Athens Journal of Sciences- Volume 12, Issue 3, September 2025 – Pages 171-188

Systematic Review and Meta-analysis: The Application of Robotic and Drone Technology in Waste Management

By Tyrone Bright[*]

This systematic review and meta-analysis aims to evaluate the application of robotic and drone technology in waste management, specifically focusing on image recognition and deep learning for waste identification and categorisation. Due to urbanisation and the rapid growth of modern cities, ecosystems face challenges such as waste management. Therefore, there is a growing trend to develop innovative, efficient and environmentally sustainable solutions. These solutions include integrating advanced technologies such as robotic and drone technologies. It is coupled with artificial intelligence (AI), particularly image recognition and deep learning algorithms, which have emerged as promising tools to enhance waste management processes. The methodology of this review involves a comprehensive search of databases such as IEEE Xplore for studies published up to June 2024. The inclusion criteria are studies that describe the use of robotics and drones equipped with image recognition and deep learning capabilities in waste management settings. The primary outcomes assessed include the accuracy of waste identification, the efficiency of waste categorisation, and the overall impact on waste management practices. The results of this meta-analysis reveal significant advancements in the accuracy and efficiency of waste management processes facilitated by robotic and drone technologies. Image recognition and deep learning algorithms have shown high efficacy in identifying and categorising various types of waste, thereby optimising the sorting and recycling process. Furthermore, the application of these technologies has demonstrated potential in reducing human exposure to hazardous waste, improving the speed of waste processing, and enhancing the precision of waste data collection for better environmental management. This review discusses the implications of these findings for developing intelligent waste management systems. It highlights the role of robotic and drone technology in advancing sustainable waste management practices, addressing challenges such as waste segregation and recycling rates. Additionally, the review identifies gaps in current research. It suggests directions for future studies, emphasising the need for scalable solutions and integrating these technologies into existing waste management frameworks. Through this analysis, the review contributes to understanding how emerging technologies can be leveraged to improve environmental sustainability and waste management efficiency.

Keywords: *robotic technologies, drone technologies, waste management, deep learning, image recognition, artificial intelligence, waste categorisation*

[*]Lecturer, Durban University of Technology, South Africa.

https://doi.org/10.30958/ajs.12-3-2 doi=10.30958/ajs.12-3-2

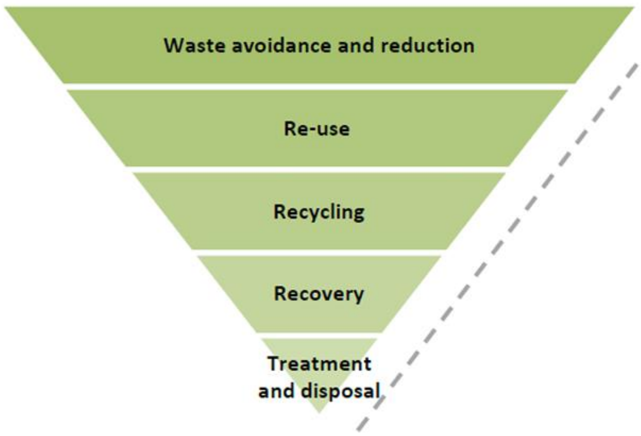
Introduction

The world is producing almost double the amount of plastic waste compared to two decades ago, with only 9% successfully recycled (OECD 2022). This is according to a recent report by the Organization for Economic Cooperation and Development (OECD) outlining climate action and statistics in developing and developed countries.

The European Union (EU) recently adopted a Circular Economy Plan that creates a framework for providing incentives for investing in close-loop material for critical raw material (CRM). This framework addresses the increasing demand for waste production and the potential shortfall of CRMs for European manufacturers by recovering and recycling electronic waste. Electronic waste, known as e-Waste, is the fastest-growing waste stream globally, with 53.6 million tons of e-Waste being generated globally in 2019 (Johnson et al. 2022).

With the significant increase in plastic waste and the recent adoption of the EU circular Economy Plan, waste management is important in developing and developed worlds. Waste management focuses on the control of waste streams. It is based on the hierarchy approach (see Figure 1). This approach consists of various categories for waste through its lifecycle and is arranged in descending order of priority. Primarily, waste should always be avoided and reduced. It would reduce the number of waste management systems required, which is the foundation of the hierarchy. If waste cannot be avoided, it should be recovered, reused, recycled, or treated. Disposal of waste should be a last resort. This research will focus on the recovered category of waste management.

Figure 1. *Waste Management Hierarchy (Sibeko & Adeniji 2020)*



With a focus on waste recovery, classification, identification, and sorting play fundamental roles in this process. Research shows that many countries still rely on manual waste classification, especially in third-world countries (Ferronato & Torretta 2019). It has significant drawbacks as it poses health risks to waste operators, it is costly and highly inefficient. With recent developments in machine learning, robotic technology, drone technology and artificial intelligence as outlined by Koskinopoulou et al. (2021), Bhavana et al. (2022), Bobulski & Kubanek (2021) and Liu et al.

(2023), waste classification and identification have become a popular research area. A systematic review and meta-analysis were conducted to understand the state of research on waste identification, classification and sorting with advanced technologies.

This systematic review and meta-analysis aims to evaluate the effectiveness of robotic and drone technology in waste management, specifically focusing on image recognition and deep learning for waste identification, categorisation and sorting. There is a growing trend to develop innovative, efficient and environmentally sustainable solutions in this field of research. These solutions include integrating advanced technologies such as robotic and drone technologies. It is coupled with artificial intelligence (AI), particularly image recognition and deep learning algorithms, which have emerged as promising tools to enhance waste management processes.

The methodology of this review involves a comprehensive search of the IEEE Xplore database for studies published from 2019 to 2024. The inclusion criteria are studies that describe the use of robotics and drones equipped with deep learning and image recognition capabilities for waste management systems. The primary outcomes assessed included the accuracy of waste identification, the efficiency of waste categorisation, and the overall impact of these technologies on waste management practices.

This meta-analysis revealed significant advancements in the accuracy and efficiency of waste management processes facilitated by robotic and drone technologies. Image recognition and deep learning algorithms have shown high efficacy in identifying and categorising various types of waste, thereby optimising and enhancing the recovery process. Furthermore, these technologies have demonstrated the potential to reduce human exposure to hazardous waste, improve the speed of waste processing, and enhance the precision of waste data collection for better environmental management.

This review discusses the implications of these findings for developing intelligent waste management systems. It highlights the role of robotic and drone technology in advancing sustainable waste management practices, addressing challenges such as waste segregation and recovery rates. Additionally, the review identifies gaps in current research. It suggests directions for future studies, emphasising the need for scalable solutions and integrating these technologies into existing waste management frameworks. Through this analysis, the review contributes to understanding how emerging technologies can be leveraged to improve the sustainability and efficiency of waste management solutions.

Section 2 of the research will focus on the literature review to develop intelligent waste management systems with advanced technologies. Section 3 will outline the methodology of the systematic review and meta-analysis. Section 4 highlights the results of the systematic review and meta-analysis. The study's impact and future research direction will be discussed in sections 5 and 6.

Literature Review

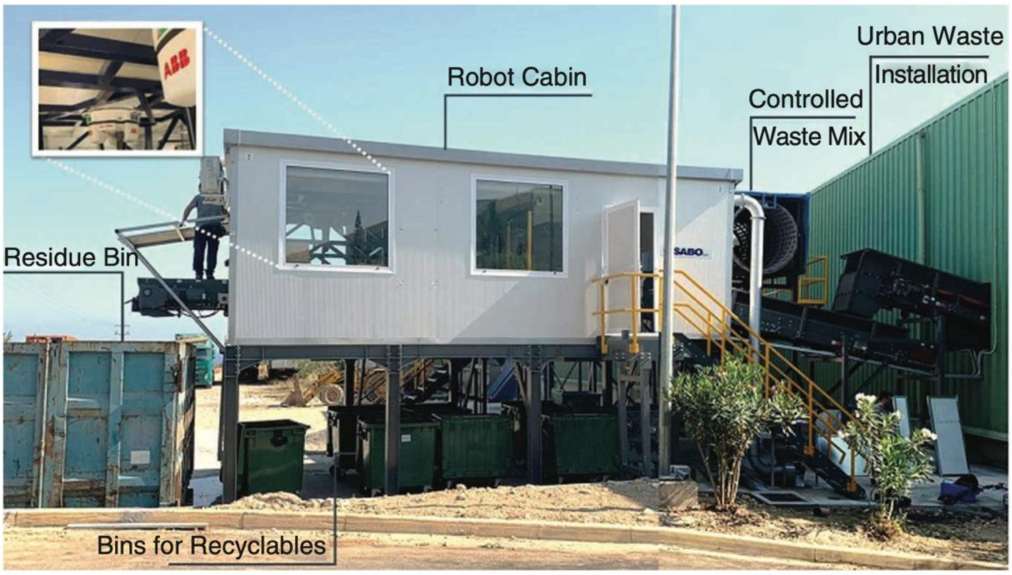
Waste management can be defined as processes and actions required to control waste. These processes include collecting, transporting, treating, monitoring and disposing waste. Since waste management consists of treating and disposing of waste, it has legal and regulatory frameworks that govern how, where and what waste can be disposed of. As such, waste management remains a manual and costly process in most parts of the world. It has presented various challenges to the industry, such as unsafe labour conditions, high costs and low efficiency. Therefore, there is a significant focus on researching more 'smart' and efficient methods to manage waste.

In recent decades, substantial research has been conducted on innovative and intelligent waste management processes. Initially, the focus was on using sensors in recycling plants to improve the sorting process and monitor waste movement. It included using magnetism, air columns and cameras to sort or identify waste throughout the waste management facility. This allowed waste to be sorted into various base categories, i.e. plastic, paper, metals, cardboard and solid waste. This has developed further through robotic technology, drone technology and advanced neural networks.

Researchers such as Joseph et al. (2023), Koskinopoulou et al. (2021), Tornero et al. (2022) developed advanced robotic systems that used sensor data and advanced neural networks for the identification and sorting/collection of waste. Joseph et al. (2023) leveraged a deep learning algorithm and robotic arm, known as E-Waste Intelligent Robotic Technology (EIRT), to detect, sort and classify waste. The deep learning algorithm used an EfficientNET-D2 architecture with waste classification, sorting, and pressure testing modules. The algorithm was trained using a TrashBox dataset, which included pictures of waste and e-waste. The performance matrix of the system showed that Accuracy classification was 82.32%, the precision of the model varied between 76,21 % to 91,14 %, and the F1 score ranged from 78.24% to 90.97%. The F1 score refers to the mean of the precision and recall value. It is used to gain a better understanding of model performance. The system was only tested in a controlled, closed environment where it identified objects in isolation. It was noted that while it displayed promising results, more work could be done to train the module. This would increase its ability to accurately classify features and waste faster.

Koskinopoulou et al. (2021) focused on developing an autonomous robotic system for categorising and sorting recyclables according to the material type. The autonomous robotic system was designed with a low-cost computer vision system based on deep learning technology. The autonomous robotic system was developed with a low-cost computer vision system coupled with deep learning technology. The system used an ABB IRB360 Delta robot, a ZED camera module, a vacuum gripper module and a Mask Regional CNN (R-CNN) network. Data from TrashNet and TacoNet were augmented to create a greater dataset for the network training. The composite system was tested and produced an average success rate of 91.8%. This indicated that the combination of rotation, translation, and scaling contributed to improvements in the Mask R-CNN performance. This system was implemented in an industrial research installation at the Crete MRF, as seen in Figure 2. The system was tested with multiple waste objects on a single conveyor.

Figure 2. *A Depiction of the Industrial Research Installation at the Crete MRF*



Starting from the right, two feeders place waste on a conveyor belt. The feeders are located above the belt to provide a controlled waste. The waste mixture is passed through the robot cabin, where the system identifies and separates the waste according to class. The separated waste is dumped into its respective recyclable bins for further processing. Any non-recyclable objects are disposed of in the residue bin.

Tornero et al. (2022) developed a sensory system using colour and depth images to detect instances of waste. The system could classify waste into four categories (plastic bottles, boxes, cans and glass bottles). It would determine the type of waste and the 3D coordinate for collection by the robotic arm. The system comprises an Autonomous Robot (Blue), an NVIDIA DGX-A100 GPU, an RGBD Camera (Intel Realsense d435i with LIDAR) and a YOLO detection algorithm. Data augmentation techniques were used with various versions of YOLO algorithms (YOLOv3, YOLOv3-SPP, YOLOv5s, YOLOv51, YOLOv51 Augmented). The system results highlighted that YOLOv51 Augments achieved the most efficient and promising option with precision parameter – 0.991, recall – 0.992 and rate of detection – 36 ms. This project was conducted in an open and dynamic environment with isolated objects. One of the shortcomings of the results is that it can't achieve the same performance when waste objects are piled together.

Jalali et al. (2023) developed a real-time waste detection and recycling delta parallel robot based on deep learning. The system focused on the use of two methods for waste detection. It compared multi-stage detection, which focused on localisation, segmentation and classification, to one-stage detection (YOLOv5).

Samsudeen et al. (2023) and Kumar et al. (2021) have developed drone surveillance models to detect waste. They use technology such as Geo-location and mapping, image stitching and deep learning to analyse the data collected. This data produces notifications and alert systems for waste collection and management. Kumar et al. (2021) developed a proposed advanced deep learning solution for solid waste detection using UAVs/drone technology. The main focus of the research was to provide a platform for waste in specific areas to be shared and viewed by anyone in the world. This would encourage transparency in municipals and NGOs that deal with waste management. The system's structure consisted of a drone, Rasberry Pi, Tensor flow and OpenCV. While the system achieved its main focus as a proof of concept, no results were recorded. The researchers highlighted that a shortcoming of the research was its inability to collect the waste once it was identified and the lack of application testing conducted on the research. While the system could capture and share data, it could not valorise the waste.

Samsudeen et al. (2023) developed a drone surveillance model using deep learning for plastic waste monitoring. The proposed system was built with a modified YOLOv8 object detection algorithm and an Nvidia Nano kit. CSPDarkNet53 was used as the dataset for feature extraction for the waste detection model. The researchers showed that the YOLOv8 outperformed comparative systems with a precision parameter of 98.6%, a recall parameter of 96.13% and a detection success rate of 99.3%. Researchers identified challengers by identifying very tiny plastic wastes of various types. Further work was identified using more advanced YOLO versions to yield better results. i.e. training the algorithm with large datasets and applying further data augmentation.

Researchers such as Rashida et al. (2022), Zhou et al. (2021) and Johnson et al. (2022) have researched various uses of deep learning techniques for object detection using computer vision modules. These modules include R-CNN (Regional Convolutional Neural Network), Single Shot Detectors (SSD) models, and You Only Look Once (YOLO) models. Each module can be developed differently based on the base network or architecture and the database set used to train and test the algorithm. Some modules are developed from a fundamental level, while others are developed through transfer learning.

Rashida et al. (2022) developed an automatic waste segregation system for ground operation. It was developed with a robotic arm, Raspberry Pi, ultrasonic sensors, infrared sensors, SSD-Mobile Netv2 module and a Garbage Classification dataset. The SSD-Mobile Netv2 module enabled a real-time object detection system through the Mobile Net feature extractor. It extracts high-level features from a streamed image and generates a feature map to detect the type of waste. It concurrently determines a bounding box around the waste to determine its location in the image. It achieved an average accuracy detection of 81%, with paper – 68%, plastic – 84%, glass – 85%, and metal 87%. The researcher highlighted possible improvements by implementing a motion algorithm using fuzzy logic.

An automated system for battery detection for close-loop battery recovery and resource efficiency through identifying and sorting E-waste was developed by Johnson et al. (2022). The solution, known as RoboCRM, integrated computer vision, robotics, artificial intelligence, and machine learning technology, is an ideal solution for hazardous waste handling and sorting. The system was built with an optical scanning system, robotic sorting system, Fast R-CNN classification and identification model, feature detection and identification system with a DenseNet121 (find tuned) dataset for training and testing. This development was purely theoretical and was based on research currently being conducted in the field. The researcher identified possible improvements to the system by utilising thermal imagery. This could improve the feature vectors extracted from the data and the categorisation accuracy.

Zhou et al. (2021) developed a novel segregation algorithm based on Improved YOLOv4. The researchers integrated the Ghost module to improve the network structure in the YOLOv4 architecture. A CSPDarkNet53 was used as the backbone of the architecture to reduce the number of network connections and enhance the network feature learning ability. The neck of the architecture featured a spatial pyramid pooling module and path aggregation network. The head accounted for the regression and the classification operations. The Ghost module was implemented in the backbone. It reduced the feature redundancies, therefore resulting in fewer loss errors, confidence errors and classification errors. The researchers used DToU NMS and the centre point distance between two frames, which improved the detection accuracy of overlapped and occluded targets. The accuracy of the YOLOV4 was 94.83% and 91.25%. This represented an increase of 2.29 % and 1.49 %. Therefore, the improved YOLOv4 architecture was feasible to increase the accuracy of the trash segregation algorithm.

Methodology

There has been significant production of research papers, i.e. conference or journal articles, that have been produced based on robotic and drone technology for intelligent waste management systems. This study investigates the combination of these topics and predefines the objectives to guide the researchers through the study. The study required the researcher to review the state of the research on the application of robotic and drone technology in waste management – specifically using deep learning and image recognition techniques to identify and categorise waste. The objectives of the study are to:

- Understand the state of research in robotic and drone technology for waste management using artificial intelligence – specifically on identifying and categorising waste using deep learning algorithms and image recognition.
- Perform a meta-analysis of the research to determine its efficiency.
- Highlight critical limitations of the study.
- Conclude on the impact and future research direction of the study.

Eligibility Criteria

This study was defined as a systematic review. Therefore, it is a review of a specific research question or topic of interest that aims to identify, evaluate, and summarise all available evidence in a structured approach (Moher et al. 2009). The study required a robust review of existing research that had been performed and produced research outputs. Research outputs were defined as conference papers or journal articles associated with accredited organisations/institutions. This was defined as the type of study.

The study intended to understand the latest scope and application of robotic and drone technology in smart waste management systems. This included research such as the use of advanced UAVs in the detection of municipal solid waste using deep learning and remote sensing, and robotic waste sorting technology powered by vision-based categorisation systems (Koskinopoulou et al. 2021, Youme et al. 2021).

Based on the research, the study will be able to understand the efficiency of different strategies, the performance of the systems and the future research direction of the study. Therefore, the following criteria were chosen based on:

- Accredited academic research papers published within the last five years (since 2019 and up to June 2024) from organisations or institutions such as IEEE. This was to ensure that relevant research and information were collected.
- All English studies were considered due to the constraints of the researcher.
- Studies that produced comprehensive results from a physical system. This allowed the researcher to analyse the performance data and conclude on the efficiency of the study.
- The study needed to identify, categorise or sort waste with drone or robotic technology. It was a core technology that had shown significant advancements in this research field and was fundamental to future research.
- Studies using Artificial intelligence, specifically image processing and deep learning techniques. This core technology has shown significant advancements in this research field and is fundamental to future research.

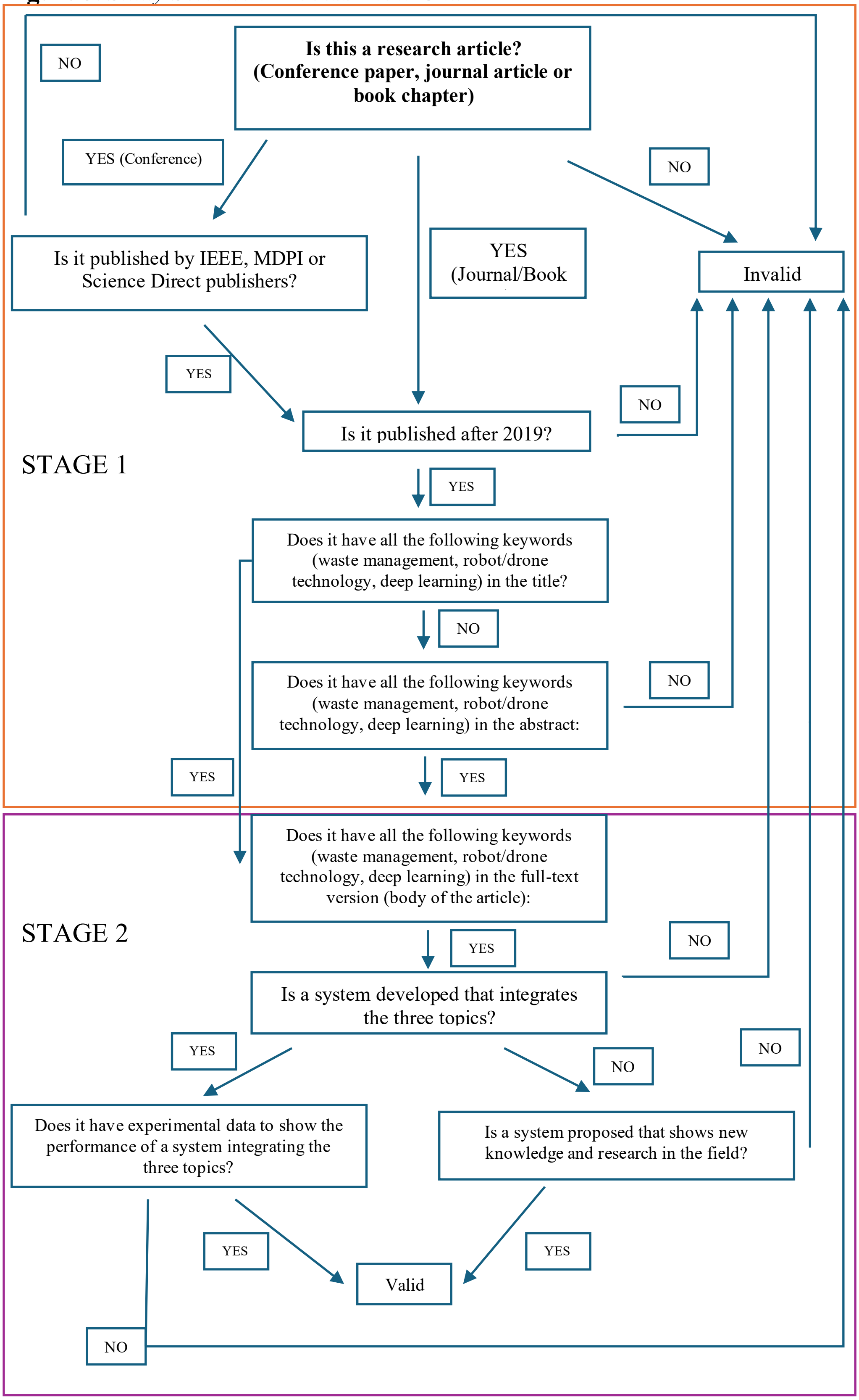
Information Source and Search Strategy

The database chosen for this research was IEEE Xplore. This database was selected as it covers engineering, computer science and technology research topics. It had an added advantage that these research articles were primarily published in accredited journals or conference proceedings that were internationally reviewed. This ensured that the research is peer-reviewed by experts in the engineering field.

To search for research articles, the database required terms, keywords and publication year. To ensure that all the databases were used effectively, the following information was used:

- Terms/Keywords: robotic and drone technology, waste management, deep learning.
- Publication year: from 2019 to 2024 (June).
- Type of publication: research articles (conference papers or journal articles) and book chapters (books). Conference papers will only be considered provided that they are published in conference proceedings by IEEE publishers. This will ensure the research is reviewed and accepted at an academic standard.

Figure 3. *Study Selection Process Flow Chart*



Study Selection Process

Once the search results were completed, the researcher began with a pilot test to ensure that the inclusion and exclusion criteria were applied correctly. The researcher choose a small sample set from each database and confirmed the eligibility. This was done by screening the research papers' titles and abstracts. Once completed, the researcher began stage one of the screening process. The researcher screened all the academic papers from IEEE and confirmed the eligibility using the same method. Once the eligibility was confirmed, the remaining papers were disregarded. Stage two of the screening process involved retrieving and evaluating full-text versions of the academic papers. The flow diagram in Figure 3 outlined both phases described.

After the screening process, all eligible academic documents were collated and were ready for data collection.

Data Extraction Process

The researcher developed a data extraction form. The data extraction form was created to ensure consistent data was extracted from the study during analysis. It's a critical step in the research, allowing the researcher to synthesise evidence and draw conclusions. The data extraction form required the following information:

1. General Information (study ID and year).
2. Study Character (study focus).
3. Methodology (technology used).
4. Results (key findings and statistical analysis).
5. Reviewer Information (Extracted by date and completion details). – It was ignored as one reviewer conducted the research over a period of 6 months.

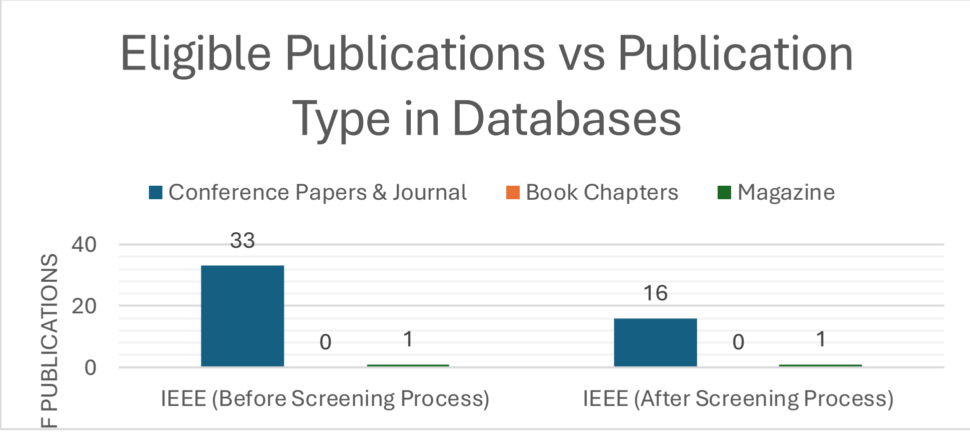
Data Synthesis Method

Since the focus was on understanding the state of drone and robotic technology research in waste management, a qualitative synthesis was chosen. This was sufficient as it provided a method for integrating and interpreting findings from various studies to draw a comprehensive conclusion on the state of research.

Results

The systematic review and data analysis results began with the study selection process. The results of this process are highlighted in Figure 4. The graph in Figure 4 shows the number of eligible publications versus the publication type. This was based on the eligibility criteria outlined in the study selection process.

Figure 4. *Number of Eligible Publications Versus the Publication Type per Database*



Once the study selection process was complete, the data extraction process began. The process was outlined in the data extraction section of the Methodology. This information was summarised and can be seen in Table 1. This highlights a few samples of research papers that underwent data extraction. This ensured that there was a fair process to ensure that sufficient data was collected for the research analysis. The full table can be seen in Appendix.

Table 1. *Data Extraction Form Summary (A Sample)*

Year	Study ID	Study Focus	Technology Used	Results
2021	(Rashida et al. 2022)	Implementation of Faster Region-Based Convolutional Neural Network for Waste Type Classification	Faster R-CNN (with ROI Pooling Layer); Data Augmentation; Pascal VOC (Format); ALEXNET	Precision - 95.87%; Recall - 90.1%; Average Detection Time - 0.119s, Overall Accuracy - 91.2
2023	(Joseph et al. 2023)	Use of deep learning algorithm and robotic technology, known as EIRT, to detect, classify and sort waste.	EfficientNET-D2 architecture, e-waste hunting module, robotic arm module, waste classification module, sorting module, pressure testing module, TrashBox dataset, Waste Pictures, eWaste.	Accuracy classification - 82.32%, recall - 72.92% to 97.12%, precision of model – 76.21% to 91.14%. F1 score - 78.24% to 90.97%.
2023	(Jalali et al. 2023)	Practical Implementation of Real-Time Waste Detection and Recycling based on Deep Learning for Delta Parallel Robot	3-DOF Delta Robot, MultiStage Detection (ResNet50), One-Stage Detection (YOLOv5), TrashNET.	ResNet50 Accuracy - 99.31%. Capable of classifying over five images per second. YOLOv5x achieved mAP (@IoU = 0.75) of 97.4% at 33 FPS.
2021	(Assis et al. 2021)	Garbage Collecting Robot Using YOLOv3 Deep Learning Model	One-Stage Detection (YOLOv3), MultiStage Detection (CNN), Raspberry Pi 3B+, Arduino Uno R3, Ultrasonic sensor.	YOLOv3 Accuracy, Precision, Recall & F1 Score - 0.9341, 0.9722, 0.84, 0.9012. CNN Accuracy, Precision, Recall & F1 Score - 0.849, 0.85, 0.8491, 0.8512.
2023	(Thanh et al. 2023)	Designing of A Plastic Garbage Robot With Vision-Based Deep Learning Applications	3 DOF Robot Arm (SCARA), Pneumatic end-defectors, cameras, One-Stage Detection (YOLOv5), Polygon Method using RoboFlow (Labelling Method), Bounding Box using	YOLOv5 (Polygon Method): Precision – 92.1%, recall - 87.3%, Success Rate – 91.5%

			RoboFlow (Labelling Method), Data Augmentation	
2023	(Samsudeen et al. 2023)	Sky Sweeper: A Drone Surveillance Model Using YOLOV8 and Jetson Nano for Plastic Waste Monitoring System	Nvidia Jetson Nano Kit, CSPDarkNet53, YOLOv8 (Object Detection Algorithm)	Precision (98.6%); Recall (96.13%); Success Rate (99.3%)

Based on the data extracted from IEEE, the research has shown significant advancements in the application of technology in waste management through the use of deep learning algorithms and robotic systems. One of the notable systems by (Badoi & Lie 2022), utilising Faster R-CNN with ROI Pooling, Data Augmentation, Pascal VOC Format, and ALEXNET, achieving a precision of 95.87%, recall of 90.1%, and overall accuracy of 91.2%. The efficient average detection time of 0.119 seconds highlights the potential for real-time applications.

The EfficientNET-D2 architecture used by (Joseph et al. 2023) integrates e-waste hunting and robotic modules, displaying an accuracy classification of 82.32%, with precision ranging from 76.21% to 91.14% and F1 scores between 78.24% and 90.97%. This showcased the robustness of integrated systems of robotic technology and deepening learning through single detection for e-waste management.

The research conducted by (Jalali et al. 2023) on real-time waste detection using a 3-DOF Delta Robot with ResNet50 or YOLOv5 achieved a remarkable accuracy of 99.31% or mAP of 97.4% at 33 FPS. This study provided a comparison between multi-stage detection networks versus single-stage detection networks. While the multi-stage detection network (ResNet50) achieved greater accuracy, the single-stage detection architecture achieved the results in real-time environments. This highlighted the improved efficacy of waste management systems using deep learning models as it enhanced detection speeds and accuracy.

In terms of drone technology and deep learning, (Samsudeen et al. 2023) used YOLOv8 and Jetson Nano for drone surveillance exhibited precision of 98.6% and a success rate of 99.3%, highlighting the effectiveness of drones in environmental monitoring.

These studies collectively demonstrate that the integration of advanced deep learning models with robotic systems significantly enhances the efficiency and accuracy of waste management processes. Technologies like YOLO, Faster R-CNN, and EfficientNET, combined with real-time data processing capabilities, present promising solutions for automating waste segregation and recycling, potentially leading to substantial environmental benefits.

Discussion

The primary objective of this research was to evaluate the effectiveness of applying robotic and drone technology in waste management, with a specific focus on image recognition and deep learning for waste identification, categorisation, and sorting. This study aligned with the overarching goal of improving waste management practices and advancing sustainable solutions in response to the increasing global waste production.

In terms of assessing the precision of robotic and drone systems in identifying various waste types, research demonstrated significant advancements in the accuracy of waste identification using image recognition and deep learning algorithms. For instance, the study by (Rashida et al. 2022) using Faster R-CNN achieved a precision of 95.87% and an overall accuracy of 91.2%. This high accuracy indicates that these technologies can effectively distinguish between different waste materials, which is crucial for efficient waste sorting and recycling processes. This highlights the effectiveness of Faster R-CNN networks with data augmentation and AlexNet. (Samsudeen et al. 2023) showcased the use of YOLOv8 and Jetson Nano for drone surveillance, exhibited precision of 98.6% and a success rate of 99.3%. While this research highlighted significant results, little application work was conducted when verifying the results.

The efficiency of robotic and drone technologies in categorising waste was substantially more when the integration of advanced neural networks and robotic/drone were developed. Studies such as Joseph et al. (2023), Jalali et al. (2023) and Thanh et al. (2023) using robotic/drone systems coupled with deep learning technology to achieve a significant success rate (which can be seen in the results above). These success rates highlight the potential of deep learning technologies to enhance the waste sorting process, reducing manual labour and increasing overall efficiency.

In order to determine the overall impact of robotic and drone technologies on waste management practices, the application of these technologies have demonstrated potential in reducing human exposure to hazardous waste, improving the speed of waste processing, and enhancing the precision of waste data collection. This is present in all the research that was investigated and analysed. These findings indicate that such technologies can significantly enhance the effectiveness and safety of waste management practices.

Conclusion

The findings of this systematic review and meta-analysis highlighted the transformative potential of robotic and drone technologies in waste management. The results aligned with the research objectives, demonstrating advanced image recognition and deep learning algorithms that can enhance the accuracy, efficiency, and overall impact of waste management processes.

Effective waste management increasingly relies on innovative technologies that can handle the growing volume and complexity of waste. The studies reviewed provide compelling evidence that integrating robotic and drone technologies with deep learning algorithms offers a viable solution for modern waste management challenges. These technologies enhance the precision of waste identification and categorisation while contributing to safer and more efficient waste management practices.

Future research should address the identified gaps, such as improving the scalability of these technologies and integrating them seamlessly into existing waste management frameworks. Further advancements in deep learning models and robotic systems will be crucial for developing more robust and adaptable waste management solutions. Additionally, exploring the application of these technologies in diverse environmental contexts can provide deeper insights into their potential global impact.

Overall, this research highlights the success of robotic/drone systems coupled with deep learning for sustainable waste management. Which is essential for addressing the environmental challenges posed by increasing waste production.

References

Akram SV, Dixit AK, Bisht K (2022) AutomaticRobotic Action Towards Plastic Collection. In *2022 International Interdisciplinary Humanitarian Conference for Sustainability (IIHC)*.

Assis A, Biju AR, Alisha NA, Dhanadas A, Kurian N (2021) Garbage Collecting Robot Using YOLOv3 Deep Learning Model. In *2021 International Conference on Advances in Computing and Communications (ICACC)*.

Badoi IR, Lie I (2022) Automatic Waste Segregation System. In *2022 International Symposium on Electronics and Telecommunications (ISETC)*.

Bhavana D, Rajeswari TR, Pasyanthi P, Sai KY (2022) Garbage Segregation System with SMART Technology Subtitle as needed (paper subtitle). In *2022 International Conference on Computer Communication and Informatics (ICCCI)*.

Bobulski J, Kubanek M (2021) Vehicle For Plastic Garbage Gathering. In *2021 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME)*.

Ferronato N, Torretta V (2019) Waste Mismanagement in Developing Countries: A Review of Global Issues. *Int J Environ Res Public Health* 16(6).

Hossain S, Debnath B, Anika A, Junaed-Al-Hossain M, Biswas S, Shahnaz C (2019). Autonomous Trash Collector Based on Object Detection Using Deep Neural Network. In *TENCON 2019 - 2019 IEEE Region 10 Conference (TENCON)*.

Jalali H, Garjani S, Kalhor A, Masouleh MT, Yousefi P (2023) Practical Implementation of Real-Time Waste Detection and Recycling based on Deep Learning for Delta Parallel Robot. In *2023 13th International Conference on Computer and Knowledge Engineering (ICCKE)*.

Johnson M, Khatoon A, Fitzpatrick C (2022) Application of AI and Machine Vision to improve battery detection and recovery in E-Waste Management. In *2022 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME)*.

Joseph IO, Wangare NL, Mahoque TP, Tewari P, Majumdar S (2023) E-Waste Intelligent Robotic Technology (EIRT): A Deep Learning approach for Electronic Waste Detection, Classification and Sorting. In *2023 14th International Conference on Computing Communication and Networking Technologies (ICCCNT)*.

Koskinopoulou M, Raptopoulos F, Papadopoulos G, Mavrakis N, Maniadakis M (2021) Robotic Waste Sorting Technology: Toward a Vision-Based Categorization System for the Industrial Robotic Separation of Recyclable Waste. *IEEE Robotics & Automation Magazine* 28(2): 50–60.

Kumar S, Kumar RS, Pant H, Agrawal M, Tandon A (2021) Drone Clean-Zilla. In *2021 International Conference on Forensics, Analytics, Big Data, Security (FABS)*.

Liu H, Wu T, Qi C (2023) Design of a garbage sorting robot based on machine vision. In *2023 IEEE 5th International Conference on Civil Aviation Safety and Information Technology (ICCASIT)*.

Liu J, Balatti P, Ellis K, Hadjivelichkov D, Stoyanov D, Ajoudani A, et al. (2021) Garbage Collection and Sorting with a Mobile Manipulator using Deep Learning and Whole-Body Control. In *2020 IEEE-RAS 20th International Conference on Humanoid Robots (Humanoids)*.

Moher D, Liberati A, Tetzlaff J, Altman D, Moher D, Liberati A, et al. (2009) Group PPreferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med 6: e1000097. *Open Medicine: A Peer-Reviewed, Independent, Open-Access Journal* 3: e123–130.

OECD (2022) *OECD POLICY HIGHLIGHTS Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options*. OECD.

Rashida J, Hamzah R, Samah KAFA, Ibrahim S (2022) Implementation of Faster Region-Based Convolutional Neural Network for Waste Type Classification. In *2022 International Conference on Computer and Drone Applications (IConDA)*.

Rumahorbo BN, Josef A, Ramadhansyah MH, Pratama H, Budiharto W (2021) Development of Robot to Clean Garbage in River Streams with Deep Learning. In *2021 1st International Conference on Computer Science and Artificial Intelligence (ICCSAI)*.

Samsudeen MS, Faiz SF, Kapoor A, Gudimella S, Kirushakkarasu AY (2023) Sky Sweeper: A Drone Survelliance Model Using YOLOV8 and Jetson Nano for Plastic Waste Monitoring System. In *2023 6th International Conference on Contemporary Computing and Informatics (IC3I)*.

Sibeko M, Adeniji A (2020) Trends in the management of waste tyres and recent experimental approaches in the analysis of polycyclic aromatic hydrocarbons (PAHs) from rubber crumbs. *Environmental Science and Pollution Research* 24.

Thanh LT, Lam LH, Nguyen TN, Tran DT (2023) Designing of A Plastic Garbage Robot With Vision-Based Deep Learning Applications. In *2023 International Conference on System Science and Engineering (ICSSE)*.

Tornero P, Puente S, Gil P (2022) Detection and Location of Domestic Waste for Planning Its Collection Using an Autonomous Robot. In *2022 8th International Conference on Control, Automation and Robotics (ICCAR)*.

Youme O, Bayet T, Dembele J, Cambier C (2021) Deep Learning and Remote Sensing: Detection of Dumping Waste Using UAV. *Procedia Computer Science* 185: 361–369.

Zhou P, Zhu Z, Xu X, Liu X, He B, Zhang J (2021) Towards the Urban Future: A Novel Trash Segregation Algorithm Based on Improved YOLOV4. In *2021 IEEE International Conference on Robotics and Biomimetics (ROBIO)*.

Appendix

Year	Study ID	Study Focus	Technology Used	Results
2021	(Badoi & Lie 2022)	Automatic Waste Segregation System	Faster R-CNN (with ROI Pooling Layer); Data Augmentation; Pascal VOC (Format); ALEXNET	Precision - 95.87%; Recall - 90.1%; Average Detection Time - 0.119s, Overall Accuracy - 91.2
2023	(Joseph et al. 2023)	Use of deep learning algorithm and robotic technology, known as EIRT, to detect, classify and sort waste.	EfficientNET-D2 architecture, e-waste hunting module, robotic arm module, waste classification module, sorting module, pressure testing module, TrashBox dataset, Waste Pictures, eWaste	Accuracy classification - 82.32%, recall - 72.92% to 97.12%, precision of model – 76.21 % to 91.14 %. F1 score - 78.24% to 90.97%.
2023	(Jalali et al. 2023)	Practical Implementation of Real-Time Waste Detection and Recycling based on Deep Learning for Delta Parallel Robot	3-DOF Delta Robot, MultiStage Detection (ResNet50), One-Stage Detection (YOLOv5), TrashNET.	ResNet50 Accuracy - 99.31%. Capable of classifying over five images per second. YOLOv5x achieved mAP (@IoU = 0.75) of 97.4% at 33 FPS.
2021	(Rumahorbo et al. 2021)	Development of Robot to Clean Garbage in River Streams with Deep Learning	Autonomous River Robot, VGG16 Network	Accuracy – 72%
2021	(Kumar et al. 2021)	Dronezilla	Image Stitching, Drone, Firebase, Raspberry Pi, YOLO (One-Stage Detection), Tensor Flow , Datasets - Github & Kaggle, OPENCV & SIFT (Image processing & feature extraction method), Drone.	Detects waste. No parametric results.
2021	(Assis et al. 2021)	Garbage Collecting Robot Using YOLOv3 Deep Learning Model	One-Stage Detection (YOLOv3), MultiStage Detection (CNN), Raspberry Pi 3B+, Arduino Uno R3, Ultrasonic sensor.	YOLOv3 Accuracy, Precision, Recall & F1 Score - 0.9341, 0.9722, 0.84, 0.9012. CNN Accuracy, Precision, Recall & F1 Score - 0.849, 0.85, 0.8491, 0.8512.
2022	(Rashida et al. 2022)	Implementation of Faster Region-Based Convolution Neural Network for Waste Type Classification	Robotic arm, raspberry pi, ultrasonic sensors, infrared sensors, SSD-Mobile Netv2 module and Garbage Classification dataset	Average accuracy detection of 81% with paper – 68%, plastic – 84%, glass – 85%, and metal 87%
2021	(Koskinopoulou et al. 2021)	Robotic Waste Sorting Technology	ABB IRB360 Delta Robot, ZED camera, Vacuum gripper module, Mask-regional CNN, Region proposal network, TrashNet & Taco dataset, Data Augmentation	RCNN (with Data Augmentation) Precision – 87.4%, recall – 90.1% & F1 scores – 88.7%.
2023	(Thanh et al. 2023)	Designing of A Plastic Garbage Robot With Vision-Based Deep Learning Applications	3 DOF Robot Arm (SCARA), Pneumatic end-defectors, cameras, One-Stage Detection (YOLOv5), Polygon Method using RoboFlow(Labelling Method), Bounding Box using RoboFlow (Labelling Method), Data Augmentation	YOLOv5 (Polygon Method): Precision – 92.1%, recall - 87.3%, Success Rate – 91.5%
2023	(Samsudeen et al. 2023)	Sky Sweeper: A Drone Surveillance Model Using YOLOV8 and Jetson Nano for	Nvidia Jetson Nano Kit, CSPDarkNet53, YOLOv8	Precision (98.6%); Recall (96.13%);

		Plastic Waste Monitoring System	(Object Detection Algorithm)	Success Rate (99.3%)
2022	(Johnson et al. 2022)	Application of AI and Machine Vision to improve battery detection and recovery in E-Waste Management	RoboCRM, DenseNet121, Fast R-CNN	No Results
2022	(Tornero et al. 2022)	Detection and Location of Domestic Waste for Planning Its Collection Using an Autonomous Robot	Autonomous Robot (Blue), NVIDIA DGX-A100 GPU, an RGBD Camera (Intel Realsense d435i with LIDAR) and various YOLO ((YOLOv3, YOLOv3-SPP, YOLOv5s, YOLOv51, YOLOv51 Augmented))	Precision – 0.991, recall – 0.992 and Rate of Detection – 36 ms
2022	(Bobulski & Kubanek 2021)	Vehicle For Plastic Garbage Gathering	Custom-built Plastic Sorting Robot, Rasberry Pi3, CNN (with Relu)	Accuracy – 87 % with Learning Rate (0.01), Max epoch (30), Regularization (0.1)
2019	(Hossain et al. 2019)	Autonomous Trash Collector Based on Object Detection Using Deep Neural Network	Customised Robot Vehicle, Raspberry Pi 3 & camera module, CNN (with Relu, Maxpool & Softmax functions), Arduino Mega, Ultrasonic sensor (HC-SR04)	Accuracy (training) – 0.98, accuracy (testing) – 0.96, Loss (training) – 0.389, Loss (testing) – 0.392.
2020	(Liu et al. 2021)	Garbage Collection and Sorting with a Mobile Manipulator using Deep Learning and Whole-Body Control	GarbageNet (Recognition & Localisation), Taco dataset (with augmentation), ROS, Grasp Pose Detection (GPD) system, Robotnik SUMMIT-XL Steel mobile platform, Franka Emika Panda robot, Whole Body Impedance Controller, RGB-D RealSense camera	GarbageNet: Mean average precision – 40.43 (with IoU of 0.75) Capture rate – 30 fps GPD system: Success rate – 90%
2022	(Akram et al. 2022)	Automatic Robotic Action Towards Plastic Collection	MultiStage Detection (Mask R-CNN), ResNet101, COCO (pre-trained), Region Proposal Network (RPN), ROI pooling, Arduino Uno R3, VGG Annotator, Data Augmentation,	Prediction Confidence (0.98 – 0.95), speed of detection (Moderate to high)
2021	(Zhou et al. 2021)	Towards the Urban Future: A Novel Trash Segregation Algorithm Based on Improved YOLOV4	Single Stage Detection (YOLOv4), CSPDarkNet53, Ghost module, DToU NMS, Spatial pyramid pooling module, Path aggregation network.	Accuracy (YOLOV4) - 94.83% and 91.25%.