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Electronic Waste Management: Fourth Industrial Revolution Technology Advancements and Opportunities

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Abstract: This paper examines the application of Fourth Industrial Revolution (4IR) technologies in electronic waste management. The rapid expansion of the technology sector and the increase in demand for electronic devices, which as a result produced millions of tons of discarded electronic waste. Traditional disposal methods have become unsustainable and environmentally harmful. The integration of 4IR technologies such as blockchain, artificial intelligence, Internet of Things (IoT), and big data can significantly improve the entire process of e-waste management, from collection and sorting to recycling. However, there is limited research that explores the application of 4IR technologies in e-waste management. This paper provides a comprehensive mapping of previous studies that have applied advanced ICT solutions and analyzes the advantages and challenges associated with these approaches. Furthermore, the paper proposes a recommended solution for e-waste management using 4IR technologies, emphasizing the importance of implementing a safe and intelligent e-waste collection method. The research showcases the potential of 4IR technologies to revolutionize e-waste management and contribute to a more sustainable future. The study examines prior work on the implementation of 4IR technologies in e-waste management and describes the current state of each technology in the context of e-waste management. The results of this mapping study showcase the potential of 4IR technologies in sustainable e-waste management.

Keywords: E-Waste, 4IR, Blockchain, IoT, Artificial intelligence, deep learning, big data

1. Introduction

E-waste, or Waste Electrical and Electronic Equipment (WEEE), refers to the discarded devices containing circuits, electronic components, and electrical parts. This encompasses a wide range of items, from household appliances to ICT equipment and even devices used in sectors like health and security. E-waste management involves handling, disposing, and recycling these items, which includes collection, transportation, sorting, and dismantling. It plays an essential role in protecting the environment by preventing the release of toxic metals, reducing greenhouse emissions, conserving resources, establishing a secondary source of raw materials, and promoting health and safety.

The Global E-waste Monitor reports that in 2019, a staggering 53.6 million tons of e-waste was generated worldwide, with only 17.4% being documented, collected, and properly recycled [1]. E-waste components contain hazardous metals, acids, non-degradable plastics, and toxic chemicals such as mercury, lead, cadmium, and others. Improper disposal of e-waste has harmful impacts on both human health and the environment. According to the global monitoring report, a total of 50 tons of mercury and 71 kilotons of Brominated Flame Retardant (BFR) plastics were discovered in e-waste. The presence of such a massive amount of mercury can lead to the destruction of the genitourinary, central, and peripheral nervous systems. On the other hand, e-waste also contains valuable and precious metals like gold, copper, silver, iron, and other secondary raw materials. In 2019, the estimated value of raw materials worldwide generated from e-waste reached $57 billion USD, with $10 billion USD being recovered from the 17% of recycled e-waste

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[1]. By extracting these valuable materials from e-waste, substantial profits can be generated, highlighting e-waste as a significant source of secondary raw materials.

Most of the e-waste is disposed of in landfills alongside other types of waste, creating several risks associated with toxic metals, complex structures, and chemical reactions with environmental factors. The manual handling of e-waste further increases the risks of diffusing and exposing toxic substances. To address this problem, new technological advancements have been utilized to provide safe and effective management, particularly within the context of the Fourth Industrial Revolution (4IR). The 4IR refers to the current and upcoming advancements in technologies such as Artificial Intelligence (AI), Internet of Things (IoT), Big Data, and blockchain [2]. These technologies offer numerous solutions to the challenges faced by developing countries in the field of e-waste management, including unknown quantities of e-waste, a lack of technological advancements, and insufficient safety and health awareness.

This paper aims to provide a comprehensive review of studies conducted between 2018 and 2023 that utilized the 4IR technologies in e-waste management. Some technologies, such as IoT and AI, have already been applied to e-waste management, while blockchain is still under investigation. A review of papers on AI technology in e-waste management revealed that deep learning and IoT were the major fields explored in the studies collected between 2015 and 2020 [3]. Furthermore, recent papers published in the past five years extensively examined the 4IR technologies in e-waste management and highlighted the additional benefits they bring to the field. These benefits include: (a) increasing the recycling rate, (b) enhancing the efficiency of e-waste treatment in terms of processing speed, (c) ensuring safe and healthy disposal practices, (d) improving transparency in tracking the amount of e-waste generated, and (e) facilitating better decision-making using data analytics tools for production, disposal, and recycling processes.

We reviewed existing literature on 4IR technologies in e-waste management. To access various research sources, we used Google scholar, and focused on English-language journals published from 2018 to 2023. Our screening process used keywords, titles, and abstracts to ensure relevance and accuracy. Furthermore, we analyzed the methodologies employed in each paper to gain deeper insights. A data extraction table is created to compare the papers in terms of technology, functionality, and development methodology. The analysis findings indicate that various technologies offer different functionalities. For instance, AI and deep learning can be used for e-waste classification, IoT enables real-time e-waste monitoring, blockchain facilitates tracking and tracing, and big data allows for data analysis and storage. The paper highlights the potential of these technologies in improving e-waste management through automation, efficient data management, and remote monitoring. The study concludes with suggestions for future improvements in implementing 4IR technologies in e-waste management.

This paper is arranged into six sections. Section 1 described a review on previous relevant contribution, section 2 presents the overall methodology and approaches, section 3 presents the current state of E-waste management, section 4 explained advance computer technologies in E-waste management in depth, section 5 represent discussion along with future recommendation. Finally, section 6 illustrates the conclusion of the work.

2. RSEARCH BACKGROUND

According to the global E-waste monitor, it is expected that the amount of E-waste will increase up to 74.7 million tons in 2030 [1]. Fig. 1 represent the e-waste generation estimation, there is gradual increase in e-waste for the next years which cause huge amount of e-waste disposed. The poor management of E-waste generates several issues, including the harmful effects of hazardous substances on the environment if not properly handled, as well as the wastage of a significant amount of secondary raw materials. Therefore, proper E-waste management becomes necessary, especially with the rapid advancement of technology and the emergence of 4IR. 4IR technologies include AI, IoT, Blockchain, and Big data. AI is utilized to simulate human thinking and learning, enabling machines to think, learn, decide, and act with minimal or no human interaction, which is already being used in waste classification. The IoT technology connects devices into one network, where connected devices can function as sensors, embedded together to communicate, and exchange data with each other via the internet. Implementing IoT in any waste management will enhance tracking and monitoring of the waste to ensure safe disposal, collect and analyze the data on E-waste generation, disposal, and recycling. Big data technology can also play a significant role in E-waste management by providing the insights needed to make better decisions on handling E-waste. It also helps to create a predictive model that can forecast the amount of E-waste. On other hand blockchain technology is a novel topic in E-waste management. A study [4] suggested that blockchain can be used for tracking and tracing of waste. It can control the cycle of E-waste treatment starting from production, distributed, stored, disposed, processed, and recovered, each phase is stored on blockchain network.

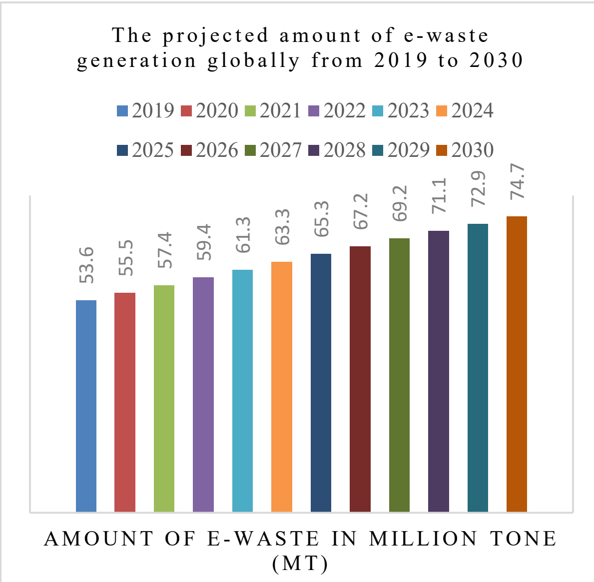

Figure 1. Projection of E-waste generation from 2019 to 2030

A. Current State and Case Studies

As mentioned previously, E-waste contains both toxic substances and valuable metal. By extracting the precious material, a hug profit can be produced. According to E-waste global monitor $ 57 million USD generated in 2019 from extracting E-waste's metals like gold, copper, and aluminum [1] listed in Table I. Hence, E-waste can be considered as a secondary raw material source.

TABLE I. METAL ESTIMATION

Metal	Kilo ton (Kt)	Mill.USD
Silver (Ag)	1.2	579
Aluminum (Al)	3046	6062
Gold (Au)	0.2	9481
Cobalt (Co)	13	1036
Antimony (Sb)	76	644
Copper (Cu)	1808	10960
Bismuth (Br)	0.1	1.3
Iridium (Ir)	0.001	5
Iron (Fe)	204666	24645
Palladium (Pd)	0.1	3532
Platinum (Pt)	0.002	71
Rhodium (Rh)	0.01	320
Indium (In)	0.2	17
germanium	0.01	0.4
Total		$ 57 million USD

By leveraging 4IR technologies, e-waste management can become more efficient, transparent, and sustainable. These opportunities offer the potential to add remote, real-time monitoring. The IoT sensors and devices can be deployed to check real time factors such as temperature and humidity and monitors collection point and disposal sites. The big data enables analysis of large amounts of data used to give insight of disposal pattern, recycling rate. Blockchain can enhance transparency, traceability, it tracks the movement of E-waste ensuring proper disposal and enable secure data management. On other hand, AI improves efficiency of sorting and recycling process by using e-waste classification and reduces human interaction.

- TOMRA E-scrap is hardware machine used in recycling companies utilizes artificial intelligence sorting machines to extract valuable metals from electronic waste. TOMRA uses 4 different technologies: (1) Ultra-High Resolution near infrared spectrometer, (2) Camera detection, (3) High resolution metal sensors, (4) Deep Laser object detection with AI (artificial intelligence). By employing an intelligent sensor-based sorting system, the machine effectively identifies metal objects within the e-waste, guaranteeing a high level of precision. This machine is specifically designed for the processing of complex electronic waste and metal materials. In terms of 4IR, the system integrates two primary technologies, namely artificial intelligence for object detection and IoT for sensor functionality [5].
- Evreka is a unified platform that facilitates the digitization and monitoring of the complete e-waste management and recycling process by leveraging advanced technologies like IoT, sensors, and tracking systems. This innovative solution is tailored for recycling organizations and has already been implemented in Singapore as part of their smart city initiative by ALBA, one of the leading companies in waste management. 300 fill level sensors are used for e-waste bins, these sensors monitor real-time parameters like temperature, bin fullness and location. The Evreka platform helps to monitor and track the 300-e-waste bin using a single platform

B. Related Work

One previous review [3] collected 50 papers published between 2015 and 2020 to study the various AI techniques used to segregate e-waste. Out of the 50 papers, only 28 were relevant to e-waste management. Through data extraction, it was found that AI was not only used for segregation but also for the collection and recycling phases. The author analyzed various AI algorithms and found that deep learning and IoT are the major fields in which AI is applied. Another interesting finding is that AI was mostly implemented in all processes of e-waste management, followed by the e-waste collection process. One drawback of this paper is its narrow focus only on studying the AI field within e-waste management.

Another research review [6] conducted in China examined the potential of smart technologies and their applications in e-waste management. The study focused on internet-based systems, IoT, Big data, cloud computing, and AI, all of which can facilitate specific processes in e-waste management. The review analyzed various smart collection systems for e-waste using the Internet and IoT, which can be employed for data collection and optimizing waste collection routes. The findings clearly indicate that smart collection systems ensure the convenience of e-waste recycling and collection. Additionally, the review summarized the main barriers and challenges in implementing smart e-waste management, which can be categorized into three areas: consumer, platform, and government. Consumer-related challenges include a lack of awareness and knowledge, while government-related challenges involve the absence of appropriate taxation, guidelines, and promotion. Platform-related challenges encompass the absence of a viable business model and high operational costs. However, in summary the previous work does not provide clear detailed data on the advanced technologies and their methodologies.

The paper [25] studies various technologies such as IoT, AI, and QR code, to facilitate the process of e-waste sorting. The author has conducted literature reviews of 10 papers for almost the last 10 years. The paper concluded with a proposed structure or system that explains how those technologies can be implemented in one system. Another paper [14] specifically studies blockchain technology and its potential implementation in e-waste management. The author suggests that tracking and tracing is the best solution that can be used in e-waste management and recycling.

The objectives of this mapping review are to identify and summarize the current state of research on E-waste management using advanced technologies such as 4IR. This research questions are: (1) what are the potential opportunities and challenges of integrating 4IR into E-waste management? (2) how can 4IR be used to improve E-waste management? (3) what is the current state of research on 4IR technologies on E-waste management?

3. Research Design

This study is a mapping review based on previous research, which includes experimental studies and review papers. A data extraction form was designed based on each paper's abstract. The most relevant data extracted from each paper is the publication year, publisher, technology employed, and purpose of the technology.

We conducted an extensive review of existing literature to identify previous studies that focused on 4IR technologies in e-waste management. To access a diverse range of research sources, we utilized multiple databases. Our search was limited to English-language journals published from 2018 to 2023, allowing us to examine advancements made over the past five years. Our journal screening process relied on keywords, title, and abstract to ensure relevancy and accuracy. However, additional examination of the content was carried out to analyze the methodologies employed in each paper. The search study utilized a combination of keywords and subject headings (E-waste management) terms related to 4IR technologies. The following search strings were used: E- waste management AND (AI |Deep learning | Machine learning), E- waste management AND (Big data | Data analysis), E- waste management AND (IoT| Internet of thing), E- waste management AND Blockchain.

Additional search parameters were considered to narrow down the selection of articles to relevant research studies. To ensure a diverse range of results, the option of word occurrence was chosen to include instances of the keywords anywhere within the articles. The Table II shows the advance research parameters applied in google scholar.

TABLE II. SEARCH PARAMETERS OPTIONS

With all the words	Big data in management "E waste electronic waste" Artificial intelligence in management "E waste electronic waste" Internet of Thing management "E waste electronic waste" Cloud management "E waste electronic waste"
with the exact phrase	E-waste, electronic waste
with at least one of the words	Big data, AI, Artificial intelligence, IoT, Internet of Thing management

To ensure precise and pertinent results, we adhered to specific inclusion and criteria when selecting articles. The criteria employed are outlined below.

Inclusion criteria:

- Studies published in English language.
- Studies relevant to electronic waste type
- Studies employ AI, IoT, Big data, Cloud.

After conducting search across multiple database and journal sources (IEEE, google scholar), a total of 202 paper potentially relevant articles were identified as initial step. During the title, key words, and abstract screening phase, 90 papers were included as they matched the inclusion criteria. Further screening conducted based on text reading 33 papers were mostly relevant to e-waste management. However, after carefully reviewing each paper, 4 studies were excluded for reasons such as irrelevance research questions or insufficient data. The remaining 25 articles were considered eligible for inclusion in this review and formed the final set of papers to be analyzed in detail.

The Table III shows the progression of articles published in e-waste management using 4IR technologies.

A noticeable trend emerged after 2020, indicating a significant increase in the integration of technology in e-waste management. This shift can be attributed to the rapid advancements in 4IR technologies, growing awareness of e-waste management, and the high demand and consumption of electrical and electronic devices.

TABLE III. NUMBER OF PUBLISHED PAPERS BY YEAR

Year	Number of published papers	Ref.
2018	2	[7] [8]
2019	1	[9]
2020	7	[10] [11] [12] [13] [15]
2021	8	[16] [17] [18] [19] [20] [21] [22] [23]
2022	7	[4] [24] [26] [27] [28]
2023	4	[29] [30] [31] [32]

4. TECHNICAL ADVANCEMENT IN ELECTRONIC WASTE MANAGEMENT

In this section, the results of the review are presented. It includes the data extraction form and the summary of key findings. Data extraction involves the extraction of relevant information from the selected articles. Standard data extraction form developed to summarize the key details from each article. The extracted data included study characteristics (e.g., title, year of publication, technology field, and purpose of the study). The information taken from the title and abstract of the study. Additional information such as methodology and study limitations were recorded after the full review of the content. The total number of primary research found on google scholar was 50 papers, after review and selecting the relevant we have analyzed is 29 papers for this study. Table IV present the data extraction form of the final 29 selected papers. The sources of the papers are taken from popular scientific publishers such as (Elsevier, IEEE, IJERT, Springer, SAGE Publications, IJSDR, IRJET, Cybernetics and Systems, Association for Computing Machinery, VIVA, and Emerald). Most research papers used for this study have been published on IEEE

Table V shows further analyzes the methodologies and tools used by each technology. As shown CNN deep learning is a widely discussed algorithm, followed by sensors as a hardware implementation.

TABLE IV. DATA EXTRACTION FORM OF THE REVIEWED PAPERS

Ref.	Technology	Functionality	Software development	Hardware development
[17]	AI	Classification	Simulation	NA
[16]	AI	Detection	Simulation	NA
[26]	AI	Classification	Simulation	NA
[28]	AI	Classification	NA	Mobile robot
[12]	AI	Classification	Mobile app server	NA
[19]	AI, IoT	Detection, monitoring	Website server	Sensor, bin
[3]	AI	Classification	NA	NA
[30]	AI, IoT, Cloud	Classification, cloud storage, data collection		IoT nodes
[31]	AI, IoT, Cloud	Monitoring, cloud database, classification	Mobile app server	NA
[23]	IoT	Data collection, monitoring	Mobile app server	E-bin
[24]	IoT	Monitoring,	Mobile app server	E-bin
[4]	IoT, Blockchain, Cloud	Tracking and Tracing, Monitoring, Cloud data server	NA	e-bin
[11]	IoT	Collection, monitoring	Mobile app server	E-bin
[18]	AI	Classification	NA	e-bin, sensor
[29]	AI	Classification	Simulation	---
[15]	IoT	Collection, Monitoring	Mobile app server	Sensors, e-bin
[10]	Blockchain	Tracking	Simulation	
[6]	IoT, Big data, cloud, AI	Collection, monitoring	NA	NA
[25]	AI, IoT	Classification, monitoring	NA	---
[27]	AI	Detection	NA	NA
[7]	Cloud, IoT	Detection, storage server	Mobile app server	NA
[32]	AI	Classification	NA	NA
[22]	Big data	Predictive analysis	simulation	NA
[9]	Big data, cloud	Tracking	Simulation	
[13]	AI	Collection	Mobile app server	vehicle model
[14]	Blockchain	Tracking	NA	NA
[20]	AI	Prediction	NA	NA
[21]	Blockchain	Storage	NA	NA
[8]	Blockchain	Tracking and tracing	NA	NA

TABLE V. TECHNOLOGIES ADOPTED BY THE REVIEWED PAPERS

Technology	Methodology/ tools/algorithm
AI	Transfer learning [17] [16] CNN approach [26] [28] [12] [16] [19] [31] [30] Machine learning [20] [18]
IoT	Sensors [23] [24] [4] [11] [18] [29] [15] Web application/ mobile application [26] [11] [15]
Big data	Database server [31] [30] Computing server [11]
Blockchain	IPFS (distributed storage system) [4] Smart contract [8] [10]

A notable finding, fig. 2 represents chart distribution of advanced technologies, the data collected from reviewed research papers. The chart is divided into 4 segments, each representing a different technology. The largest segment, comprising 43% of the chart, represents artificial intelligence technology. This technology is a widely discussed topic in waste management, where mostly used for e-waste detection and recognition. Internet of thing follows at 27%. Usually, IoT integrated with AI. Including big data and cloud, make up 15% of the chart. The remaining is blockchain 15%. This chart reveals a significant reliance on advanced technologies for e-waste management with AI and IoT being primary contributors. The information highlights the potential for increasing the use of 4IR technologies to enhance e-waste management.

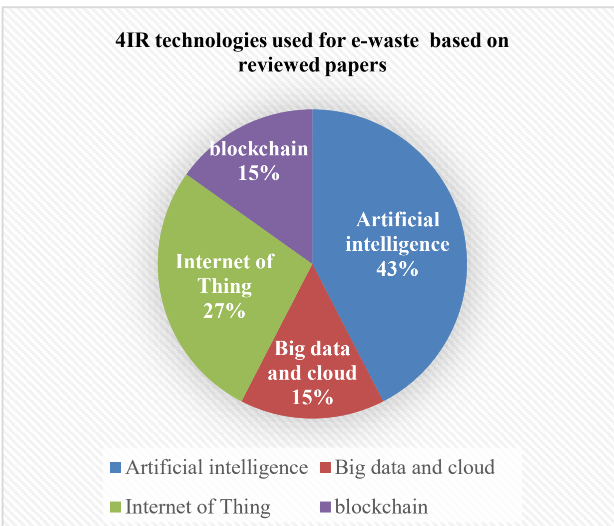

Figure 2. 4IR technologies chart distribution in E-waste management

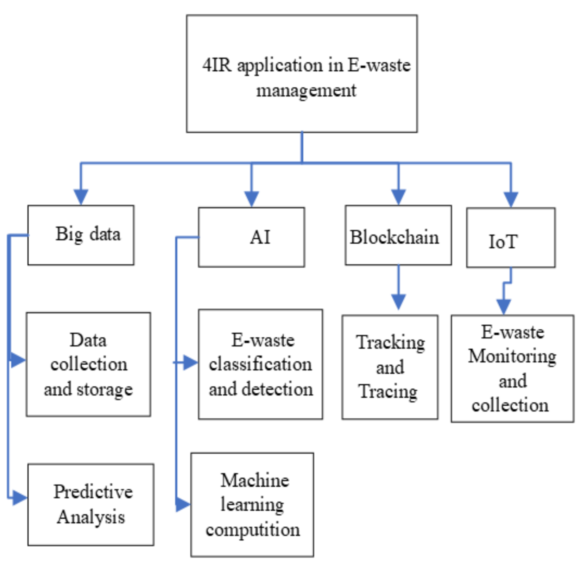

Figure 3. 4IR applications in E-waste management

The integration of 4IR technologies has enabled innovative approaches to e-waste-related challenges. Several fields of E-waste management applied using 4IR technologies, fig. 3 represent a summary diagram of those application. According to the study observation CNN deep learning classification approaches are the major field used by AI.

A. Artificial Intelligence

- E-waste classification and detection: AI algorithms can analyze data from images/videos and extract valuable information using cameras. E-waste classification is an automated sorting system that identifies and classifies different types of e-waste. In E-waste management several Convolutional Neural Network CNN-deep learning models are used for classification, such as (SSD) Single-Shot MultiBox Detector in [19]. The paper [5] introduced a comparative analysis of two deep learning approaches for classifying e-waste components. The study revealed that the You Only Look Once (YOLO) method achieved superior results compared to RetinaNet50. However, a separate study [6] reported that ResNet50 outperformed VGG16 in terms of accuracy for e-waste classification. On other hand, some paper had implemented a detection system to identify the area covered by e-waste as paper [7] introduced.

- Machine learning prediction: On the other hand, machine learning is a subset of AI which provides a powerful computation and prediction algorithm. The goal of the paper [32] is to predict the level of toxicity in discarded e-waste and the future usage of e-waste generation. The paper proposed a prediction technique to predict certain e-waste using Hybrid Neural Networks algorithm. A hybrid system refers to any system combining two or more advanced technologies. The proposed model performs prediction of e-waste generation and a prediction of the re-usable components through old samples and using machine learning methodology called Fusion-based Real-Time Analytical framework.

B. IoT

- E-waste monitoring and data collection: IoT monitoring enables more efficient management processes through the integration of smart devices and sensors. The papers [23] [24] [4] [11] [18] [29] [15] implemented smart sensors in IoT to collect data of various parameters such as temperature, power level, location, and humidity. This information is essential for ensuring a safe environment and to identify any potential hazards associated with E-waste management. The IoT system provides remote real-time monitoring which allows seamless and continues data collection, hence IoT can be used also for tracing e-waste. Additionally, several papers such as [26] [11] [15] support IoT system with web/mobile application to facilitate the process of e-waste collection in collection points. The mobile application gives the users a dashboard to check the management process, collection scheduling time, notification on health condition of each collection point. Besides, the application allows the user to track the journey of the disposed devices.

C. Blockchain

- Tracking and Tracing: Blockchain has been suggested as a potential solution for implementing traceability by generating an audit history as ensuring data integrity and security. Traceability based on blockchain allows secure information to be shared and enhances E-waste control and monitoring process. The paper [4] introduced a traceability system using smart contracts, aimed to track and trace the electronic device from the time its manufacturer to the disposal. Smart contract is a program that that runs on blockchain when predefined conditions are met, usually used for self-execution of an agreement. As known E-waste moves through various stages like sorting, recycling and disposal, the smart contract based blockchain track and record the E-waste current statue, location, date and tracks the amount of toxicity in E-waste. Another paper [10] presented similar idea in tracking the process of a product till disposal.

D. Big data

- Data collection and storage: The management of large amounts of data requires the utilization of large storage databases. Consequently, cloud storage serves an essential function in e-waste management as it offers storage of collected data and information which is related to e-waste. The paper [7] proposed system aims to analyze images captured from e-waste dumping sites to determine the area occupied by e-waste. Many images are accessed using DROPBOX server system. The result images transferred to the server system's Dropbox folder, along with the corresponding date and time, enabling regular monitoring of e-waste disposal. The paper clearly mentioned that files can be accessed through the Android application on a smartphone by using the same Dropbox account as the server system allowing the users to access the system easily. In addition, the papers [30] [31] implemented cloud database within the system to store images and results.
- Predictive analysis: Big data is used for complex systems where large amounts of data are collected, organized, stored, and processed. Big data supports all types of data to get insight through horizontal and vertical analysis of E-waste data. In E-waste management, the paper [22] proposed prediction model that predicts the amount of e-waste produced. The process involved several steps. Firstly, data is collected to identify and gather details of expired devices. These gadgets are categorized based on their field of use during the period of expiration proposed a big data system that is used to analyze the expired electronic devices and predict the amount of waste produced using predictive analysis.

5. Discussion and Recommendations

The finding from reviewed works provides valuable insights into the effectiveness of advanced technologies in E-waste management. A comparison between related researches has been summarized in Table VI. This work covers the gap in previous studies by analyzing the implementation of 4IR technologies in e-waste management. The opportunities of 4IR technologies in e-waste management and recommendations are presented in this section based on the technologies: i) artificial intelligence, (ii) IoT, (iii) blockchain, and (iv) big data.

TABLE VI. COMPARISON BETWEEN RELATED WORK AND PROPOSED WORK

Ref.	No of Papers	Coverage	Methodology	Technology
[3]	28	2015-2020	Mapping review	AI
[6]	13	China, 2016- 2020	Mapping review	Big data, Cloud AI IoT
[25]	10	2010-2021	Literature review	AI Blockchain GIS QR code IoT and sensors
[14]	NA	Not specified	Scoping review	Blockchain
This work	25	2018-2023	Mapping review	AI Big data and cloud Blockchain IoT

Deep analysis conducted to study how exactly 4IR provides solutions to enhance e-waste management. Fig. 4 describes the extent to which 4IR applications are utilized in different areas of e-waste management. The studies have demonstrated that classification offers an intelligent approach to categorize and classify e-waste with minimal human involvement, ensuring safe management practices. Various algorithms are employed for classification, with the CNN deep learning method being widely utilized. Beside classification, AI can also provide a mechanism to predict e-waste as [20] proposed. AI offers powerful computational algorithms that can provide additional solutions beyond classification and detection in e-waste management. For instance, AI can identify defective components or materials in e-waste devices, a concept that has not been previously explored in existing literature.

The second widely employed approach is e-waste monitoring, which commonly utilizes the Internet of Things (IoT) and connected devices equipped with sensors. The integration of IoT offers numerous advantages in enhancing e-waste management, particularly in terms of data collection. This process plays an important role in e-waste monitoring. Many studies focusing on monitoring have extensively used IoT nodes and sensors to collect various data points such as temperature, fill level, and power consumption. The monitoring process has demonstrated clear benefits in enabling real-time tracking of the e-waste management condition and system health. Furthermore, IoT can be expanded to provide additional solutions beyond data collection and monitoring. For instance, it can enable remote diagnostics and troubleshooting of e-waste systems by leveraging the collected data to identify potential issues, thereby reducing the need for physical inspections.

As per explored research papers, blockchain implementation in e-waste management provides auditing features, few papers have only considered e-waste tracking using blockchain. The paper [8] [10] has effectively highlighted the advantages of utilizing smart contract algorithms to track and trace electronic waste throughout its lifecycle, from manufacturing to disposal. This approach offers two key advantages that are not provided by other technologies: transparency and security. The paper [4] highlighted how blockchain can be also used for storage, IPFS is a blockchain-based storage database that provides a secure storage system which can store huge files related to e-waste manufacturing, disposal, and recycling. However, further research is required to explore the integration of blockchain in e-waste management and its algorithms in which can enhance the process of recycling.

In E-waste management large amounts of data related to e-waste are handled with their components and recycling process. Big data technologies provide the capability to collect, store, and manage large volumes of data efficiently. Additionally, cloud computing provides scalable and adaptable storage solutions to meet the increasing data requirements of e-waste management. The combination of big data and cloud computing enables predictive analytics, which aids in forecasting future e-waste trends and behaviors. Through analyzing old samples data and patterns, predictive models can estimate e-waste generation, identify recycling opportunities, and forecast demand for recycled materials. Overall, the technical advancements of big data and cloud computing have had a significant impact on e-waste management by enabling better data management, analysis, and scalability.

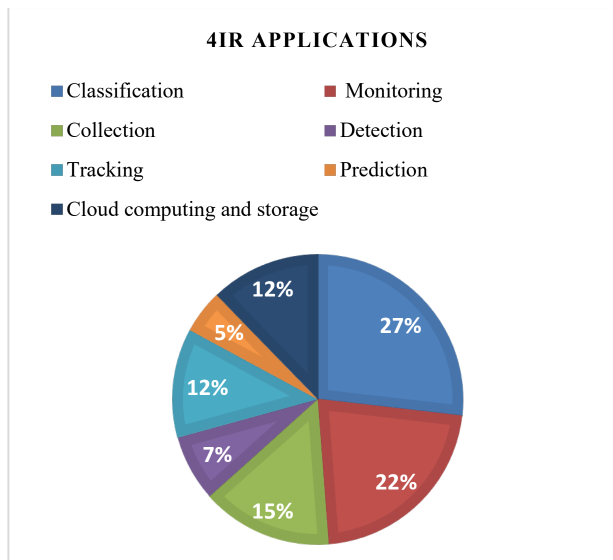

Figure 4. E-waste fields in which 4IR technologies are implemented

The literature studies present valuable insight into the current state of e-waste management, several solutions and systems have been introduced to enhance e-waste management. However, it's important to acknowledge some of the gaps in literature. In the previous literature, none of the papers studied the integration of 4IR technologies in e-waste management. Thus, the goal of this work was to study the advancement of 4IR technologies, highlighting the important trends and providing comprehensive analysis of the literature. As per finding, integration Ai, IoT, Big data, and Blockchain can improve higher efficiency, transparency, security, real-time control, and monitoring. Table VII presents a summary of the key benefits observed in using 4IR technologies in e-waste management. Future research should address all limitations by integrating 4IR technologies in e-waste management system in real time sample size.

TABLE VII. BENEFITS OF 4IR TECHNOLOGIES

Technology	Key Advantages	Description
AI	Automation	▪ Provide streamlined and scale decision making. ▪ Automation in this case speeds up the process of classification, reducing the risk. ▪ Reduce human interaction.
Blockchain	Data Security and privacy Transparency	▪ The sensitive information in blockchain is encrypted and prevents unauthorized activities. ▪ Create an audit trail that records the location of e-waste at every step on its journey.
IoT	Real time monitoring and control.	▪ Deliver continuously updated data of the process or system.
Big data and cloud	Scalability and Cost-Effectiveness	▪ Handle large amount of data. ▪ Reduce the cost of hardware storage

After conducting a literature analysis, we have discovered an interesting proposal to address the challenges of integrating all 4IR technologies. The solution involves the development of e-waste smart bins as the papers [19] [23] [4] [11] [18] [15] proposed. Smart bins offer a practical solution for enhancing e-waste management, it allows an implementation of AI for e-waste classification, IoT and sensors for real-time monitoring, big data for storage and computing on a server, Blockchain for tracking and tracing. However, a notable observation is that most of the research studies do not explicitly address the safety procedure of handling of different types of e-waste. Given the diverse structures, sizes, and compositions of e-waste, it can be hazardous to handle all these types in the same bin. Considering these findings, future work objectives should involve the integration of various 4IR technologies into a single system, aiming to establish an efficient e-waste management system. This system should consider the specific type of e-waste it targets and incorporate appropriate safety protocols that need to be implemented and verified.

6. Discussion and Recommendations

This review paper provides a comprehensive overview of the current state of research on the topic of "4IR in E-waste management: opportunities and challenges." Through an extensive analysis of the literature, we have identified key themes, trends, and gaps in the existing studies related to the integration of Fourth Industrial Revolution (4IR) technologies in the management of electronic waste. The review findings indicate that 4IR technologies, such as artificial intelligence (AI), big data and cloud computing, Internet of Things (IoT), and blockchain, have great potential to transform different aspects of e-waste management. AI-driven solutions offer efficient sorting and recycling processes, while big data analytics enable data-driven decision-making and resource optimization. IoT-based systems provide real-time monitoring and tracking of e-waste management processes. The blockchain enhances traceability and transparency throughout the lifecycle. Moreover, cloud computing offers scalable and accessible platforms for data storage and collaboration among stakeholders. However, the review has also highlighted certain challenges and limitations in the current literature. There is lack of review papers that highlight the current state and challenges of integrating 4IR technologies in e-waste management, some have small sample sizes, which may impact the reliability and generalizability of the findings. Additionally, there is a need for further research in specific areas, such as the long-term effects of 4IR interventions on e-waste management and the socio-economic implications of these technologies. In conclusion, this mapping review offers valuable insights into the field, laying the foundation for future research and guiding the development of effective waste management using 4IR technologies. By building upon existing knowledge and addressing the identified gaps, we can collectively strive for a more sustainable and circular approach to e-waste management in the digital age.

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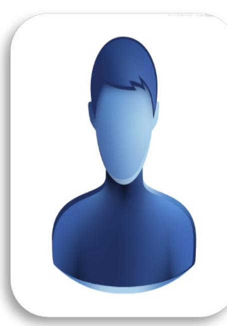

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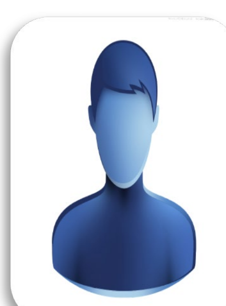

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