APPLICATION OF ARTIFICIAL INTELLIGENCE IN OPTIMIZING THE RECYCLING PROCESSES OF ORGANIC MATERIALS, POLYMERS, AND COMPOSITES

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REVIEW, RESEARCH ARTICLE

Abstract

The accelerated growth in the volume of polymer and composite waste globally places an increasing pressure on traditional recycling systems, which can no longer efficiently meet current requirements. Artificial Intelligence (AI) is beginning to play an increasingly important role in modernizing these processes, offering solutions for more precise material sorting, rapid quality assessment of recycled products, and real-time optimization of industrial plant operations [1]–[3].

This paper presents the main directions in which AI can be successfully integrated into the recycling industry — ranging from image analysis and automated material recognition to complex digital modeling of equipment. The essential purpose of the study is to demonstrate how these emerging technologies can contribute to more efficient processes, lower operational costs, and a significantly higher quality of recovered materials.

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INTRODUCTION

The recycling of organic materials, polymers, and composites is becoming a fundamental topic in a global economy that attempts to redefine its production flows to become increasingly circular. In recent decades, modern materials — ranging from widely used high-performance polymers to complex fiber-reinforced composites — have become ubiquitous in key industrial sectors such as automotive, aerospace, and consumer goods. However, the very remarkable structural complexity that makes them useful also represents the main obstacle in the post-consumer phase. Each material presents a different molecular structure, a highly variable composition, and an often unpredictable or degrading behavior during classical thermal and mechanical reprocessing.

In recent years, AI has begun to offer viable and highly precise solutions to these structural problems [1], [2]. Through its native capacity to analyze massive amounts of data and recognize extremely complex geometric and spectral patterns, AI can support decision-making at critical stages of the recycling flow. The application of these tools brings immediately quantifiable advantages: a much faster sorting process free from human errors, an exact estimation of the physical-mechanical properties of recycled materials without resorting to costly destructive testing, the optimal and autonomous regulation of temperatures, pressures, or process times, as well as a drastic reduction in energy consumption and total operational costs [1], [2]. For these reasons, integrating AI into recycling is no longer viewed merely as an optional technological alternative, but as an absolutely necessary and strategic direction for the future of global sustainability.

CURRENT STATUS OF AI UTILIZATION IN RECYCLING

Intelligent Sorting

The correct and early sorting of materials is the essential phase for any successful recycling process. In the absence of efficient sorting, materials end up mixed on conveyor belts, becoming mutually contaminated and extremely difficult, if not impossible, to process later. At this point, AI holds a major advantage over simple optical systems or manual sorting. Through *Computer Vision* algorithms and convolutional neural networks (CNN), automated systems can "see", analyze, and recognize types of polymers, the intimate texture of composites, or the degree of surface contamination much better and faster than a human operator [1].

For example, multispectral cameras combined with AI can identify subtle differences in chemical reflection between polymers that look identical to the naked eye, such as polyethylene terephthalate (PET), polyvinyl chloride (PVC), or polypropylene (PP) [1]. Moreover, in the case of high economic value composites, AI has the ability to recognize the presence and orientation of carbon fibers within the polymer matrix. This decisively helps in their clean isolation and separation for reuse — an extremely delicate process that would otherwise require complex laboratory chemical analyses and huge financial costs [2], [3].

To highlight the technological leap achieved, Table 1 presents a direct comparison between the characteristics of the conventional process and the one optimized through artificial intelligence:

Table 1

Comparative analysis between conventional sorting and AI-based sorting

Operational Parameter	Manual / Conventional Sorting	AI-Assisted Sorting (CNN)
Classification Accuracy	60% - 75% (drops with fatigue)	90% - 95% (constant)
Detection Methodology	Macroscopic visual inspection	Multispectral imaging and textures
Composite Identification	Difficult, requires batch analysis	Automatic (carbon fiber isolation)
Processing Speed	Low, dependent on the human factor	High, adapted to fast conveyor belts

Prediction of Material Behavior

One of the greatest advantages of using AI in recycled materials engineering is its advanced ability to anticipate the behavior of polymers during melting and reforming stages. Intelligent models can establish non-linear correlations and estimate the thermal degradation of polymer structures, microstructural changes inherent to reprocessing, and the final mechanical properties of the obtained materials [3], [4]. This predictive capability is particularly useful for advanced polymers, where even a slight temperature variation inside the extruder can dramatically affect the final tensile or impact strength of the recycled part.

Recent studies in the literature confirm that AI can accurately predict the quality of finished products, being much more precise and efficient than traditional empirical methods based on repeated trials and sample destruction [3]. Yildirimoglu & Ozturk (2024) demonstrated that the mechanical and physicochemical performances of PEKK (polyetherketoneketone) composites reinforced with recycled carbon fibers can be predicted with minimal statistical error using Machine Learning models [3]. The system analyzes previously transmitted data and eliminates the need for manufacturing costly experimental pilot batches [3], [4].

Optimization of Technological Processes

Modern recycling of polymers and organic waste is no longer limited to simple mechanical shredding but utilizes complex chemical and thermal methods, such as pyrolysis, controlled extrusion, or catalytic depolymerization reactions. Each of these industrial processes requires an extremely careful, rigorous, and continuous control of temperature profiles, chamber pressures, and material retention times in reactors [1], [4]. Due to the rapid dynamics of the reactions, manual control becomes inefficient and generates losses.

AI-based technology can intervene directly in the control loop, adjusting these critical parameters in real time based on data continuously provided by industrial sensor networks [1], [4]. This type of intelligent and adaptive management brings major operational benefits:

- **Reduction of energy consumption:** By maintaining temperatures exactly at the optimal threshold required for the reaction, avoiding overheating.
- **Minimization of technological errors:** Preventing blockages or material burning inside the machinery.
- **Increase in yield:** Maximizing the amount of pure polymer recovered per operating hour.
- **Consistency of quality:** Obtaining a recycled plastic mass with constant physical properties from one batch to another.

Plant Simulation (Digital Twin)

Digital Twin technology represents one of the most revolutionary innovations within Industry 4.0, allowing the creation of an exact, mathematical, and three-dimensional virtual copy of a real industrial plant [2]. This digital model runs in parallel with the physical factory and is continuously fed with sensor data. The model can simulate various complex operating scenarios, identify critical wear points ahead of time, and accurately predict how the entire plant will behave under varying load conditions or when a new type of waste is introduced [2].

Combined with AI algorithms, this technique becomes an invaluable tool for engineers in recycling plants. The main advantages include:

1. It allows complete optimization of material and energy flows without needing to shut down the real plant for testing.
2. It significantly reduces experimental costs associated with developing new material formulations.
3. It provides a deep and transparent understanding of the internal thermochemical processes occurring inside isolated reactors.

METHODOLOGY

The workflow methodology described in this paper reflects the modern trends identified in the specialized literature and is configured to ensure a rigorous scientific path, being perfectly alined with recent results in the field of polymer and composite recycling [1], [3], [4].

The fundamental stages of the methodological approach are logically structured into the following operational flow:

[Data Collection] → [CNN Classification] → [Random Forest/XGBoost Prediction] → [Digital Twin Simulation]

- Collection of raw data: Real-time data is collected from actual recycling processes, including high-resolution images, detailed thermal parameters, operating pressures, and physical-mechanical properties of the resulting materials [2].

- Advanced optical classification: The collected images are processed using convolutional neural networks (CNN) to perform optical sorting, separation by polymer types, and structural identification of contaminants [1].

- Material quality prediction: Numerical data is run through advanced Machine Learning models, such as *Random Forest* and *XGBoost*, to predict the final structural properties of the recycled batch (e.g., the strength of PP or PEKK composites) [2], [3].

- General simulation and optimization: All data and predictions are integrated into the Digital Twin platform to simulate the long-term behavior of the plant and to validate the efficiency of the proposed ecological scenarios [2].

RESULTS AND DISCUSSION

Detailed analysis of the literature and recent experimental studies demonstrates that the utilization of AI brings direct, measurable, and stable benefits in waste reprocessing plants [1]–[4]. Centralized data confirms that sorting systems based on neural networks can achieve a stable accuracy located between **90% and 95%**, clearly outperforming manual methods or simple older-generation optical systems, which are limited by human fatigue or waste heterogeneity [1].

Furthermore, the determination and estimation of the mechanical properties of recycled polymer composites proved to be much more accurate when using predictive AI models compared to classical linear approximation equations and techniques [3]. This high level of mathematical precision provides confidence to companies wishing to reintroduce recycled plastics into demanding production circuits. From a macro-economic standpoint, using intelligent algorithms in planning and managing the recycling of fiber-reinforced composites (FRP) drastically reduces both the negative ecological impact (carbon footprint) and industrial production costs by eliminating unnecessary physical testing [2]. These concrete results definitively confirm that AI does not represent just a simple tool for the brute automation of repetitive tasks, but a complex system that significantly improves substantial material quality and overall resource efficiency [1]–[4].

CONCLUSIONS

The integration of Artificial Intelligence into the recycling processes of organic materials, polymers, and composites represents, undoubtedly, an essential strategic direction for the evolution of modern industry and for achieving the real objectives of the circular economy. The studies and articles analyzed in this paper confirm the full applicability and utility of AI tools at all key points of the technological flow: high-precision automated sorting, dynamic optimization of thermochemical parameters, and predictive modeling through advanced Digital Twin concepts [1]–[4].

In conclusion, AI proves to be an extremely powerful technological ally. It transforms traditional technical barriers into economic opportunities. The continuous development of these software tools and the expansion of their implementation at an industrial level will fundamentally redefine waste management in the coming years, ensuring substantial savings of the planet's resources and a major decrease in global pollution.

REFERENCES

[1] Podara C., et al. (2024). *Recent Trends of Recycling and Upcycling of Polymers and Composites: A Comprehensive Review*. Recycling, 9(3), 37.

[2] Li H., et al. (2025). *The challenge of recycling fast-growing fibre-reinforced polymer waste*. Nature Reviews Materials, 10, 81–82.

[3] Yildirimoglu Y.S., Ozturk F. (2024). *Advances in mechanical and physicochemical performances of recycled carbon fiber reinforced PEKK composites*. Polymer Bulletin, 81, 14453–14478.

[4] Teodorescu G.M., et al. (2023). *Properties of Composites Based on Recycled Polypropylene and Silico-Aluminous Industrial Waste*. Polymers, 15(11), 2545.