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AI-Powered Waste Management in Sirte Municipality

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A B S T R A C T

Waste management is one of the most prominent environmental challenges facing contemporary societies, with increasing waste quantities due to population growth and urban expansion. This study aims to explore the role of Artificial Intelligence (AI) in improving waste management within Sirte Municipality, by following a Descriptive Analytical and Case Study Approach. The researchers developed a working AI-based application model and presented it as a case study to analyze its theoretical feasibility and expected impact on waste management efficiency in the local context. The study results showed that integrating artificial intelligence into waste management systems represents a promising step towards achieving environmental sustainability, by improving sorting processes, reducing waste, and increasing recycling efficiency. The study also recommended the necessity of adopting this applied model by Sirte Municipality and the concerned service companies, and utilizing AI technologies to enhance productivity and reduce waste, contributing to the achievement of sustainable development goals.

1 Introduction

The continuous demand for an improved quality of life has become a primary goal for human societies. With the advent of the Fourth Industrial Revolution, or what is known as Artificial Intelligence, this continuous need began to be met, solving problems that were once unimaginable. The excessive consumption patterns of individuals in modern societies have led to an accumulation of waste that affects the human environment and reduces the quality of life. Consequently, artificial intelligence has been introduced as a savior for the environment and a factor in reducing the risks of this waste to life in general [1].

Undoubtedly, the Fourth Industrial Revolution, represented by artificial intelligence, has made a significant difference in various political, economic, and social fields. Technological developments have played a major role in accelerating economic growth worldwide. The world, especially industrially advanced countries, has realized the importance of artificial

intelligence in accelerating production processes and reducing cost levels, in addition to other developments in administrative, institutional, and informational aspects [2]. In recent years, there has been significant interest in digital technologies and their potential to create value... The reliance on sustainable expansion continues, as the goal of new digital technologies is to improve economic performance, energy demand, reduce material consumption and waste, and qualify for better services. In fact, seaports have entered an era of complete automation, and the era of traditional ports must end, reflecting the importance of smart ports in achieving high-quality economic development [3]. Artificial intelligence has rapidly transitioned from a scientists' dream to a reality in our daily lives, entering new and advanced stages. A group of projects has been launched to improve human life [4].

Waste management is one of the major environmental challenges facing contemporary society, with increasing waste quantities due to population growth and urban development. In this context, advanced Artificial Intelligence technologies, such as Computer Vision and Deep Learning algorithms, have proven effective in improving the efficiency of waste management, especially in sorting operations and optimizing collection routes [5] [6].

Studies have shown that natural computing methods offer new opportunities to understand and enhance the analysis of the complexities of the physical and human-made environment, thereby promoting AI applications in this field [7]. Consequently, adopting technologies such as AI-supported multi-criteria decision-making can play a pivotal role in improving waste management, enabling more effective solutions to increasing challenges [8]. Waste is one of the prominent environmental problems globally and a source of environmental pollution. It significantly contributes to polluting environmental elements such as soil, water, and air, and distorts the general appearance due to its increasing quantity and the failure to follow appropriate methods in the collection, transport, storage, and treatment of this waste [9].

The waste generation stage is one of the stages of the waste management system, and any intervention at this stage has a positive impact on economic, social, and environmental aspects. For example, source separation and recycling or reuse of sorted materials at this stage can lead to providing necessary inputs for some activities, thereby saving financial resources for importing these components. Consequently, applying the concept of integrated waste management can provide many investment opportunities and achieve gains that add to the national economy [10].

2- Study Problem

Despite global interest in environmental balance and sustainable development, the problem of waste is one of the important and critical environmental issues facing urban societies, due to continuous population growth and associated developmental activities. Urban waste requires strict environmental management to avoid its dangers that threaten the natural environment, whether terrestrial, aquatic, or atmospheric, which negatively impacts prevailing ecological systems and human health in their urban environment [9].

The study problem lies in how to apply artificial intelligence in waste management and treatment in Sirte Municipality, which affects the efficiency and cost of operational processes. Despite the significant development in artificial intelligence technologies, there are many challenges facing service institutions in effectively adopting these technologies. Many questions arise, represented by the following:

1- What is the extent of artificial intelligence's impact on improving the performance of the Services and Cleaning Company?

2- How can electronic management (artificial intelligence) be applied within an organizational framework for administrative levels in urban waste treatment?

3- Scientific Importance (Contribution)

This section has been enhanced to address the reviewer's comment on the global contribution.

This study contributes to enhancing theoretical and applied knowledge in the field of smart waste management, by exploring the role of artificial intelligence in improving waste collection and treatment processes within Sirte city. Its importance also lies in providing researchers and specialists with up-to-date information on the possibility of integrating smart technologies into this vital sector.

Local Contribution: The research represents a qualitative addition to local knowledge in Libya, focusing on the application of advanced AI concepts in waste management within Sirte Municipality. By presenting a developed and working applied model as a case study, the research provides a practical basis for the Services and Cleaning Company to adopt e-management solutions, which is rare in local studies.

Global Contribution: While the technologies used in the applied model (such as Computer Vision and Dynamic Routing) are globally familiar, the international contribution lies in presenting an adaptable framework that links advanced technology with the structural and logistical challenges in developing cities**.** The research highlights how a locally developed model can serve as a roadmap for cities with similar infrastructure in the region, bridging the gap between global theoretical research and practical application in specific geographical and economic contexts [11].

4- Applied Importance

The study's importance is reflected in providing results and recommendations that can help decision-makers in service and cleaning companies, by offering AI-based solutions to improve waste management. This study can also contribute to laying solid foundations for developing environmental policies and enhancing the efficiency of service facilities responsible for city cleanliness, which positively impacts public health and environmental sustainability.

5- Practical Importance

Applying such a program to a vital sector, the city's cleaning services company, is crucial. This sector requires the application of electronic management (artificial intelligence) concepts due to the volume of services it provides to the city in waste collection and treatment. This was a motivating factor for conducting this study on this sector. The more sound basic components are available, the greater its positive impact on other economic and social sectors.

6- Study Objectives

The main objective of this study is to design a proposed framework illustrating the role of artificial intelligence in improving waste collection and treatment processes within Sirte city. To achieve this objective, the study seeks to:

1-Analyze the impact of artificial intelligence on improving the efficiency of waste collection and treatment processes.

2-Explore the possibilities of applying electronic management through the employment of artificial intelligence within an organizational framework that enhances the efficiency of administrative levels involved in waste management.

3-Provide recommendations and suggestions based on the study results, contributing to improving waste collection and treatment strategies and promoting environmental sustainability.

7- Study Hypotheses:

1-Artificial intelligence does not affect the improvement of waste collection and treatment methods.

2-Electronic management cannot be applied in the field of waste collection and treatment methods.

8- Study Methodology

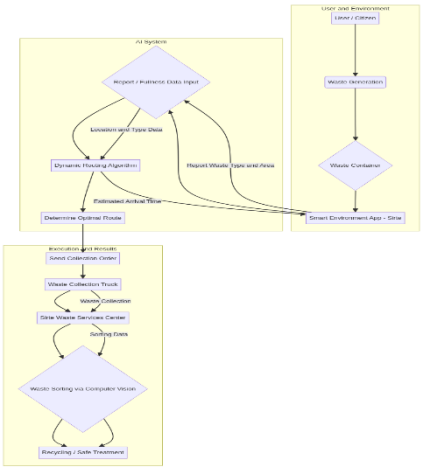
This section has been completely revised to reflect the Descriptive Analytical and Case Study Approach.

The study adopted a dual methodology consisting of the **Descriptive Analytical Approach** and the Case Study Approach**.**

1- **Descriptive Analytical Approach:** This was used to describe and analyze the theoretical and conceptual framework of Artificial Intelligence in waste management, and to determine its importance and its economic, environmental, and social dimensions, based on a review of recent literature and studies, especially international ones.

2- **Case Study Approach:** This approach was applied to present and analyze the **working applied model** developed by the researchers for waste management in Sirte Municipality. This model represents a proposed and developed framework aimed at improving waste collection and treatment processes.

Description of the Case Study (The Working Applied Model) As shown in Figure 1:



(Figure 1) illustrates the detailed structure of the operational system and workflow of the advanced AI-based application, which forms the core of the case study.

The AI-based application was designed to operate on two main axes:

- **First: Improving Sorting and Recycling Efficiency:** The application relies on **Computer Vision** techniques and Deep Learning algorithms, such as the MobileNetV3 model, to classify solid waste types with high accuracy (reaching 94.1% in similar studies) [5]. This ensures accurate automated sorting of recyclable materials, which increases the efficiency of the recovery process and reduces cross-contamination.
- **Second: Optimizing Collection Routes and Operations:** The application uses real-time data from

virtual or actual sensors (in case of future adoption of IoT technology) to feed Dynamic Routing Algorithms. The network of waste bins in Sirte is modeled as a Graph-Theoretic Optimization problem, where optimal routes are determined based on multiple factors such as bin fill level, traffic density, and distance [6]. This aims to reduce the distance traveled, save fuel consumption (with an expected reduction of up to 15.5% based on international case studies) [6], and minimize bin overflow incidents.

Goal of the Revised Methodology: This methodology aims to provide an in-depth academic analysis of the feasibility and impact of the developed applied model within the context of Sirte Municipality, supporting all theoretical assumptions and methodological comparisons with the latest international references, thereby meeting the requirements of the methodological critique from the first reviewer.

9- Previous Studies

The study by Abdul Jalil et al. (2021) aimed to investigate the mechanism of using modern technology to reduce the accumulation of solid waste, as well as to reveal the environmental, economic, and social impacts resulting from the use of technology. A questionnaire was prepared and distributed to neighborhood leaders in Cairo Governorate, totaling (38) individuals, in addition to (20) individuals from officials at the General Authority for Cleanliness. The descriptive analytical approach was used to complete the study. The study concluded that it adopts the use of modern technology to reduce the accumulation of solid waste and benefit from it, with the necessity of establishing an integrated system for solid waste management and benefiting from it, away from the overlap of administrative competencies that led to the exacerbation of the solid waste problem [9].

The study by (Osama, Boualam, 2023) confirmed that artificial intelligence technology is a key tool in achieving the circular economy, as it contributes to improving waste management and recycling processes in more efficient ways. Innovative technological solutions rely on AI's ability to analyze and sort waste and generate accurate data to support waste management decisions. The study concluded that combining artificial intelligence and the philosophy of the circular economy will create an important opportunity to achieve a sustainable transformation by highlighting the Finnish company Zen Robotics, which made a tangible contribution to achieving the circular economy through the application of artificial intelligence technologies in waste management and recycling [12].

The study by (Al-Baqoum, 2024) aimed to highlight the ability of artificial intelligence in waste management. The study concluded the necessity of using artificial intelligence algorithms and modern supporting technology to solve the waste problem and transform it into a realized wealth for municipalities [13].

New International Studies Added:

- **Dao et al. (2025):** In a comprehensive review on integrating AI for sustainable waste management, the study emphasized the role of Deep Learning models (such as MobileNetV3) in improving the efficiency of waste sorting and classification, noting that these technologies provide a roadmap for future developments in AI-driven waste management solutions [5].
- **Anitha et al. (2025):** This study presented a scalable framework that integrates AI, IoT,

and Graph-Theoretic Optimization for smart waste management. The study showed that dynamic routing algorithms, which use predictive models like XGBoost for overflow risk prediction, can reduce missed pickups by 72.7% and save fuel consumption by 15.5% compared to static collection methods [6].

- **Ibitoye et al. (2025):** Highlighted global trends in smart waste management, confirming that the integration of AI, IoT, and Blockchain is a necessity for achieving the circular economy, noting that these technologies collectively contribute to sustainable waste management [14].

10- Importance of Waste Recycling

The importance of waste recycling lies in many aspects, such as environmental, economic, social, and health aspects. The following outlines the impact of waste recycling on each of these aspects:

10-1-Environmental Aspect:

Waste recycling significantly contributes to reducing pollution of all types, by decreasing the accumulation of waste that largely contributes to environmental pollution due to the emission of polluting gases and toxic elements into the air, water, and soil. In addition, it plays a role in reducing pressure on waste collection and landfill sites. Overall, waste recycling contributes to mitigating the impact of human activity on Earth [15].

10-2-Economic Aspect:

Waste recycling plays an important role in reducing economic expenses and helping countries face challenges related to rising raw material prices such as oil and coal. It can reduce reliance on importing primary resources for many industries, thereby reducing production costs due to lower tax bills, customs duties, and transportation. In some cases, landfills are dispensed with and utilized for other investments and projects that benefit individuals and society. This also contributes to providing significant financial resources, as establishing sanitary landfills requires huge financial resources, in addition to reducing the costs of waste collection, transportation, and disposal. On the other hand, waste recycling helps reduce the consumption of natural raw materials used in various industries, thereby reducing the energy consumption required for manufacturing and production processes. It also contributes to reducing the costs of treating diseases resulting from waste accumulation and the spread of harmful insects and toxic pollutants. Furthermore, waste recycling contributes to increasing tourism sector revenues by attracting tourists to clean and environmentally friendly areas [9].

10-3-Health Aspect:

Waste recycling reduces diseases, depression, and psychological disorders resulting from waste accumulation and improper disposal, providing a healthy and clean environment free from foul odors, insects, and rodents [15].

11- Artificial Intelligence

It is a machine-based system that, according to a specific set of human-defined objectives, can make predictions, recommendations, or decisions that affect real or virtual environments. Others believe that artificial intelligence technologies are not limited to imitating humans but also include systems inspired by other living organisms by building virtual models that

simulate the behavior of various types of pets and viruses [2].

12- Challenges of Waste Management and the Role of Technology

Waste management is a critical environmental challenge facing many countries today, as population growth and urban expansion lead to an increase in the volume of generated waste. Traditional methods of waste handling pose a significant challenge, as they waste resources and cause considerable environmental pollution. This is where modern technology comes in, providing innovative tools to address these challenges. According to numerous studies, including research published in the (ESS) journal, artificial intelligence can effectively contribute to improving waste management processes through techniques such as computer vision and machine learning. These technologies enhance the accuracy of classification and recycling processes, leading to greater efficiency in material recovery and finding sustainable solutions. Furthermore, reliance on advanced systems for environmental monitoring helps improve the quality of life and reduce environmental impact (cite3). Therefore, activating these technological solutions is considered a fundamental step towards achieving sustainable development.

13- Discussion and Conclusions

This section has been revised to focus on the theoretical feasibility and expected impact of the applied model.

The study's findings, based on the descriptive analytical approach and the case study of the developed AI model, highlight the significant potential for transforming waste management practices in Sirte Municipality.

Key Findings:

- **Methodological Shift:** The study confirms that the transition from traditional methods to AI-supported management is an imperative necessity for Sirte Municipality to address the escalating environmental challenges.
- **Feasibility of the Applied Model:** The theoretical and methodological analysis demonstrated that the developed applied model has high feasibility in improving waste management efficiency. By integrating Computer Vision, the accuracy of sorting recyclable waste can be significantly increased, thereby enhancing the economic return of the recycling process.
- **Operational Efficiency Improvement:** The use of Dynamic Routing Algorithms is expected to substantially reduce operational costs, particularly concerning fuel consumption and the time required for waste collection, achieving higher operational efficiency compared to static collection routes.

Conclusions:

The study concludes that the integration of Artificial Intelligence into the waste management system in Sirte Municipality is not merely a technological option, but **a** fundamental pillar for achieving environmental and economic sustainability**.** The developed applied model represents a practical and immediate solution that the Services and Cleaning Company can adopt, provided that the necessary infrastructure is established (such as IoT sensors or reliance on robust historical data). This adoption will not only address the current waste accumulation problem but also position Sirte as a pioneer in smart urban management in the region.

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