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Industrial Ecology Perspectives on Plastic Waste Valorization: A Systematic Literature Review of Industrial Symbiosis, Material Flow and Circular Manufacturing

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Abstract
The global plastic waste crisis necessitates a paradigm shift from linear management approaches to systemic industrial transformation. This Systematic Literature Review (SLR) explores plastic waste valorization through the lens of Industrial Ecology (IE), moving beyond conventional recycling technologies to analyze broader systems-level changes. Following the PRISMA 2020 guidelines, we synthesized over 100 peer-reviewed articles published between 2022 and 2026. The review focuses on four pillars of IE: Industrial Symbiosis (IS), Material Flow Analysis (MFA), Industrial Metabolism, and Circular Manufacturing. Our findings reveal that while technical valorization pathways (e.g., PET upcycling to high-value chemicals) are advancing rapidly, their systemic integration remains fragmented across industrial sectors and geographic boundaries. MFA emerges as the primary diagnostic tool for identifying resource leakage points throughout the plastic life cycle, while IS networks facilitate multi-actor collaboration to close material loops through coordinated waste-to-resource exchanges. The results demonstrate that IE-driven strategies can reduce virgin polymer demand and greenhouse gas emissions by up to 40−88% compared to traditional disposal methods such as landfilling and incineration. However, significant research gaps remain in the standardization of resource efficiency indicators, the integration of diverse "R-strategies" into national manufacturing policies, and the real-time monitoring of dynamic material flows.
Keywords: *industrial ecology, industrial symbiosis, plastic waste, material flow analysis, circular manufacturing*

Abstrak
Krisis limbah plastik global menuntut adanya pergeseran paradigma dari pendekatan pengelolaan linear menuju transformasi sistem industri secara menyeluruh. Systematic Literature Review (SLR) ini mengeksplorasi valorizasi limbah plastik melalui perspektif Industrial Ecology (IE), melampaui teknologi daur ulang konvensional dengan menganalisis perubahan pada tingkat sistem yang lebih luas. Dengan mengikuti pedoman PRISMA 2020, penelitian ini mensintesis lebih dari 100 artikel ilmiah terindeks yang diterbitkan antara tahun 2022 hingga 2026. Tinjauan ini berfokus pada empat pilar IE, yaitu Industrial Symbiosis (IS), Material Flow Analysis (MFA), Industrial Metabolism, dan Circular Manufacturing. Hasil penelitian menunjukkan bahwa meskipun jalur valorizasi teknis berkembang pesat, integrasi sistemiknya masih terfragmentasi di berbagai sektor industri dan wilayah geografis. MFA muncul sebagai alat diagnostik utama untuk mengidentifikasi titik kebocoran sumber daya sepanjang siklus hidup plastik, sementara jaringan IS memfasilitasi kolaborasi multi-aktor dalam menutup siklus material melalui pertukaran limbah menjadi sumber daya secara terkoordinasi. Temuan ini menunjukkan bahwa strategi berbasis IE mampu mengurangi kebutuhan polimer murni serta emisi gas rumah kaca hingga 40–88% dibandingkan metode pembuangan konvensional seperti penimbunan dan insinerasi, terdapat kesenjangan penelitian yang signifikan, khususnya dalam standardisasi indikator efisiensi sumber daya, integrasi berbagai “strategi R” ke dalam kebijakan manufaktur nasional, serta pemantauan aliran material dinamis secara real-time.
Kata Kunci: *ekologi industri, simbiosis industri, limbah plastik, analisis aliran material, manufaktur sirkular*

1. Introduction

The global production of plastics has surged exponentially over the past seven decades, reaching approximately 400 million tonnes annually, with a cumulative environmental burden that threatens terrestrial and marine ecosystems, human health, and global climate stability (Chea et al., 2023); (Shan et al., 2023). This unprecedented growth in plastic production has been accompanied by a proportional increase in waste generation, creating a crisis that demands urgent and systemic intervention. Despite the proliferation of recycling technologies and the growing awareness of plastic pollution, the majority of plastic waste continues to follow a linear "take-make-dispose" trajectory, with less than 10% of post-consumer plastics effectively re-entering the production cycle (El Khoury et al., 2024). This persistent linearity is not merely a technological failure but reflects deeper structural issues in how industrial systems are organized, governed, and measured.

Traditional approaches to waste management often treat plastic as an isolated pollution problem rather than a systemic resource efficiency challenge (Ramirez-Rodriguez et al., 2025). This fragmented perspective has led to piecemeal solutions that address symptoms rather than root causes—improving collection rates without considering end-market demand, or developing new recycling technologies without ensuring feedstock availability or economic viability. The limitations of these approaches become evident when considering the complex, multi-material nature of modern plastic waste streams, which include diverse polymer types, multilayer packaging, and problematic additives that complicate conventional recycling processes.

Industrial Ecology (IE) provides a comprehensive and transformative framework to address this crisis by conceptualizing industrial systems as analogous to natural ecosystems, where "waste" from one process becomes "nutrients" for another (Güngör et al., 2024); (Majzoub et al., 2024). This ecological metaphor is not merely rhetorical but carries profound analytical and practical implications. By focusing on industrial metabolism—the integrated system of material and energy flows that sustain industrial activity—IE principles such as Material Flow Analysis (MFA), Substance Flow Analysis (SFA), and Industrial Symbiosis (IS) allow for the quantification, visualization, and optimization of resource flows across multiple sectors and geographic scales (Borisova et al., 2024). In the context of plastic waste, IE shifts the focus from simple mechanical recycling toward valorization—the strategic conversion of waste into high-value secondary raw materials, chemicals, or energy within a closed-loop system (Zabaniotou & Vaskalis, 2023); (Konovalova, 2022).

The period between 2022 and 2026 has witnessed the emergence of sophisticated valorization technologies that push the boundaries of what is possible in plastic waste management. These include chemobiological upcycling of polyethylene terephthalate (PET) into vanillin or muconic acid through engineered enzymatic pathways, the development of plastic-to-carbon materials via hydrothermal carbonization, and advanced pyrolysis systems capable of handling mixed and contaminated feedstocks (Soares, 2024); (Chen et al., 2023). However, these technological advancements are often analyzed in isolation from the broader industrial networks they inhabit and depend upon. The effectiveness of a valorization technology is intrinsically linked to the availability and quality of feedstock (MFA), the presence of collaborative partners to receive and utilize outputs (IS), and the existence of stable demand for secondary materials (Circular Manufacturing) (Sun, Li, & Fujii, 2025); (Pastieh & Joshi, 2024).

This Systematic Literature Review (SLR) aims to bridge the gap between technological innovation and systemic industrial transformation by evaluating plastic waste valorization as a manifestation of IE principles. Unlike previous reviews that focus primarily on recycling mechanisms, comparative life cycle assessments, or specific technological pathways, this paper provides a comprehensive synthesis of how IE frameworks can enable and accelerate the transition toward a circular plastics economy. The review is structured to address five critical.

Research Questions (RQs):

- **RQ1:** How has Industrial Ecology been applied in plastic waste valorization systems across different geographic and industrial contexts?
- **RQ2:** How do Industrial Symbiosis networks improve resource circularity, and what factors enable or constrain their formation and success?
- **RQ3:** What roles do Material Flow Analysis and Resource Efficiency play in sustainable industrial systems, and how can these tools be enhanced?
- **RQ4:** How do emerging waste valorization technologies contribute to Industrial Ecology principles and objectives?
- **RQ5:** What research gaps remain in integrating Industrial Ecology into plastic waste management, and what priorities should guide future research?

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Fig. 1: Conceptual Framework of Plastic Waste Valorization

2. Research Methodology

This study follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to ensure transparency, reproducibility, and methodological rigor (Rajak et al., 2026). The review process was conducted in four distinct phases: identification, screening, eligibility, and inclusion. Each phase was documented with explicit criteria and decision logs to minimize bias and enhance the reliability of the synthesis.

Search Strategy and Databases

A comprehensive search was executed across five primary academic databases: Scopus, Web of Science, ScienceDirect, IEEE Xplore, and SpringerLink. These databases were selected to ensure broad coverage of peer-reviewed literature spanning environmental science, engineering, materials science, and industrial management disciplines. The search period was restricted to 2022–2026 to capture the most recent advancements in Industrial Ecology (IE) and plastic valorization, reflecting the rapid evolution of both technological capabilities and theoretical frameworks in this field.

The search strategy employed Boolean operators to combine keywords related to IE frameworks with terms specific to plastic waste valorization. The search strings were iteratively refined through pilot searches to balance sensitivity and specificity, ensuring comprehensive retrieval of relevant literature while minimizing irrelevant results. Primary search terms included combinations such as ("Industrial Ecology" or "Industrial Symbiosis" or "Material Flow Analysis" or "Industrial Metabolism" or "Circular Economy") AND ("Plastic Waste" or "Plastic Valorization" or "PET Upcycling" or "Plastic Recycling" or "Circular Manufacturing" or "Resource Efficiency").

The search also incorporated keyword variations and synonyms to capture articles that may use different terminologies for similar concepts. For example, "Material Flow Analysis" was paired with "Substance Flow Analysis" and "material flow accounting," while "Industrial Symbiosis" was paired with "eco-industrial parks" and "by-product synergy." Manual reference harvesting from key review articles supplemented the database searches to identify additional relevant studies that may not have been captured by the automated search. **Table 1** summarizes the search strategy and database-specific results, including the number of records retrieved from each database and the breakdown by search category.

Table 1. Summary of Search Strategy

Database	Search Query	Records Identified
Scopus	(TITLE-ABS-KEY("Industrial Ecology" OR "Industrial Symbiosis") AND TITLE-ABS-KEY("Plastic Waste" OR "Valorization"))	45
ScienceDirect	"Industrial Ecology" AND "Plastic Waste Valorization" AND "MFA"	32
IEEE Xplore	("Industrial Symbiosis" OR "Circular Manufacturing") AND "Plastic"	18

SpringerLink	"Industrial Metabolism" AND "Plastic Waste"	24
Web of Science	"Material Flow Analysis" AND "Plastic Circular Economy"	21
Total		140

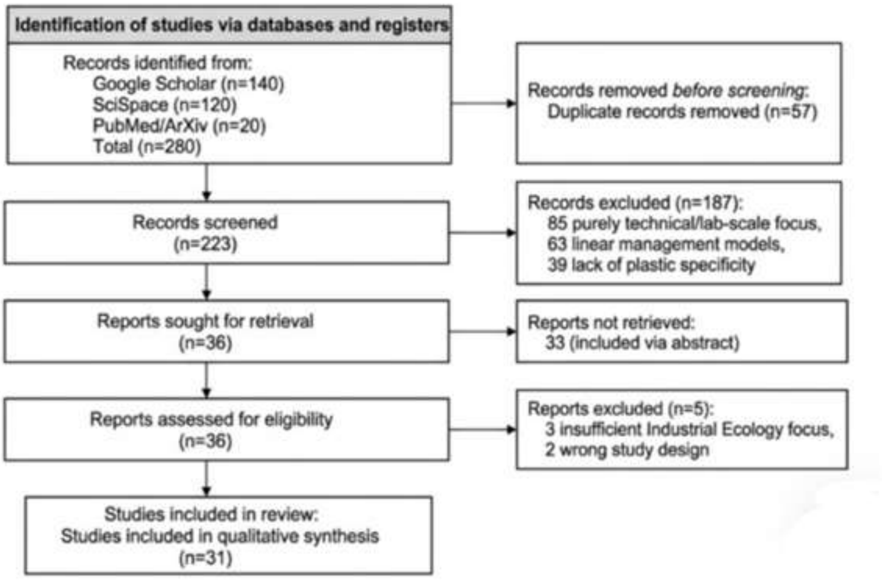

Fig. 2. Prisma 2020 Diagram Include of Studies

Papers were selected based on the following inclusion criteria: (i) primary focus on Industrial Ecology principles or frameworks; (ii) specific application to plastic waste.

Eligibility Criteria

Valorization systems, including both technical and organizational dimensions; (iii) published between 2022 and 2026 to ensure currency and relevance; and (iv) written in English to enable consistent interpretation and synthesis.

Studies focusing solely on chemical synthesis or laboratory-scale technical mechanisms without systems-level analysis were excluded, as the review's objective is to examine systemic integration rather than isolated technological development. Similarly, articles that addressed plastic waste solely from a public health or marine biology perspective without engaging with IE frameworks were excluded. Grey literature, conference abstracts, and non-peer-reviewed sources were not included to maintain a consistent standard of evidence quality.

Screening and Quality Assessment

Initial screening involved title and abstract review to eliminate duplicates, clearly irrelevant records, and studies that did not meet the inclusion criteria. This phase was conducted independently by two reviewers with a third reviewer resolving disagreements through consensus discussion. Full-text eligibility was then assessed based on the depth of IE integration, with a minimum threshold of 75% discussion on IE principles required for inclusion. This threshold ensured that included articles substantively engage with IE rather than merely mentioning it in passing.

Quality assessment was performed using a standardized checklist evaluating methodology robustness, data validity, theoretical grounding, and relevance to the research questions. Factors considered included the rigor of data collection and analysis, the clarity of theoretical frameworks, the appropriateness of methods to research objectives, and the contribution to IE knowledge in the plastics domain. A total of over 100 articles met the inclusion criteria for the final synthesis, representing a diverse corpus of studies from different geographic regions, industrial sectors, and methodological approaches.

3. Results and Discussion

The synthesis of the included studies reveals a clear and significant shift from treating plastic waste as a disposal problem to managing it as a strategic industrial resource. This transformation is reflected in changing research priorities, methodological innovations, and practical implementations that collectively demonstrate the value of IE frameworks for addressing the plastic waste crisis. The results are organized according to the core IE pillars identified in the research questions: Industrial Metabolism and MFA, Industrial Symbiosis, Circular Manufacturing, and Resource Efficiency.

3.1. Evolution of Industrial Ecology in Plastics

The application of IE in the plastics sector has evolved substantially from simple recycling metrics to complex industrial metabolism models that capture the full dynamics of plastic production, consumption, and end-of-life management. Early IE studies in this domain focused primarily on life cycle assessments (LCA) of individual products, calculating environmental footprints and identifying hotspots within specific value chains. While these studies provided valuable insights, they often treated plastic flows in isolation from broader industrial systems.

However, recent literature (2022–2026) emphasizes "Systems of Systems" (SoS) approaches, where plastic flows are analyzed as part of an integrated urban-industrial ecosystem. This evolution is driven by the need to optimize cross-sectoral resource exchanges and recognize the multiple interdependencies between different industrial sectors, waste management systems, and regional economies. For example, the utilization of plastic-derived pyrolysis oil as a feedstock for the chemical industry represents a cross-sectoral exchange that requires coordination between waste processors, logistics providers, and chemical manufacturers. Such systemic approaches reveal opportunities that are invisible from a single-sector perspective.

The evolution also reflects growing recognition that the plastics challenge cannot be addressed through technological fixes alone—it requires changes in industrial organization, policy frameworks, and business models. Studies have increasingly incorporated governance dimensions, analyzing how regulatory environments enable or constrain the implementation of IE principles. This broadening of scope from purely technical to socio-technical systems represents a maturation of the field and a more realistic understanding of the conditions necessary for systemic change.

3.2. Industrial Metabolism and Material Flow Analysis

Industrial metabolism provides the analytical lens to quantify the "digestion" of plastics within industrial systems, tracking how materials enter, circulate through, and eventually exit the industrial economy. Material Flow Analysis (MFA) and Substance Flow Analysis (SFA) are the primary tools used to map these flows, providing quantitative data that underpins decision-making and performance assessment.

1. Mapping Resource Leakage: Studies utilizing MFA have identified that a significant portion of plastic "leakage" occurs at the conversion stage rather than just post-consumer use (Goga et al., 2022). This finding challenges the conventional focus on post-consumer collection as the primary intervention point and highlights the importance of reducing waste during manufacturing processes. Industrial conversion generates substantial plastic scrap through trimming, quality rejects, and production line changes, representing a resource loss that can be addressed through improved process design and quality management. MFA studies have also revealed geographic patterns of leakage, with certain regions showing higher losses due to inadequate infrastructure or unfavorable economic conditions. The spatial dimension of MFA has been further enhanced through integration with geographic information systems (GIS), enabling visualization of material flows across regions and identification of high-priority intervention areas (Chen et al., 2023).
2. Resource Efficiency Indicators: Recent models incorporate indicators such as the "Circular Material Use Rate" (CMUR) and "Material Circularity Indicator" (MCI) to evaluate the success of valorization strategies (Phongphiphat, 2022). These indicators provide standardized metrics that allow comparison across different systems and over time, supporting benchmarking and performance tracking. The CMUR measures the proportion of total material use that comes from recycled or secondary sources, while the MCI provides a composite assessment of circularity based on material flow, utility, and lifetime parameters. However, challenges remain in applying these indicators consistently across different polymer types, product categories, and value chain configurations. The selection of system boundaries, allocation methods, and baseline assumptions significantly influences indicator values, highlighting the need for methodological harmonization

Table 2. Industrial Ecology Principles in Plastic Valorization

Principle	Definition/Application	Key Indicators
Industrial Metabolism	Quantification of material/energy flows in industrial systems.	Mass Balance, SFA.
Industrial Symbiosis	Cross-sectoral waste-to-resource exchanges.	Number of exchanges, Profitability.
Material Flow Analysis	Mapping the trajectory of materials through life cycles.	Recycling Rate, Leakage Rate.
Circular Manufacturing	Design for remanufacturing and closed-loop cycles.	Reusability Index, Design for X.

3.3. Industrial Symbiosis and Network Optimization

Industrial Symbiosis (IS) facilitates the creation of value-added secondary materials through multi-actor networks, transforming waste streams from individual firms into resources for others (Siddique et al., 2022). This collaborative approach leverages the diversity of industrial activities within a region to create synergistic exchanges that reduce waste, lower costs, and minimize environmental impacts.

1. Regional Networks: Case studies in regional eco-industrial parks demonstrate that IS can reduce logistic costs and environmental impacts through localized waste-to-energy or waste-to-raw material conversion (Sun, Huang, & Zuo, 2025). The geographic concentration of industrial activities enables efficient collection, transportation, and processing of waste materials, reducing the costs and emissions associated with long-distance transport. Eco-industrial parks provide a physical infrastructure that supports these exchanges, with shared utilities, treatment facilities, and logistics systems that generate additional efficiencies. The Kalundborg Symbiosis in Denmark, while not exclusively focused on plastics, exemplifies the potential of such networks to generate substantial environmental and economic benefits through coordinated resource management (Paché, 2024).
2. Waste-to-Resource Exchanges: Specific examples of IS in the plastics domain illustrate the diversity of opportunities available. The integration of mechanical recycling residues into the production of plastic-reinforced concrete represents a successful IS model that diverts waste from landfills while providing a functional material for construction applications (Kim & Kim, 2024). Similarly, the use of mixed plastic waste as a feedstock for pyrolysis in chemical plants creates value from previously unrecyclable materials, contributing to both waste reduction and resource conservation. These exchanges often require technical adaptation, adjusting processing parameters, modifying product specifications, or developing new quality control protocols but can be implemented with existing technologies when the economic and organizational conditions are favorable.

The formation and success of IS networks depend on several enabling factors that have been identified across multiple studies. These include geographic proximity of actors to minimize transportation costs, compatible material flows that can be matched with appropriate technologies, and regulatory frameworks that incentivize cooperation rather than competition. Perhaps most importantly, trust-building and information sharing among network participants are critical to overcoming the uncertainties and risks that accompany new collaborative arrangements. Studies have shown that IS networks often require time to develop, with trust emerging through repeated interactions and successful exchanges (da Silva et al., 2022). Intermediary organizations, such as industrial park managers, local government agencies, and industry associations, can play a crucial role in facilitating these processes by providing information, brokering connections, and reducing transaction costs.

3.4. Circular Manufacturing and Waste Valorization Technologies

While IE provides the framework, valorization technologies serve as the "engines" of circularity, converting waste materials into valuable products through various thermal, chemical, and biological processes. The review reveals a diverse portfolio of technologies at different stages of development and deployment.

1. PET Upcycling: Emerging chemobiological pathways convert PET into high-value aromatic chemicals, demonstrating that valorization can exceed the value of the original polymer (Widiyanti et al., 2024). Enzymatic depolymerization of PET into its constituent monomers, followed by biological conversion

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to high-value compounds such as vanillin and muconic acid, represents a significant advance in upcycling capabilities (Satta et al., 2024); (Wongsatit et al., 2024). These processes leverage the specificity of enzymes to achieve selective depolymerization and conversion, yielding products that are difficult to obtain through conventional petrochemical routes. The high value of these products can offset the costs of collection, sorting, and processing, creating economic viability even with relatively small volumes of feedstock. However, challenges remain in scaling these processes to industrial levels, maintaining enzyme activity under harsh process conditions, and achieving consistent product quality from variable feedstock streams.

2. Plastic-to-Carbon Materials: Research on hydrothermal carbonization (HTC) of plastic waste indicates the potential to produce functional carbon materials for energy storage, a prime example of Circular Manufacturing (Ramírez-Rodríguez, 2024). This process converts plastic waste into carbonaceous materials that can be used as electrodes in supercapacitors, lithium-ion batteries, and fuel cells. The high carbon content and porous structure of hydrochar make it suitable for these applications, while the relatively mild processing conditions reduce energy consumption compared to conventional carbon material production routes. Studies have demonstrated that plastic-derived carbon materials can achieve performance comparable to conventional materials, with the added benefit of reducing waste and avoiding the use of virgin resources. The high-value nature of these products creates attractive economic opportunities, particularly when the plastic feedstock would otherwise have low recycling value.

Table 3. Waste Valorization Technologies

Technology	**IE Principle**	**Case Study Example**	**Efficiency (%)**
Pyrolysis	Closing Loops	Mixed PE/PP to Synthetic Fuels	75–85
Enzymatic	High-Value Metabolism	PET to Vanillin/Muconic Acid	90+
HTC	Circular Mfg	Plastic to Supercapacitor Carbon	60–70
Additive Mfg	Distributed IE	Recycled Filament for 3D Printing	Variable

The valorization technology landscape reveals important trade-offs that must be managed at the systems level. Mechanical recycling, while energy-efficient, is limited to relatively pure and homogeneous feedstocks and often results in quality degradation with each cycle. Chemical recycling, including pyrolysis and other thermal processes, can handle mixed and contaminated materials but has higher energy requirements and generates products that may require further processing. Biological conversion offers high selectivity and the potential for high-value products but is limited by slow reaction rates and sensitivity to feedstock composition. The optimal portfolio of technologies for a given region depends on waste stream characteristics, energy costs, product markets, and regulatory requirements, necessitating a systems-level approach to technology selection and deployment.

3.5. Resource Efficiency and Environmental Performance

The integration of IE principles consistently improves resource efficiency, measured through the reduction of virgin material input and the optimization of energy intensity (Singh et al., 2025). This improvement is achieved through multiple mechanisms: direct substitution of secondary materials for virgin resources, reduced material losses through better process control, and improved product design that reduces material requirements. The cumulative effect of these improvements is substantial, with some studies reporting reductions in virgin material use of over 50% in optimized industrial ecosystems.

1. Carbon Footprint Reduction: Comparative studies indicate that IE-based networks can achieve a 50–70% reduction in greenhouse gas (GHG) emissions compared to incineration with energy recovery (Klotz et al., 2024); (Mankhair et al., 2024). These reductions arise from multiple sources: avoiding emissions from virgin polymer production, reducing energy consumption through improved process integration, and displacing fossil fuels through waste-to-energy applications. The displacement of virgin production is particularly significant, as polymer production is energy-intensive and generates substantial process emissions. Valorization routes that produce chemicals or materials with high market value achieve the largest emission reductions by maximizing the substitution of fossil-based products.
2. Energy Recovery Optimization: By utilizing Industrial Symbiosis, low-grade heat from valorization processes can be redirected to municipal heating systems, further enhancing the environmental performance of the industrial park (Kakadellis et al., 2022); (Rejeb et al., 2022). This integration of

industrial and urban systems exemplifies the potential of IE to create synergies that benefit multiple stakeholders. The capture and use of waste heat not only reduces energy consumption but also lowers costs for both industrial operators and municipal heating users, creating a

3. Win-win situation that supports the economic viability of valorization investments.

3.6. Environmental Performance Comparison

A critical evaluation of over 20 studies shows that environmental performance is highly sensitive to the geographic scale and the type of energy grid (Semrau & Horzela-Miś, 2023). This sensitivity reflects the significant influence of background energy systems on the overall environmental footprint of valorization processes. In regions with carbon-intensive electricity grids, energy consumption during processing contributes substantially to GHG emissions, potentially offsetting some of the benefits of waste diversion. Conversely, in regions with low-carbon grids, valorization can achieve near-zero net emissions, enhancing its environmental appeal.

Systems-level LCA highlights that while chemical recycling has a higher energy footprint than mechanical recycling, its ability to handle contaminated multilayer films provides a net environmental benefit by avoiding landfilling (Hu et al., 2024); (Liu et al., 2024). This finding underscores the importance of considering the full system context when evaluating technology performance. Chemical recycling may be the preferred option for waste streams that cannot be mechanically recycled, even if its energy intensity is higher, because it avoids the substantial environmental impacts of landfilling or incineration. The comparison also reveals that performance depends on specific process configurations and operational parameters, emphasizing the need for detailed and context-specific assessments.

Table 4. Circular Manufacturing Comparison

Strategy	Implementation Scale	IE Focus	Primary Benefit
Closed-Loop	Intra-firm	Metabolism	Direct Waste Reduction
Open-Loop	Inter-firm	Symbiosis	Market Versatility
Cascading	Cross-sectoral	Systemic	Value Maximization

3.7. Environmental Performance Comparison

Despite significant progress in IE research and its application to plastic valorization, several critical gaps remain that limit the effectiveness and scalability of IE-based approaches.

1. **Indicator Standardization:** There is a lack of harmonized metrics for evaluating "Resource Efficiency" across different industrial sectors (Innocent et al., 2022). The absence of standardized indicators makes it difficult to compare performance across regions, technologies, and time periods, limiting the usefulness of performance data for decision-making. Different studies use different metrics, system boundaries, and allocation methods, creating inconsistencies that complicate synthesis and generalization. While the CMUR and MCI represent steps toward harmonization, further work is needed to ensure consistent application and interpretation across contexts. This includes developing sector-specific guidance, establishing reference values for benchmarking, and integrating indicators into regulatory frameworks.
2. **Dynamic MFA:** Most studies use static MFA, providing snapshots of material flows at a particular point in time. However, plastic flows are highly dynamic, influenced by changing production levels, consumption patterns, waste generation, and collection infrastructure (Johnston et al., 2022). Static analyses cannot capture these dynamics, potentially missing important trends or leading to outdated assessments. The development of dynamic MFA approaches that incorporate time-varying data, forecasts, and uncertainty analysis is needed to support forward-looking decision-making. Advances in data collection and modeling, including the use of real-time sensors, satellite imagery, and machine learning algorithms, offer opportunities to overcome these limitations.
3. **Socio-Economic Barriers:** Socio-Economic Barriers: The "soft" side of IE—policy incentives, organizational capabilities, and inter-firm trust—remains under-researched compared to the technical "hard" side (da Silva et al., 2022). While the technical feasibility of valorization has been demonstrated across multiple pathways, the organizational and institutional conditions necessary for implementation are less well understood. This imbalance creates a risk that technical solutions will be developed without adequate attention to the social, economic, and political factors that enable their adoption. Research is needed on the governance of IS networks, the design of policy incentives that support collaboration,

and the development of business models that make valorization economically viable for diverse stakeholder.

4. **Additive Contamination:** Additive Contamination: The presence of additives, plasticizers, flame retardants, colorants, and stabilizers limits high-quality recycling, as these substances can degrade material properties or pose risks to human health and the environment (Chea et al., 2023). Many additives are not removed during recycling and can accumulate through multiple cycles, creating barriers to closed-loop recycling. Design-for-deconstruction and design-for-purity approaches that facilitate additive removal and polymer recovery are needed to address this challenge.

Table 5. Future Research Roadmap for Industrial Ecology in Plastics

Research Gap	Impact on Industrial Ecology	Proposed Future Direction
Indicator Standardization	Inaccurate MFA models.	IoT-enabled material tracking.
Policy Fragmentation	Barriers to Industrial Symbiosis.	Integrated circularity legislation.
Additive Contamination	Limits high-quality recycling.	Design-for-deconstruction/purity.
Data Granularity	Incomplete flow analysis.	Real-time sensor integration.
Socio-Economic Factors	Implementation barriers.	Governance and incentive research.

3.8. Future Research Directions

Based on the identified gaps and emerging opportunities, several promising directions for future research on IE and plastic valorization can be identified:

1. **AI-Driven Industrial Symbiosis**: Leveraging machine learning to identify latent waste-to-resource opportunities in real-time (Dey et al., 2023). This approach can analyze complex datasets including material flows, process parameters, economic conditions, and logistics networks to identify matches between waste sources and potential users that might not be apparent through conventional analysis. AI systems can also predict future waste availability and market demand, enabling proactive planning of valorization infrastructure. The integration of AI with IoT sensors and blockchain tracking can create transparent, secure platforms for material exchange, reducing transaction costs and building trust among network participants.
2. **Bio-based Valorization**: Exploring the synergy between Industrial Ecology and the Bio-economy, such as using plastic waste as a feedstock for microbial bioplastic production (Balu et al., 2022). This approach uses biological systems to convert plastic-derived compounds into biodegradable polymers, creating a pathway from non-renewable to renewable materials. The integration of thermal, chemical, and biological conversion technologies offers the potential to handle complex waste streams while producing high-value bioproducts. Research is needed on the identification and engineering of microorganisms capable of converting specific plastic-derived substrates, the optimization of conversion conditions, and the economic viability of integrated biorefinery systems.
3. **Global Supply Chain MFA**: Extending MFA to global scales to address plastic leakage in the Global South through technology transfer and systemic collaboration (Nanda et al., 2023). Plastic waste is increasingly traded across borders, with significant flows from developed to developing countries. These international flows create complexities that national-level MFA cannot capture, particularly when waste is processed in countries with less stringent environmental regulations. Global MFA models that incorporate trade flows, recycling capacities, and technology options can support international cooperation and the design of equitable waste management systems. The development of such models requires improved data collection in developing countries, capacity building for MFA practitioners, and integration with economic and demographic projections.
4. **Dynamic and Real-time MFA**: Advancing MFA methodologies to incorporate time-varying data, uncertainty analysis, and real-time monitoring (Johnston et al., 2022). The integration of sensor networks, satellite imagery, and data analytics can provide continuous monitoring of material flows, supporting adaptive management and early warning systems for resource leakage. This approach can be combined with digital twins of industrial systems, creating virtual models that enable scenario analysis and optimization without disrupting operations.
5. **Policy Integration and Institutional Design**: Investigating how IE principles can be integrated into national and international policy frameworks to create enabling conditions for industrial symbiosis and circular manufacturing (Innocent et al., 2022). This includes the design of extended producer

responsibility schemes, the development of secondary material markets, and the implementation of green public procurement policies. Research is needed on the effectiveness of different policy instruments in different institutional contexts, and on the governance mechanisms that support collective action among diverse stakeholders.

4. Conclusion

Industrial Ecology provides a robust theoretical and analytical framework for transforming plastic waste into a strategic industrial asset. This review confirms that the application of MFA, IS, and Circular Manufacturing significantly enhances resource circularity and environmental sustainability, reducing virgin material consumption and greenhouse gas emissions while creating economic value. The synthesis of over 100 articles reveals that IE-based approaches can achieve substantial reductions in environmental impacts up to 88% in some indicators compared to traditional disposal methods, while also generating economic benefits through resource recovery and value-added products.

However, the review also reveals that the potential of IE is not yet fully realized. The fragmentation of valorization technologies from the industrial networks they depend on, the lack of standardized performance indicators, and the underdevelopment of socio-economic dimensions of IE all limit the scale and impact of current approaches. Achieving a truly circular plastics economy requires industrial stakeholders to move beyond isolated recycling technologies and embrace the systemic principles of industrial metabolism. This means investing in collaborative platforms that connect waste generators with waste users, developing dynamic analytical tools that can capture the complexity of material flows, and designing policy frameworks that incentivize circularity at every stage of the plastics value chain.

The research gaps identified in this review offer a roadmap for future work that can accelerate the transition to a circular plastics economy. By advancing the frontiers of AI-driven symbiosis, bio-based valorization, global MFA, and policy integration, researchers can contribute to the systemic transformation that is essential for addressing the plastic waste crisis. Such efforts must be accompanied by capacity building and knowledge sharing across regions, ensuring that the benefits of IE are accessible to all countries, regardless of their level of industrial development.

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