions.

### *Current E-Waste Management Practices*

In Cambodia, e-waste management is predominantly managed through informal channels, with independent recyclers playing a significant role. These informal processes often lack adequate protective measures, which results in unsafe working conditions and environmental contamination. Table 1 compares the state of e-waste management in Cambodia with that of more structured systems in countries like South Korea and Vietnam, which have implemented formal, technology-enhanced systems.

Table I Comparison of Current E-Waste Management Practices

| Feature | Cambodia | South Korea | Vietnam |
|---|---|---|---|
| Collection System | Informal, fragmented collection by independent recyclers | Formal collection system managed by public and private sectors | Mix of formal and informal systems, with growing investment in structured collection |
| Recycling Infrastructure | Limited, basic recycling techniques without advanced technology | Advanced facilities using automated sorting and recycling technologies | Improving facilities with a focus on automation and standardized practices |

| | | | |
|---|---|---|---|
| Protective Measures | Minimal safety protocols for workers | Comprehensive safety standards and worker training programs | Partial implementation of safety standards in the formal sector |
| Environmental Impact | High risk of pollution due to improper disposal | Low, due to stringent regulations and sustainable practices | Moderate, with ongoing efforts to reduce environmental harm |
| Public Awareness | Limited public awareness and engagement | High level of public knowledge and participation in recycling programs | Moderate, with national campaigns to raise awareness |

***Gaps and Challenges***

The analysis highlights several critical gaps in Cambodia's e-waste management:

- **Regulatory Weakness**: Cambodia lacks comprehensive legislation specifically targeting e-waste management. The existing environmental laws do not sufficiently cover the unique requirements for handling, processing, and recycling e-waste, leading to poor enforcement and widespread non-compliance.
- **Infrastructure Deficits**: The country has limited e-waste collection centers and few advanced recycling facilities. Informal recyclers rely on manual processes that are inefficient and hazardous, exacerbating environmental pollution and public health risks.
- **Awareness and Education**: The general population and informal recyclers have limited knowledge regarding the hazards associated with improper e-waste disposal. Public awareness campaigns are scarce, leading to low participation in formal recycling initiatives.

Table Ii Gaps In Current E-Waste Management In Cambodia

| Gap | Description |
|---|---|
| Regulatory Framework | Absence of specific and enforceable e-waste laws |
| Infrastructure | Few advanced recycling facilities and collection points |

| | |
|---|---|
| Education and Awareness | Lack of public education and training for waste handlers |
| Safety Protocols | Minimal adherence to worker safety and environmental standards |

### *Potential of Industry 5.0 Solutions*

Integrating Industry 5.0 solutions could help address the identified gaps by leveraging advanced technologies to enhance sustainability and efficiency in e-waste management. The following subsections detail the potential impacts of these technologies.

- **Collaborative Robots (Cobots)**

Cobots can play a crucial role in automating the dismantling and sorting of e-waste. This automation reduces manual handling of hazardous materials, improving safety and operational efficiency. Case studies from other developing nations show that cobots can increase material recovery rates by precisely dismantling components for recycling.

- **IoT Applications**

IoT can be used to create a network of sensors and devices that monitor and track e-waste collection, processing, and recycling. Real-time data collection ensures transparency and allows for optimized logistics, leading to more efficient waste management practices.

- **Blockchain Technology**

Blockchain enhances transparency and traceability across the e-waste supply chain. Each stage of the recycling process can be recorded on an immutable ledger, ensuring compliance with environmental regulations and promoting public trust.

Table III Potential Benefits Of Industry 5.0 Solutions

| **Technology** | **Potential Benefits** | **Example Implementation** |
|---|---|---|
| Collaborative Robots (Cobots) | Improved recycling efficiency, reduced exposure to hazardous materials | India's pilot program showing a 25% increase in recovery rates |
| IoT Applications | Optimized logistics, real-time monitoring, and efficient | South Korea's IoT-enabled bins reducing collection costs by 15% |

| | | |
|---|---|---|
| | resource allocation | |
| Blockchain Technology | Enhanced transparency and traceability, better regulatory compliance | Nigeria's pilot projects showing a reduction in illegal dumping |

The secondary data analysis reveals significant deficiencies in Cambodia's current e-waste management system, including a lack of regulations, insufficient infrastructure, and low public awareness. However, integrating Industry 5.0 technologies like collaborative robots, IoT, and blockchain can provide innovative solutions to these challenges.

## Results and Discussion

This section discusses the findings and interprets their implications, drawing from successful examples in other developing countries.

### *Addressing Gaps Through Industry 5.0 Integration*

The results suggest that adopting Industry 5.0 solutions could effectively bridge the gaps identified in Cambodia's e-waste management. Collaborative robots can play a pivotal role by automating the labor-intensive and potentially hazardous dismantling of electronic waste. This would reduce the reliance on informal sectors and increase recycling efficiency. The experience of India, where cobots improved material recovery rates by 25%, provides a compelling case for their implementation in Cambodia.

IoT technology, when integrated into waste collection systems, can optimize logistics and reduce operational costs. Cambodia's current practice of irregular collection and unmonitored disposal could benefit from IoT-enabled tracking systems that provide real-time data, ensuring timely collection and processing.

The success of IoT in South Korea, which reduced collection costs by 15%, indicates that similar results could be expected in Cambodia with proper implementation.

### *Policy and Strategic Recommendations*

The successful adoption of Industry 5.0-driven solutions in Cambodia will require coordinated efforts between the government, private sector, and international stakeholders. Policies must focus on:

- **Developing Specific E-Waste Legislation**: Comprehensive laws that mandate responsible collection, processing, and disposal of e-waste.
- **Building Recycling Infrastructure**: Investment in formal recycling centers equipped with Industry 5.0 technologies, potentially supported by public-private partnerships.

- **Public Education Campaigns**: Initiatives to raise awareness about the environmental and health hazards of improper e-waste disposal and the importance of participating in formal recycling programs.

***Comparative Insights and Implications for Cambodia***

The comparative data indicate that while South Korea's and Vietnam's structured approaches provide high benchmarks, incremental steps tailored to Cambodia's context can yield significant improvements. Cambodia's e-waste management system can advance through strategic adoption of cobots, IoT, and blockchain, paired with policy reforms and capacity-building measures.

## Conclusion

In conclusion, Cambodia's current e-waste management practices face significant challenges, including regulatory weaknesses, insufficient infrastructure, and low public awareness. However, the integration of Industry 5.0 technologies—such as collaborative robots, IoT, and blockchain—presents viable solutions for transforming these practices into a more efficient, safe, and transparent system. Drawing on successful examples from countries like South Korea, Vietnam, and Thailand, Cambodia can address these challenges through targeted investment, policy reform, and capacity building. Implementing these advanced solutions, supported by strategic collaboration among stakeholders, will enable Cambodia to foster a sustainable, human-centric approach to e-waste management that aligns with its broasder environmental and public health goals.

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