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EXPLORING DIGITAL TECHNOLOGIES AND SMART SYSTEMS USED IN E-WASTE MANAGEMENT IN CHINA: SEMINAL RESEARCH THEMES

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Due to the dramatic increase in the volume of e-waste and its complex composition, containing hazardous components, improper e-waste management poses significant risks to the environment, human health, and socio-economic sustainability. The application of intellectual technologies has given new opportunities for more effective e-waste management. This research aims at providing a comprehensive landscape of the body of research on smart e-waste management in China through a systematic literature review accompanied by content analysis. On this basis, the seminal research themes of the advanced digital technologies used in e-waste management literature were unfolded and discussed. The most recent developments of smart e-waste collection and sorting initiatives in China, which have been implemented and scaled up through local businesses and entrepreneurship programs as alternatives to informal approaches, were presented. It turns out that the results highlight the potential of smart technologies in e-waste management through (i) delivering the most recent academic research on smart e-waste recycling, (ii) showcasing cutting-edge smart e-waste recycling solutions, primarily from business and emerging technology firms, (iii) enhancing academic debate and bridging the gap between industry practitioners and the research community, (iv) identifying the main challenges and provide countermeasures for future smart e-waste management.

Key words: *E-Waste, Digital Technologies, Smart System, E-Waste Management, Smart E-Waste Collection, Circular Economy.*

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Formulation of the problem in general terms. With the development of the electronic industry, various types of electronic products convenient for life were produced. Due to technological progress and the inexpensive of electronic products, the use of electronic products has increased significantly. Meanwhile, Waste Electrical and Electronic Equipment (WEEE), always known as e-waste, has been becoming one of the world's fastest-growing waste sources [1]. It was estimated that close to 50 Mt of WEEE is generated annually worldwide [2]. According to calculations, more than 5 Mt of e-waste is produced in the United States per year. The European Union (EU) is predicted to produce 7 Mt of e-waste with an average of 15 kg by each citizen [3]. China is currently in the top place with an expected 15.5 Mt of e-waste output for the year 2020, followed by the USA, and Europe [4].

Electronic products include more than 1000 different materials and substances, most of which are toxic, such as lead, mercury, cadmium, chromium, and arsenic. Informal e-waste collection accounts for more than 80% of the total e-waste collected in China, which dominates the e-waste collection industry. This causes a burden both to the environment and human health, and results in a substantial loss of vital natural resources. Now many countries apply the CE paradigm as a viable solution to strengthen the sustainability of the current e-waste management system [5]. Research shows that e-waste products not only contain base metals such as copper, aluminium, and zinc, as well as components such as plastic and glass, but also hide valuable metals like gold, platinum, palladium, and silver. If we handled e-waste correctly, the usable material stocks in it could be employed as resources in the reverse supply chain. However, the implementation of circular strategies is still in its infancy stages, because the shift from a linear to a circular business model involves several practical challenges and obstacles.

Analysis of recent research and publications. The increase in publications over the past twenty years shows that e-waste management has become an emergent requirement to meet both in developed and developing countries. To improve health care, education, security, and other living circumstances in the city, many smart cities are being built in the world. Sustainable Municipal Solid Waste Management (MSWM) is a crucial part of smart cities. Smart waste management is being developed as a result of the rapid development of digital technologies, such as the Internet of Things (IoT), cloud computing, artificial intelligence (AI), and big data analytics.

Formation of the objectives of the article. This study aims to (I) present a comprehensive overview of the e-waste management research topics at a global level in academia and explore the smart management scenario of e-waste recycling in detail and (Ii) present the latest and progressive solutions in the field of smart e-waste management at the national level, focusing on China, the country with the largest amount of e-waste. The current study will explore the e-waste scenario of China in great detail. It will also highlight possible smart e-waste management processes and propose suggestions considering various challenges in the prospect of China.

Methodology. The present study followed an analytical approach by incorporating a systematic literature review with content analysis, and the research design is illustrated in Figure 1. The justifications for using this mixed-method approach are (i) analyzing the theoretical bases and developments of e-waste management based on various advanced digital technologies by conducting a literature review based on a massive database and (ii) conducting content analysis to identify the recent advancements and initiatives in the field of smart e-waste management in China.

Results of the study. *Global e-waste management with a focus on China.* In most countries, current e-waste legislation includes bans on e-waste import/export, recycling requirements for specific types of e-waste, and Extended Producer Responsibility (EPR). The Basel Convention was signed in Basel, Switzerland, to prevent the unlawful shipment of hazardous waste and mashes from developed countries to developing countries in Asia and Africa. The full name of it is the "Transboundary Movements of Hazardous Wastes and Their Disposal" treaty which aims to protect human health and preserve the environment. The European Union's WEEE Directive was enacted into law in 2003, and all member states had signed on by 2007. This directive is a comprehensive e-waste management law that governs the collecting, recycling, and resource recovery processes. The other directive is the Restriction of Hazardous Substances (RoHS) which restricts amounts of six specific materials: lead, mercury, cadmium, hexavalent chromium, PBB, and PBDE utilized in the manufacturing process.

E-waste generation in China has substantially increased. However, informal recovery practices emerged in China which resulted that the legal recycling rate for e-waste being relatively low. China has formulated the most authoritative and practical policy in the sphere of hazardous e-waste.

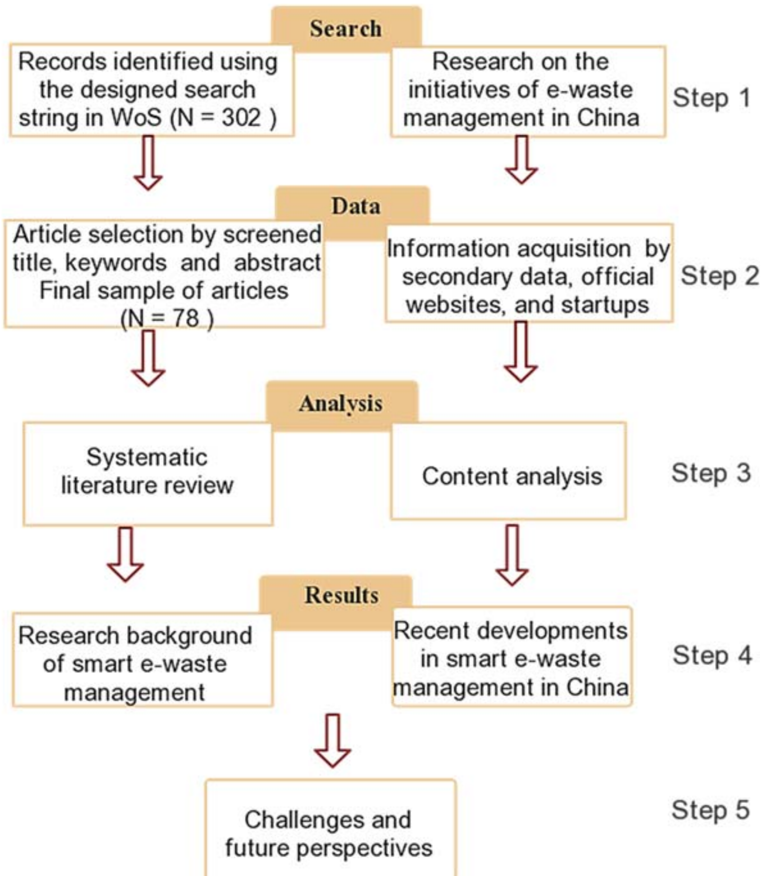

Figure 1 – Research design

In 2002, China imposed a law prohibiting the import of dangerous e-waste. In 2006, the Chinese government passed the “Ordinance on Management of Prevention and Control of Pollution from Electronic and Information Products” which was considered the China RoHS Directive. In 2009, China enacted the “Administration Regulation for the Collection and Treatment of Waste Electronic and Electrical Equipment” which is considered to be the China WEEE Directive [6]. “The Restriction of Hazardous Substances in Electrical and Electronic Equipment” went into effect in 2016 as a new edition of China's RoHS Directive.

To capture the most relevant research for analysis, a well-structured search protocol was adopted. Initially, the Web of Science (WoS) database, as one of the most reputable publisher-independent global citation databases in academia, was chosen as the primary database for the analysis. Then, the following structured search string was elaborately designed for covering target articles: (search in the topic: “e-waste”, OR “WEEE” OR “electronic waste” OR “home appliance”) AND (search in the topic: “smart” OR “IoT” OR “Internet” OR “cloud*” OR “blockchain” OR “AI” OR “artificial intelligence” OR “deep learning” OR “machine learning” OR “Convolutional Neural Networks” OR “Support Vector Machine” OR “Industry 4.0” OR “I4.0” OR “intelligent” OR “digital technolog*” OR “big data” OR “ICT” OR “information and communications technology”).

The initial running of the search string in the topic of documents (i.e., title, abstract, author keywords, and keywords plus) returned 427 articles in WoS. Only peer-reviewed journal articles and review articles were considered without a time limit, other types of documents (conference proceedings, editorials, reports, book chapters, etc.) were excluded. The search was conducted from October 2022 to March 2023, with a final sample of 302 articles. After carefully screening the remaining articles, papers that were not pertinent to the study's principal objective were removed, and a final sample of 78 articles for further analysis in the present study. Then, the systematic literature review was conducted. Finally, we got the research background of smart e-waste management.

Meanwhile, to fully grasp the progress of smart waste management, first, we search the research on the initiatives of e-waste management in China [7, 8], and some official data information, official websites of government and technology companies, and initiatives of startups were comprehensively searched. Then a content analysis is carried out to obtain the recent developments in smart e-waste management in China. After applying these two methods, in the last step of the research, we analyzed the challenges and future perspectives of smart e-waste management in China.

Analysis of advanced digital technologies in smart E-waste management. In the e-waste management system, smart recycling is crucial. The Internet-based collection emerged to overcome the limitations of traditional e-waste collection [9, 10] by making use of the rapid expansion of Internet technology and the popularity of e-commerce [11]. It provided consumers with a simple and formal channel to deal with e-waste, which is an innovative practice in formal mainstream e-waste collection systems [10]. Shevchenko et al. [12] studied a smart e-waste reverse system, integrating local delivery services to collect e-waste and connecting with interactive online maps of users' requests, and relying on information technology (IT) tools. In China's Internet-based e-waste collection system, the government, platform, and customers are the three main stakeholders [11], which is based on the current popular e-commerce model O2O (Online to Offline). Participants include recycling professionals and individuals who arrange a time and location online to meet and then collect e-waste on-site [10].

Internet-based e-waste collection is a well-known approach in the Chinese e-waste collection industry, but it is still in its infancy [11]. Tong et al. [13] created a qualitative evaluation methodology to assess the performance of the e-waste recycling system based on the Internet in urban China. Gu et al. [9] investigated the current status of e-waste recycling entities in China. Wang et al. [14] discovered the problems faced by Internet-based recycling companies and showed four typical Internet recycling models by investigation. Sun et al. [15] chose two representative Internet-based collecting firms, to represent the C2B (customer to business) and B2B (business to business) online collection models in China.

Waste management based on IoT and cloud platforms has created a smarter way of waste management and disposal. The research of Wang et al [16] found that the adoption of IoT-based technological solutions support the transition towards smart waste management for a CE by enabling accountability in waste source separation. IoT technology as part of the smart waste management initiative, monitors the lids of bins, collects information about the content and location, and transmits the information to the waste collection team via a central server. The route of waste collection vehicles can then be optimized. Kang et al. [17] designed a smart household e-waste collection bin, in which sensors were fixed to measure e-waste level. When the capacity of the smart e-waste recycling cabinet reaches the threshold value, it will automatically notify the collectors through the backend server. The system includes mobile applications, which can guide users to the nearest collection point, record the behavior of users returning household e-waste, and provide bonus points for users. The architecture of the e-waste collection IoT platform is shown in Figure 2.

There is a growing body of literature on the application of artificial intelligence (AI) in waste management. AI technology has the potential to revolutionize e-waste management by improving efficiency, accuracy, and sustainability. After collection, the e-waste can be categorized using artificial intelligence algorithms, making it easier to recycle and recover valuable elements, reducing the demand for virgin resources. AI technology can also be utilized to create decision support systems for managing e-waste that can recommend the most appropriate recycling practices, disposal choices, and resource recovery techniques based on data analysis and machine learning algorithms.

Smart waste bins can be effectively used to prevent overloading and improper waste disposal by bin level detection model. The algorithms are typically fed with real-

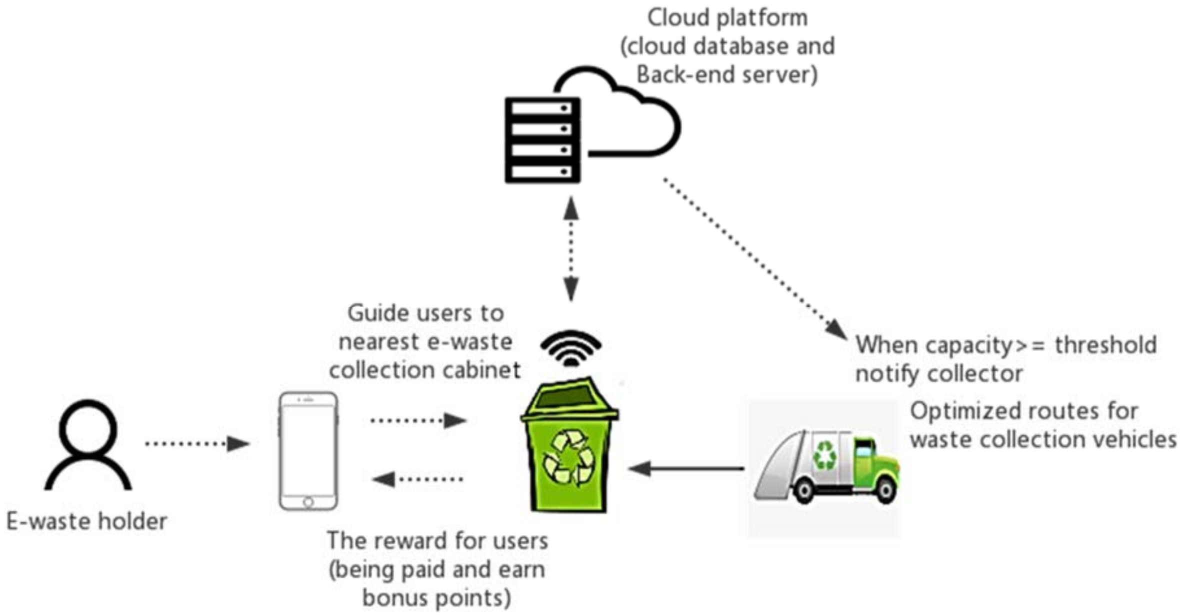

Figure 2 – The architecture of IoT-based e-waste collection platform

time data from level or image sensors installed inside to identify the level and the type of waste in smart waste bins. Morison et al. [18] detect bin level in terms of wall entropy perturbation in e-waste collection, taking the recycling of discarded mobile phones as an example. Hannan et al. [19] investigate a content-based image retrieval system to study the application of image retrieval with an extracted texture from the image of a bin to detect the bin level. Kai Dean Kang [17] designed an e-waste collection box with sensors to assess the volume of e-waste and record the disposal information. The smart system was successfully constructed, and it could help household e-waste collection. Similarly, GA Sampedro [20] developed a smart e-waste bin using You Only Look Once v4 (YOLOv4) to identify the type of e-waste stored inside and reward users for participating in e-waste recycling. The developed system can successfully and accurately (93.33% on average) identify the type of e-waste.

Collection expense typically accounts for 70 to 85% of the overall solid waste management costs, so waste collection vehicle routes optimization is an essential part of a successful smart waste management system. Genetic algorithms, their hybrid versions, artificial neural networks (ANN), and regression models are frequently used in Studies of waste collection frequency and route planning optimization models. Idwan et al. [21] use genetic algorithm operators such as selection, crossover, and mutation to compute the optimal route for the sector's dumpsters. Vu et al. [22] integrated nonlinear autoregressive neural networks with GIS route optimization to investigate the effect of waste composition and weight on the optimized vehicle routes and emissions. Nowakowski P. [23] presents an online e-waste collection system that employs the Harmony Search algorithm for waste collection vehicle route optimization.

Given that different waste types require different disposal methods, the accurate classification system is an essential part of waste management. Gupta et al. [24] used machine learning to classify the waste type, such as plastic, metal, and glass. Adedeji et al. [25] employed the 50-layer residual net pre-train Convolutional neural network model and Support Vector Machine to construct an image-based waste management system. The data set's images were utilized to identify garbage types and materials. The prediction accuracy rate of waste types reaches 87%. Chen et al. [26] discuss e-waste's effect on the climate and human health, and propose a hierarchic Artificial Intelligence Technique (AIT) model for the analysis of hazardous pollutants in e-waste. To identify and classify waste electrical and electronic equipment from photos, Nowakowski et al. [27] apply a deep learning convolutional neural network (CNN) to classify the type of e-waste, while a quicker region-based convolutional neural network (R-CNN) was used to detect the category and size of e-waste in the images.

Robot waste sorting and segregation involves the use of AI technology to identify and sort different types of waste materials based on their size, shape, and composition. To separate and grade e-waste, the WEEE ID project, supported by VINNOVA (the Swedish Agency for Innovation Systems), developed automated, intelligent sorting equipment to increase sorting accuracy and efficiency. The new robotic application enables sorting shredded e-waste that includes wires, plastics, and circuit boards. Karbasi et al. [28] explored a deep learning model which combined a ResNet101 feature extractor with the Faster R-CNN algorithm. A fast parallel robot is used to divide the materials into different bins. The results of the material classification reach an overall purity rate of 98%. According to the latest empirical research results, the training and operation of an AI robotic sorting system are promising in terms of the purity of sorted waste fragments.

Since 2015, the Internet-based e-waste recycling platforms have increased rapidly. There are many e-waste collection platforms in China based on the Internet, by which users can submit orders online and choose door-to-door pickup or express delivery for recycling. They provide services including equipment detection, classification, dismantling, and data removal. Shenzhen Taolv Information Technology Co., Ltd. (Taolv) and Shenzhen Boolv Environmental Technology Co., Ltd. (Boolv) are two representative Internet-based e-waste collection platforms. Taolv provides a site for recycling transactions of used mobile phones and tablets for industry through the business-to-business (B2B) plus online-to-offline (O2O) model. Taolv divides the waste of mobile phones and tablets into reusable and non-reusable, and eliminates user data which is the most important thing for users to protect personal information security. The reusable mobile phones are re-sold through professional second-hand terminals, and the non-reusable mobile phones are handed over to third-party companies with the qualification and ability to dispose of e-waste in a formally way. The processing flow is shown in Figure 3.

The prominent Internet company Baidu works with the United Nations to establish a big data joint laboratory, using Baidu's big data technology to explore innovative models for solving the global e-waste problem. Its mobile app "Baidu Recycle Bin" connects users who want to dispose of waste home appliances with formal recycling companies certified by the national government, allowing more e-waste to flow into formal recycling enterprises through the Internet. Users can take photos of waste home appliances and upload them, after which the system completes the evaluation, and finally, the collectors will come to the door. The Internet company Tencent which serves the largest number of users in China, has launched a WeChat mini program named Tencent micro recycling to provide convenient, high-priced, and safe recycling of old mobile phones and tablets with the help of the extensive user groups of WeChat social software. The recycling process includes online evaluation, door-to-door pickup, professional quality inspection, and fast payment. Alibaba, China’s largest e-commerce company, also focuses on the recycling of e-waste products mainly including mobile phones and laptops. Its subsidiary company Huishoubao recycled 10 million mobile phones over the past four years.

Many cities have begun to implement a mandatory waste classification in China, which has promoted the waste classification industry. The application of IoT and AI technology enables smart waste-sorting machines from the source. Yingchuang, renewable resources recycling Co., Ltd. in Beijing, independently developed a smart recycling machine for beverage bottles, which is the first example in China that combines IoT technology with a renewable resource recycling system, which motivates users through various rebate methods such as mobile phone bills and coupons. It has been put into operation at the capital airport, Beijing subway, and major universities. Little Yellow Dog, an environmental protection technology company, uses the innovative model of IoT plus smart recycling. The four-class waste recycling machine developed by them has realized the dynamic monitoring and intelligent management of waste classification. The user downloads and registers the mobile application, scans the QR code on the recycling machine, selects the type of waste under the guidance, and the system will indicate which bin the waste should be put in. It is also equipped with a smart waste recognition module to further ensure the accuracy of waste placement. Such smart waste collection machines have been installed and used in residential quarters in many cities. The smart waste bin developed by Beta Intelligence company can perform waste full-load warnings and smoke alarms. The information on equipment overflow will be pushed to the back management for timely cleaning and transportation. It is currently in use in some parks and smart communities.

Alpheus launched an automatic sorting AI bin based on the mixed object sorting technology of AI and image recognition. It integrates advanced technologies of AI, IoT, cloud computing, and big data, and establishes a scene-adaptive waste classification cloud deep learning model. The learning model realizes the automatic intelligent rapid classification of waste. Users put waste into the bin as usual, and the AI smart bin can automatically complete the classification, with an accuracy rate of over 95%. The company's smart products include: two-classification Rui Bucket, four-classification Rui Bucket, and six-classification Rui Station. In addition to classification, they also provide smoke alarms, overflow alarms, accurate weighing, voice broadcasts, and reminders of placement errors. They have been applied in municipal office halls, high-tech industrial parks, and smart parks in China.

Waste sorting is the most difficult job in the waste recycling process. With the development of artificial intelligence technology, several waste-sorting robots have been manufactured to improve classification efficiency and reduce harm to human health. Zen Robotics, a Finnish waste sorting robot, is based on a computer vision system and classifies according to the type and size of the waste. The robotic arm will accurately grab the sorted waste and

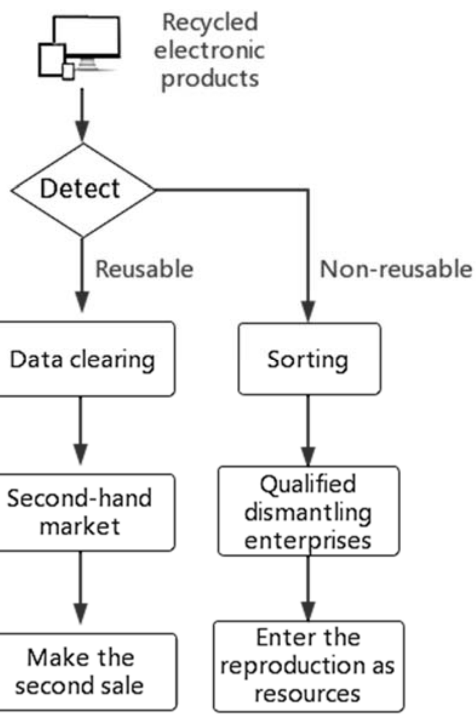

Figure 3 – The processing flow of e-waste

throw it into the target bucket. AMP Robotics developed in the United States, can sort 80 items per minute with an accuracy rate of 95%. The built-in algorithm of the robot is trained through a large number of images, and then uses the vision system to scan the waste on the conveyor belt and classify the waste according to its color, size, and material. When the sorting is completed, the suction cup on the robotic arm can be used to pick up the waste and throw it into the sorted container. Alphabet X, built by Google X in the United States, can not only sort waste, and put wrongly sorted waste in the right place, but also walk around the community to pick up the waste. The Waste Robot launched by FANUC in Japan uses a new technology of W.A.R. (Waste Robotics Autonomous Recycling Technology) specially designed for waste sorting. China has also carried out research and development of waste sorting robots. An intelligent smart identification and sorting robot developed by Bocheng Robot Company has been put into use in Hangzhou. However, compared with developed countries, the research and development of waste-sorting robot in China are still in its infancy, and the prospect is promising.

Due to the relative complexity of e-waste recycling, the current e-waste collection in China mainly relies on online services through websites or mobile applications, combined with professional local store recycling on-site. The majority of the smart sorting waste boxes based on the IoT and AI focus on the automatic classification and recycling of solid waste. IoT intelligent recycling machines for electronic waste classification and recycling are still in the laboratory stage and have not been promoted in the market. At present, the e-waste sorting process is still dominated by manual sorting in China, with only a small amount of mechanical assistance.

Conclusion. Smart e-waste management is considered to be an effective new approach to e-waste management. This research aims to provide an overview of the current state-of-the-art smart technologies applied to e-waste management, as well as the current state of academic research and application in practice. To this end, this study adopted a mixed research method in two stages, combining systematic literature review and case analysis. On the one hand, scholars have achieved fruitful academic achievements in smart e-waste recycling; On the other hand, many innovative practices have emerged in the industry. First, an overview of the global e-waste management legislation, the e-waste management policy in China, and recycling models in China were introduced. Then the major research themes of the most advanced digital technologies in smart E-waste management were identified and analyzed through literature analysis. Last, the most recent advancements of smart e-waste recycling initiatives in practice based on the Internet, IoT, and AI in China were provided. The review provided supports the use of smart technologies in e-waste management. The research progress of smart e-waste recycling and smart e-waste recycling solutions mainly from industry and start-up technology companies are introduced, which promote academic discussion and connecting industrial practitioners with the research community. The main challenges and future prospects are further investigated, including the need to promote consumers to use smart e-waste recycling systems, lower the high running costs of smart recycling systems, and provide legislative and policy support for smart e-waste recycling system.

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DIGITAL-ТЕХНОЛОГІЇ І SMART-СИСТЕМИ У СФЕРІ ПОВОДЖЕННЯ З ЕЛЕКТРОННИМИ ВІДХОДАМИ У КИТАЇ: ДОСЛІДЖЕННЯ ОСНОВНИХ НАУКОВИХ НАПРЯМІВ

Збільшення обсягів утворення та накопичення різних категорій електронних відходів і низький рівень їх роздільного збирання та утилізації створює значні ризики для навколишнього середовища та здоров'я людини. Щоб запобігти стрімкому зростанню утворення електронних відходів у світі, яке не спричинило серйозного забруднення навколишнього середовища та негативного впливу на здоров'я людини, правильне поводження з електронними відходами має вирішальне значення. В останні роки Китай почав приділяти більше уваги поводженню з електронними відходами, оскільки неофіційна переробка та утилізація неавторизованими збирачами призвела до серйозних екологічних проблем у деяких регіонах. Однак досягти ефективного поводження з відходами електронних продуктів у країні, що розвивається, як Китай, де щороку виробляється велика кількість електронних відходів, але рівень переробки якого низький, – це величезна проблема. З розвитком digital-технологій з'являються нові можливості для більш ефективного управління у сфері поводження з електронними відходами. Багато компаній у Китаї розробляють розумні системи збору та переробки електронних відходів, застосовуючи Інтернет речей (IoT), великі дані, хмарні обчислення та штучний інтелект (ШІ), але вони також стикаються з проблемами в різних аспектах. Стаття має на меті виявити та систематизувати основні наукові напрями дослідження у сфері застосування smart-технологій для збирання та утилізації електронних відходів в Китаї. В роботі представлені сучасні системи smart-збирання електронних відходів різних категорій, які були впроваджені та розширені через місцеві підприємства та програми підприємництва як альтернативи неформальним підходам роздільного збирання. За результатами дослідження встановлено, що smart-технології мають значний потенціал щодо застосування у сфері збирання електронними відходами. Це дослідження посилює академічні дебати та усуває розрив між практиками галузі та дослідницьким співтовариством. Запропоновано стимулюючі заходи щодо посилення застосування digital-технологій та smart-систем у сфері поводження з відходами цього виду.

Ключові слова: *електронні відходи, digital-технології, smart-система, поводження з електронними відходами, smart-збирання електронних відходів, циркулярна економіка.*

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