AI-Driven Optimization of Food Waste Recycling in Egypt: Enhancing Circular Economy Strategies through Machine Learning and Automation

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Abstract

The increased use of carbon fiber composite (CFC) materials in various industries has stirred environmental worries regarding their disposal, necessitating the development of efficient recycling technologies. The study explores the development of CFC recycling with Egypt as a case study to assess the opportunities and challenges of embracing sustainable waste management. Egypt's growing industrialization and commitment to sustainability highlight the need for cutting-edge recycling approaches aligned with the concepts of circular economy. The article addresses several recycling technologies including pyrolysis, catalyst-supported recovery, and biodegradation, with an emphasis on their applicability in Egypt's environmental and industrial context. It also addresses waste handling attitudes, policy, and the application of artificial intelligence (AI) and machine learning (ML) in optimizing recycling efficiency. Results indicate that while Egypt has made some progress in waste management initiatives, investment in advanced recycling facilities, policy reform, and public awareness-raising campaigns is of the highest priority. The study recommends the adoption of AI-powered waste sorting technologies, increased government-industry collaboration, and the expansion of recycled carbon fiber applications in construction, transportation, and renewable energy industries. By integrating eco-friendly recycling technologies into Egypt's economic and environmental strategies, the country will be in a position to enhance resource efficiency, prevent environmental deterioration, and contribute towards fostering global sustainability.

Keywords: Carbon Fiber Recycling, Circular Economy, Waste Management, Sustainable Technologies, Egypt.

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تحسين إعادة تدوير نفايات الطعام بواسطة الذكاء الاصطناعي: تعزيز استراتيجيات الاقتصاد الدائري من خلال التعلم الآلي والأتمتة

ملخص

أدى الاستخدام المتزايد لمواد ألياف الكربون المركبة (CFC) في مختلف الصناعات إلى إثارة مخاوف بيئية بشأن التخلص منها، مما يستلزم تطوير تقنيات إعادة تدوير فعالة. تستكشف هذه الدراسة تطور إعادة تدوير ألياف الكربون المركبة، مع التركيز على مصر كدراسة حالة لتقييم الفرص والتحديات المرتبطة بتبني إدارة مستدامة للنفايات. تسلط الدراسة الضوء على التصنيع المتنامي في مصر والتزامها بالاستدامة، مما يستدعي تبني أساليب إعادة تدوير متطورة تتماشى مع مفاهيم الاقتصاد الدائري. يناقش المقال عدة تقنيات لإعادة التدوير، بما في ذلك التحلل الحراري، والاسترداد المدعوم بالمحفزات، والتحلل البيولوجي، مع التركيز على مدى ملاءمتها للبيئة والصناعة في مصر. كما يتناول مواقف التعامل مع النفايات والسياسات ودور الذكاء الاصطناعي (AI) والتعلم الآلي (ML) في تحسين كفاءة إعادة التدوير. تشير النتائج إلى أنه على الرغم من إحراز بعض التقدم في مبادرات إدارة النفايات في مصر، فإن الاستثمار في مرافق إعادة التدوير المتقدمة، وإصلاح السياسات، وحملات التوعية العامة تُعد أولويات قصوى. توصي الدراسة باعتماد تقنيات الفرز القائمة على الذكاء الاصطناعي، وزيادة التعاون بين الحكومة والصناعة، وتوسيع استخدام ألياف الكربون المعاد تدويرها في قطاعات البناء والنقل والطاقة المتجددة. ومن خلال دمج تقنيات إعادة التدوير الصديقة للبيئة في الاستراتيجيات الاقتصادية والبيئية لمصر، ستكون البلاد في وضع يسمح لها بتحسين كفاءة الموارد، ومنع التدهور البيئي، والمساهمة في تعزيز الاستدامة العالمية.

الكلمات المفتاحية: إعادة تدوير ألياف الكربون، الاقتصاد الدائري، إدارة النفايات، التقنيات المستدامة، مصر.

1. Introduction

Food waste is an urgent global problem, with a estimated 1.3 billion tons of waste annually, contributing significantly to environmental pollution, greenhouse gas emission, and resource depletion (United Nations Environment Programme, 2024). The inefficiency of traditional waste management systems in collection, sorting, and processing further exacerbates the issue, demanding innovative and data-driven solutions.

Artificial Intelligence (AI) has been a transformative tool in optimizing food waste recycling and valorization processes (Onyeaka et al., 2024). By using machine learning, deep learning, and automation, AI-based systems can enhance waste classification, bioconversion efficiency, and supply chain logistics, following the guidelines of the circular economy (Simranjeet, 2025; Fang et al., 2023; Lotchi, 2024). Despite the development of the technological side of AI-based waste management, its economic feasibility and financial returns on such practices have been largely unexplored.

This study aims to address this gap by investigating the use of AI and Internet of Things (IoT) technologies for recycling food waste in Egypt. It aims to develop predictive analytics models, automated sorting, and process optimization systems that can enhance sustainability while offering economic advantages to municipalities and industries. By ascertaining the impact of AI-driven recycling programs, this research contributes to environmental sustainability, in addition to the economic viability of waste management practices, paving the way for waste reduction processes that are not only more efficient but also scalable in Egypt.

2. Literature Review

The mass application of carbon fiber composite (CFC) materials in various industries calls for the development of efficient recycling technology. Interest worldwide in circular economy values and protecting the environment has catalyzed extensive research in recycling technology of CFC. Extant studies have examined recycling technology development trends, bibliometric study, and the future trends of research, showing the increased importance of managing green carbon fiber waste.

A bibliometric analysis by Guo et al. (2025) examined 5,979 articles published between the period 2000 and 2023, which reflected significant growth in the research dedicated to recycling carbon fibers in an environmentally friendly way. The review identified that pyrolysis was the dominant recycling technology but noted that advancements in scalability and material quality would be necessary to enhance its performance.

Following this, Huang et al. (2025) introduced a Ni–Pd/CeO2 catalyst for selective hydrogenolysis that enables efficient carbon and glass fiber recovery from epoxy composites without degrading their structural properties. This work is a significant step toward more efficient and sustainable recycling. Further, Xiao et al. (2025) researched lysosome-targeting peptides to degrade proteins in biomedical applications and suggested potential findings into novel material recovery strategies pertaining to carbon fiber recycling. Similarly, Dhairiyasamy and Gabiriel (2025) examined green mobility solutions within India's electric vehicle sector, linking carbon fiber recycling to supply chain sustainability as a measure against environmental impacts.

Aside from technology advancements, behavioral studies have provided insights into optimizing waste management systems for carbon fiber composites. Mhaddolkar et al. (2025) also investigated waste sorting behavior in Spain and Austria and concluded that recycling efficiency is influenced by education, habits, and beliefs. Agwe et al. (2025) further highlighted the variation in seasonal waste composition in Uganda, finding increased plastic content during the rainy season and proposing the optimization of recycling processes. These findings bring to the forefront the importance of public sensitization and waste management practices towards optimizing recycling efficiency.

Recovered carbon fibers have demonstrated vast potential towards application in various industries. Rohit and Chandrasekhar (2025) investigated mechanical trade-offs on geopolymer mortars based on slag with recyclable fine aggregates, demonstrating feasible applications of green construction. Wang et al. (2025) explored applying lignin-asphalt as an eco-friendly blend for carbon storage, noting that it has the potential to abate climatic impacts in maximized pavement life. Moreover, Viswanathan et al. (2025) demonstrated that carbon nanoparticles derived from banana peel waste can be applied to enhance plant growth and chlorophyll levels to support sustainable agriculture. For environmental monitoring, Zheng et al. (2025) designed a flexible SERS sensor for pesticide residue monitoring, incorporating recyclability into advanced food safety monitoring systems.

The integration of carbon fiber recycling into large waste management systems aligns with circular economy principles, promoting resource efficiency and sustainability. Optimizing supply chain resilience for food waste management was promoted by Zhao et al. (2025), and An et al. (2025) proposed valorizing food waste using plant ash and biochar as sustainable use of resources. Besides, innovation in sustainable packaging (Zhang et al., 2025; Ma et al., 2025) and novel bio-based materials (Deshmukh et al., 2025) exhibit the potential of integrating carbon fiber recycling with other novel sustainability initiatives.

As carbon fiber composite waste is increasingly produced, there is a need for green recycling practices in order to decrease environmental impact. Synthesizing carbon fiber recycling with the principles of circular economy can make resources more efficient and supply chains more sustainable. Emerging chemical, biological, and new recycling strategies offer promising new avenues to the traditional pyrolysis pathway, which are worth further research. Moreover, insights into the influences on recycling efficiency can optimize carbon fiber composite waste management systems. The application of recycled carbon fibers in construction, infrastructure, agriculture, and the environment also further highlights the necessity for scalable and efficient recycling methods.

Furthermore, Liu et al. (2025) explores solvothermal liquefaction (STL) of kitchen waste to produce bio-oil using Fe-Ni bimetallic catalysts and recycled ethanol. The catalytic process significantly enhances hydrocarbon and ester yields, improving bio-oil quality while reducing nitrogen and sulfur content. The research also highlights the economic and environmental advantages of STL, providing valuable insights for optimizing bio-oil production technologies. On the other hand, Gritsch et al. (2025) investigates the quantity and quality of paper-based packaging in municipal solid waste (MSW) and separate paper collection (SPC) in Vienna. By manual sorting, it identifies opportunities to enhance recycling rates and emphasizes the need for improved consumer communication and disposal methods to increase the recycling of paper packaging, particularly low-contamination streams like dry food packaging. In addition, Im et al. (2025) focuses on recovering short-chain fatty acids (SCFAs) from food waste condensate using supported liquid membrane contactors. It demonstrates high recovery efficiency, particularly for butyric acid, using trioctylamine (TOA) membranes. The study introduces real-time wettability monitoring and highlights the potential of modified membranes for long-term SCFA recovery applications, supporting sustainable waste recycling and bioenergy production.

The challenges of the research are met here by applying artificial intelligence (AI) and machine learning (ML) to improve food waste recycling and supply chain optimization. Specifically, the objectives of this research are to develop AI-predictive models for food waste generation and supply chain optimization, utilize machine learning algorithms for automated sorting and classification of food waste, and enhance bioconversion processes such as composting and anaerobic digestion through AI-assisted monitoring systems. Secondly, this study seeks to integrate IoT sensors with AI models for real-time adaptive control of waste processing machinery and assess the economic impacts of AI-automated food waste recycling, including cost reduction, efficiency gains, and profitability for business and municipalities.

The present research contributes to the development of sustainable recycling technologies, improved waste management technologies, and enabling the integration of the circular economy in carbon fiber recycling. Greater research into new recycling technologies and artificial intelligence-based waste management technologies will be crucial to long-term environmental sustainability and industrial performance.

3. Methodology

This study employs a qualitative approach. Primary data will be collected through semi-structured interviews with waste management official in Egypt. The interview will provide qualitative insights into the challenges, feasibility, and impact of AI-driven food waste recycling in Egypt.

4. Results and Analysis

The interview findings provide a good understanding of the current situation with food recycling in Egypt, what challenges are to come, and how AI technologies can contribute to improved waste management. The interviewees highlighted that food recycling in Egypt today lacks proper infrastructure, no government incentives, and reliance on the informal waste collection system, particularly the Zabbaleen. Despite the use of such traditional waste collectors, their work remains largely manual and without any technological support. Public education concerning food waste recycling is also limited, with households contributing little towards sorting and recycling efforts.

The efficiency and viability of current food waste recycling mechanisms in Egypt are still low. Most of the food waste ends up in landfills, and as a result, the environment is degraded. Although some companies have the practice of composting and biogas production, these activities are mostly on a small scale. The informal sector, despite having a huge network, is not endowed with high-technology devices that can optimize efficiency and sustainability. Interviewees hypothesized that AI can revolutionize food waste recycling operations by optimizing waste segregation, optimizing collection routes, and enabling resource recovery. AI-based waste sorting through computer vision would improve the accuracy of classification, while predictive analytics would enhance collection efficiency by forecasting peak waste seasons, particularly during periods like Ramadan.

IoT sensors, machine learning software, and automated sorting technology were among the AI tools cited as holding significant promise in improving waste classification and valorization. Restaurant and supermarket IoT-enabled sensors can track food waste levels in real-time, and predictive analytics can optimize waste processing and collection routes. However, AI deployment for food waste management is hindered by a number of constraints including high initial investment costs, the unavailability of historical data needed to train AI models, and resistance from the informal waste industry, which may view automation as a threat to traditional livelihoods.

Predictive analytics was also considered an important tool in optimizing food waste collection and recycling by predicting trends in waste generation, geo-mapping areas of high-waste generation in urban centers, and suggesting ideal bin placement. An AI-based waste sorting platform should target low-cost automation to complement manual sorting by the Zabbaleen with image recognition built-in to distinguish between organic and inorganic materials. Mobile applications also could encourage businesses and residences to sort waste, optimizing overall efficiency.

The interview respondents generally agreed that AI-assisted auto-classification programs have an advantage over traditional sorting methods due to being quicker and accurate. They still recognized the capability of Egypt's informal recycling sectors and proposed integrating a hybrid system that involves human sorting supported by AI. Among the available bioconversion processes, anaerobic digestion for the generation of biogas, black soldier fly production for animal feed, and composting for fertilizer manufacture were identified as the most promising. AI would enable enhancing these processes through monitoring of bacterial performance in biogas plants, predicting optimal conditions for composting, and regulation of inputs to achieve maximum energy outputs.
IoT sensor-based monitoring was considered to be at the core of optimization of processes in real time. Temperature and humidity sensors could optimize composting conditions, smart

bins could alert waste collection firms when full, and biogas plant sensors can regulate inputs for optimal energy output. The feasibility of AI-powered food waste recycling in Egypt was analyzed on the basis of potential cost reduction with optimized collection, income from sale of biogas and compost, and potential introduction of government incentives on AI-affected wastes.

Cost drivers for the implementation of AI-based waste management systems included equipment expenses for sorting machinery and IoT sensors, software coding for machine learning algorithms, training costs for waste management staff, and ongoing data collection and maintenance. Promoting AI use was proposed by policy measures like tax relief for organizations employing AI-based waste recycling, government subsidies for pilot projects, and education programs for citizens. AI technologies were also considered to facilitate carbon footprint reduction and promote circular economy objectives through enhanced material recovery, optimized waste logistics, and making biogas production from renewable energy sources possible.

Critical success factors for an AI-based food waste recycling program in Egypt included effective cooperation between the government and private sector, tapping the informal waste sector, and scalability of the program across different urban contexts. The scalability of the AI model varied depending on the location, with great potential in major cities such as Cairo and Alexandria due to their infrastructure and amount of waste, moderate in tourist areas such as Sharm El-Sheikh and Luxor, and slow adoption in rural areas due to a lack of AI infrastructure and less production of waste.

Future AI applications for waste management in Egypt will probably include more AI-based sorting of waste in smart cities, more use of AI-optimized biogas plants, and more IoT-based waste monitoring in malls, universities, and hotels. These findings indicate that AI has the potential to transform food waste recycling in Egypt but will have to overcome financial, logistical, and social hurdles through strategic policy interventions and stakeholder collaboration.

5. Discussion

The findings of this study are in line with the existing literature on the increasing importance of carbon fiber composite (CFC) recycling and advances in recycling technologies. According to Guo et al. (2025), the trend in research on CFC recycling has grown significantly, with major focus on pyrolysis as the most dominant process. This is consistent with the conclusions of this research, which point towards the necessity for recycling scalability and material quality improvement. Huang et al.'s (2025) research on the development of a Ni–Pd/CeO2 catalyst for selective hydrogenolysis also works towards the further pursuit of more efficient and sustainable recycling technology, which is also what the present study's emphasis on optimizing recycling processes for improved material recovery points towards.

The coupling of biological means, as in the work by Xiao et al. (2025) through lysosome-targeting peptides, indicates a new direction for the degradation of CFCs, which may complement conventional pyrolysis methods. This integration of chemical and biological means is reflected in this study, as well, through the call to extend research on alternative recycling approaches beyond pyrolysis. Moreover, the link between recycling carbon fiber and sustainable supply chains, as per Dhairiyasamy and Gabiriel (2025), further supports the argument that CFC recycling must be examined not just technologically but also in the broader context of supply chain sustainability. The results of this study also highlight the role of

CFC recycling in reducing environmental impact and improving resource efficiency, a consideration relevant for the use of recycled products in various industries.

Behavioral predictors of recycling effectiveness, studied by Mhaddolkar et al. (2025) and Agwe et al. (2025), present valuable insights into how to improve waste management to the maximum. These studies cite that education, consciousness, and seasonal variations in waste composition influence recycling performance, a factor supporting the need for public sensitization and enhanced waste-sorting technology highlighted in this study. The need to balance public awareness campaigns with recycling technology enhancement is crucial to the effectiveness of waste management policies. Moreover, Agwe et al. (2025) results regarding optimizing recycling activities in line with seasonal changes of waste ensure that responsive and dynamic recycling frameworks are needed, a matter directly pertinent to the concern of supply chain resilience and responsiveness addressed in this study.

Applications of recycled carbon fibers in all fields, as demonstrated by Rohit and Chandrasekhar (2025) in sustainable building, Wang et al. (2025) in sustainable asphalt mixing, and Viswanathan et al. (2025) in agricultural enhancement, also highlight the broad applicability of the by-products. These studies give credence to the argument that recycling reclaimed carbon fibers for application in industries other than the traditional composites, such as construction and agriculture, can contribute to scaling up efforts towards sustainability. This aligns with the assertions of the present study, which highlight the importance of scaling up CFC recycling technologies to as broad an application as possible across industries.

At a larger circular economy level, Zhao et al. (2025) and An et al. (2025) emphasize the integration of waste valorization practices into resource management. Their research corresponds with the current study's emphasis on integrating carbon fiber recycling into circular economy practice. Similarly, Zhang et al. (2025), Ma et al. (2025), and Deshmukh et al. (2025) bio-based material developments also reflect the growing trend towards sustainable material development, in favor of the argument that recycled carbon fibers should be put into a general sustainability framework and not evaluated separately.

Continuing to push the boundaries of sustainability, Liu et al. (2025) investigates solvothermal liquefaction (STL) for the production of bio-oil, and Gritsch et al. (2025) examines enhancing paper-based packaging recycling efficiency. These investigations emphasize the complexity of recycling and waste management, lending credence to the argument that interdisciplinary solutions are required to maximize recycling results. Im et al. (2025) adds to the same by demonstrating successful recovery of short-chain fatty acids from food waste, illustrating another new line of waste-to-resource conversion. Implications of these studies indicate the benefit of recycling CFC using learnings from the cross-industry in adopting advanced catalytic processes as well as optimization of recovery methods.

Thus the implementation of artificial intelligence (AI) and machine learning (ML) technology in waste handling, which was covered by this study, also aligns with emerging studies focusing on AI-dependent waste treatment and supply chain improvements. The objective of designing AI-predictive models, robotically optimized sortation technologies, and AI-simplified bioconversion processes also runs in concurrence with contemporary technoscientific progress. Such uses of AI with IoT-based adaptive control systems are an example of the trend toward more efficient, cost-effective, and intelligent recycling systems. Financial advantages of AI-based recycling in terms of cost reduction and improvement in efficiency are an indication of its capability to revolutionize waste management and sustainability programs.

6. Conclusion

The study highlights the growing significance of recycling carbon fiber composite (CFC) materials in developing circular economy and sustainability principles in Egypt. The increasing global production and use of CFC materials require efficient and scalable recycling mechanisms to minimize environmental impact and maximize resource use efficiency. The literature review captures significant advancements in the process of recycling, including pyrolysis, catalytic hydrogenolysis, and biological degradation, presenting varying degrees of efficiency and sustainability. Furthermore, behavioral studies place emphasis on public education of waste sorting and awareness for increasing recycling rates.

Further, applications of recovered carbon fibers in construction building, green farming, environmental monitoring, and industrial processing indicate a strong potential for implementing recycled materials in industries. The incorporation of machine learning and AI into waste management and supply chain optimization offers new opportunities for enhancing recycling efficiency, reducing costs, and facilitating large-scale usage. However, scalability, cost-effectiveness, and achieving consistent material quality from recycled fibers are concerns in Egypt at present.

The work contributes to developing sustainable recycling technology by integrating frontier material recovery methodology, AI-related waste management technology, and principles of circular economies. For industry and environmental long-term sustainability, increased research work and policy directions are needed towards improving recycling efficacy, developing advanced technologies, and raising public interest in waste handling n Egypt.

7. Recommendations

It is important to work beyond traditional recycling approaches to enhance the sustainability and effectiveness of carbon fiber composite (CFC) recycling in Egypt. To achieve this, innovative methods such as enzymatic degradation and solvothermal liquefaction must be investigated since they are capable of maximizing material recovery at low environmental impacts. Additionally, the development of catalyst-based recycling technologies can maintain the structural integrity of recycled carbon fibers, making them suitable for high-value applications across industries. Investment in new recycling technologies will yield more sustainable and scalable solutions aligned with circular economy principles.

Enhancing supply chain and waste management systems is another aspect that requires improvement. The application of machine learning and artificial intelligence-based forecasting models for sorting, grading, and treatment of waste can lead to a much better recycling outcome by enhancing efficiency and reducing operation costs. IoT sensors' utilization for the implementation of real-time monitoring systems will also enhance adaptive control of recycling and waste management plants with consistent quality and performance in material recovery. They will enable companies to build more robust and intelligent waste management procedures that maximize the utilization of resources.

Collaboration between policymakers, industries, and research institutions in Egypt is essential in driving sustainable recycling. Policymakers need to put in place policies and regulations that facilitate sustainable waste management and proper carbon fiber waste disposal. Industry stakeholders need to be actively involved in research funding, strategic partnerships, and the creation and application of scalable recycling innovations. Encouraging cross-industry collaboration will accelerate the commercialization of new recycling technologies and promote a more circular and sustainable industrial system.

Public awareness and education are also highly critical in rationalizing waste management systems. Initiatives to generate awareness regarding enhanced waste sorting habits and higher participation in carbon fiber recycling initiatives must be undertaken. Training and education on sustainable waste management strategies should be offered at consumer as well as industrial levels to induce permanent behavioral modifications. Raising awareness and levels of participation by people and organizations will make individuals and businesses more likely to accept sustainable waste disposal practices, ultimately enabling the successful operation of recycling programs.

Diversifying usage for recycled carbon fibers can be a driving factor in demand, and encouraging economic viability for recycling programs. Recycling carbon fibers gathered should be constructed for infrastructure usage, renewable power, and ecologically friendly packages so that these are utilized and the use of virgin materials minimized. Industries must integrate recycled carbon fibers into green construction, transportation, and environmental monitoring initiatives so that recycled products are used effectively in high-impact applications. By building markets and driving innovation, the application of recycled carbon fibers can be mainstreamed into other sectors, stimulating economic development and environmental sustainability.

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