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# CONTRIBUTION OF INDUSTRIAL SYMBIOSIS NETWORKS TO GREENHOUSE GAS EMISSION REDUCTION: A QUANTITATIVE ASSESSMENT USING ENVIRONMENTAL PERFORMANCE INDICATORS

## Abstract

Industrial symbiosis has gained increasing importance as a systemic approach within the circular economy for improving resource efficiency and reducing greenhouse gas emissions. The aim of this study is to develop a theoretical framework explaining how industrial symbiosis networks contribute to greenhouse gas emission reduction within an environmental economics perspective. The study is based on a theoretical analysis and conceptual synthesis of industrial ecology and environmental economics literature.

The results identify three core operational mechanisms – material substitution, energy cascading, and waste valorization – through which industrial symbiosis reduces lifecycle emissions, and structure their relationships within a framework consisting of four interrelated components: industrial symbiosis activities, operational mechanisms, environmental performance outcomes, and environmental economic outcomes. Greenhouse gas emissions expressed in CO<sub>2</sub>-equivalent terms are conceptualized as the primary environmental performance indicator, while economic indicators such as cost savings, eco-efficiency, and emission abatement cost are integrated to explain how emission reduction aligns with economic efficiency. The framework demonstrates that industrial symbiosis functions as a decentralized coordination mechanism that reduces environmental externalities through system-level resource optimization rather than technological change alone.

The findings contribute to environmental economics theory by clarifying the relationship between industrial cooperation, environmental performance indicators, and economic efficiency, providing a structured basis for future empirical assessment and policy evaluation.

## Keywords

industrial symbiosis, greenhouse gas emissions, environmental performance indicators, environmental economics, circular economy, eco-efficiency, decarbonization, resource efficiency

**JEL Classification** Q54, Q56, Q58, D62, L23

## INTRODUCTION

Industrial production systems remain among the largest contributors to global greenhouse gas emissions due to intensive energy consumption, extensive material use, and the generation of significant volumes of industrial waste (Johansson et al., 2018). Achieving climate neutrality within industrial sectors therefore requires approaches that simultaneously improve environmental performance and maintain economic efficiency (Cooper & Hammond, 2018; Hernandez et al., 2018). In this context, industrial symbiosis solutions are increasingly



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recognized as key enablers of circular economy models, promoting both economic and environmental benefits through techno-economic approaches such as material flow cost accounting and cost-benefit analysis (Leiva et al., 2025). At the same time, recent research has emphasized the importance of systemic solutions that extend beyond individual technological improvements and instead focus on optimizing resource flows across interconnected industrial activities (Smart et al., 2017).

Despite the growing recognition of the environmental benefits, the theoretical understanding of how industrial symbiosis contributes to measurable emission reduction within an environmental economics framework remains fragmented (Neves et al., 2020). Existing research has largely focused on descriptive case studies or methodological applications such as life-cycle assessment, while fewer studies have provided integrated conceptual explanations linking industrial symbiosis activities with environmental performance indicators and economic evaluation concepts (Daddi et al., 2017; Martin et al., 2015). Consequently, the relationship between industrial symbiosis, environmental performance outcomes, and economic efficiency improvements remains insufficiently structured (Bastias et al., 2023). In particular, the economic implications of emission reduction achieved through resource flow optimization are often addressed implicitly rather than within a coherent analytical framework (Morales & Diemer, 2019).

This study addresses this gap by developing a theoretical framework that links industrial symbiosis activities with environmental performance indicators and economic outcomes relevant to environmental economics analysis. The study conceptualizes industrial symbiosis as a decentralized mechanism of emission reduction, in which environmental improvements emerge from coordinated resource exchange among firms (Mendez Alva et al., 2021). Environmental performance indicators, particularly greenhouse gas emissions expressed in CO<sub>2</sub>-equivalent terms, are used as analytical tools to explain how emission reductions occur at the system level (Fraccascia et al., 2021b). In addition, the study incorporates economic indicators such as cost savings, eco-efficiency, and emission abatement costs in order to strengthen the economic interpretation of industrial symbiosis within industrial decarbonization strategies. By integrating industrial ecology concepts with environmental economics reasoning, the study contributes to a more comprehensive theoretical understanding of how collaborative industrial arrangements can simultaneously enhance economic efficiency and environmental performance (Fraccascia et al., 2021a).

The preceding discussion demonstrates that industrial symbiosis is widely recognized as an effective approach for improving resource efficiency and reducing environmental impacts within industrial systems. However, the theoretical relationship between industrial symbiosis activities, measurable environmental performance outcomes, and economic implications remains insufficiently structured within environmental economics analysis. Existing research frequently emphasizes environmental benefits through case-based evidence or methodological approaches, while fewer contributions provide an integrated conceptual explanation of how industrial symbiosis mechanisms simultaneously lead to greenhouse gas emission reduction and economic efficiency improvements.

This study addresses this gap by developing a conceptual framework that explains industrial symbiosis as a system-level mechanism of emission reduction based on resource flow optimization.

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## 1. THEORETICAL BASIS

Industrial symbiosis has evolved into a central concept within industrial ecology, primarily concerned with improving resource efficiency through the optimization of material and energy

flows across interconnected industrial actors (Domenech et al., 2019). Early contributions to the field were grounded in empirical observations of industrial networks, where waste streams generated by one production process were utilized as inputs in another, thereby reducing both

environmental impacts and production costs (Chertow, 2000; Daddi et al., 2017; Ehrenfeld & Gertler, 1997). These foundational studies established industrial symbiosis as a mechanism capable of generating environmental and economic benefits simultaneously, demonstrating that inter-firm cooperation can achieve efficiency improvements beyond those attainable through isolated firm-level optimization (Chertow, 2000; Ehrenfeld & Gertler, 1997).

Within this broader transition toward resource-efficient and low-carbon industrial systems, industrial symbiosis has emerged as a promising concept capable of simultaneously supporting environmental and economic objectives. Industrial symbiosis refers to the mutually beneficial exchange of materials, energy, water, and by-products among traditionally separate industrial actors, transforming residual outputs into productive inputs (Domenech et al., 2019). Foundational studies in industrial ecology demonstrated that such exchanges can significantly reduce resource consumption and environmental impacts by closing material and energy loops within industrial systems (Chertow, 2000; Ehrenfeld & Gertler, 1997). Subsequent research further emphasized that these environmental improvements are primarily achieved through system-level optimization rather than isolated technological innovation, highlighting the importance of coordination and cooperation among firms (Chertow, 2007).

From an environmental economics perspective, industrial symbiosis represents a particularly relevant mechanism for addressing environmental externalities. Environmental degradation is frequently interpreted as a consequence of market failures, where the environmental costs of production are not fully reflected in market prices (Morales & Diemer, 2019). Traditional policy instruments – such as carbon pricing, environmental taxation, and regulatory standards – aim to internalize these externalities by modifying economic incentives (Bahn-Walkowiak & Wilts, 2017). Industrial symbiosis complements these instruments by enabling firms to reduce emissions and resource consumption through economically motivated cooperation (Muñoz Puche et al., 2026; Bilyaminu et al., 2024). This approach also contributes to the decarbonization of energy-inten-

sive industries and enhances economic benefits for network partners, while requiring appropriate risk management frameworks to ensure environmental sustainability (Ventura et al., 2025). By transforming waste streams into economically valuable inputs, industrial symbiosis aligns private economic incentives with broader environmental objectives, thereby improving resource allocation efficiency and reducing environmental pressure (Liu et al., 2018).

The environmental benefits of industrial symbiosis are closely associated with greenhouse gas emission reduction, which occurs through several interrelated mechanisms. Material substitution reduces emissions associated with primary resource extraction and processing by replacing virgin materials with secondary resources (Li et al., 2017). Energy cascading improves overall energy efficiency by reusing excess energy or waste heat across industrial processes, thereby reducing fossil fuel consumption (Savian et al., 2023), as demonstrated in applications such as the co-production of methanol and ammonia integrating green hydrogen within carbon capture and utilization systems (Magson et al., 2025). Waste valorization avoids emissions related to disposal and treatment processes by transforming waste streams into productive inputs, contributing to the closure of material loops within industrial systems (Yu et al., 2018). Collectively, these mechanisms enable reductions in lifecycle emissions across industrial networks (Jacobsen, 2006; Neves et al., 2020; Sokka et al., 2011).

Subsequent research extended this perspective by shifting from case-based descriptions toward a more systemic and network-oriented understanding of industrial symbiosis (Mendez Alva et al., 2021). In this context, the literature emphasizes that environmental benefits are not solely the result of technical resource exchanges but also depend on organizational arrangements, institutional conditions, and trust-based relationships among firms (Chertow, 2007; Wang et al., 2016). Industrial symbiosis is therefore increasingly conceptualized as a network-based coordination mechanism in which environmental performance improvements emerge from the restructuring of material and energy flows at the system level (Bilyaminu et al., 2024).

From an environmental economics perspective, the relevance of industrial symbiosis lies in its capacity to reduce environmental externalities through improved resource allocation and coordinated economic activity rather than through technological substitution alone (Hatsor & Jelnov, 2024; Morales & Diemer, 2019). By facilitating the circulation of materials and energy between firms, industrial symbiosis enables emission reductions that arise from systemic efficiency improvements across industrial networks (Bilyaminu et al., 2024). Harmony between industry and nature through concepts like industrial ecology and food web analysis provides a novel perspective on sustainable industrial practices (Genç, 2024).

Traditional environmental economics approaches address greenhouse gas emissions primarily through policy instruments designed to internalize environmental externalities, including carbon pricing mechanisms, environmental taxation, and regulatory standards (Bahn-Walkowiak & Wilts, 2017). While such instruments remain essential for achieving climate objectives, the framework proposed in this study suggests that industrial symbiosis may complement these policies by providing economically motivated pathways for emission reduction (Liu et al., 2018; Muñoz Puche et al., 2026). Firms participating in symbiotic exchanges reduce material and energy costs while simultaneously decreasing emissions, thereby aligning private economic incentives with broader environmental goals (Yu et al., 2018). This alignment reduces the divergence between private and social costs that typically characterizes environmental externalities.

Cost savings and additional revenue streams derived from secondary resource utilization constitute direct incentives for firms to participate in symbiotic networks (Muñoz Puche et al., 2026). At the same time, transaction costs associated with coordination, information exchange, and infrastructure adaptation may limit participation despite positive environmental outcomes. From an environmental economics perspective, these transaction costs represent coordination barriers that may justify policy intervention aimed at facilitating cooperation rather than imposing additional regulatory constraints.

Emission abatement cost represents a particularly important indicator linking industrial symbiosis with climate policy evaluation (Bastias et al., 2023). Similarly, eco-efficiency indicators illustrate how industrial symbiosis improves the ratio between economic output and environmental impact, reinforcing the argument that environmental and economic performance improvements need not be mutually exclusive (Sokka et al., 2011).

Within the European policy context, industrial symbiosis aligns closely with circular economy and industrial decarbonization strategies that emphasize resource efficiency and waste reduction as drivers of sustainable growth (Domenech et al., 2019). Policies supporting industrial clustering, information-sharing platforms, and infrastructure development may reduce transaction costs and increase the economic attractiveness of symbiotic exchanges (Bahn-Walkowiak & Wilts, 2017).

From the perspective of environmental economics, industrial symbiosis can be interpreted as a response to market failures associated with environmental externalities (Hatsor & Jelnov, 2024). Environmental degradation is commonly explained by the absence of full cost internalization, where environmental impacts are not reflected in market prices (Morales & Diemer, 2019). Traditional policy instruments – such as environmental taxation, emission trading systems, and regulatory standards – seek to correct these inefficiencies by modifying economic incentives (Bahn-Walkowiak & Wilts, 2017). Within this framework, industrial symbiosis represents a complementary mechanism, as firms voluntarily engage in resource exchanges that simultaneously reduce costs and environmental impacts (Muñoz Puche et al., 2026; Bilyaminu et al., 2024). This process also supports the decarbonization of energy-intensive industries and enhances economic benefits for network participants, while highlighting the importance of risk management in maintaining environmental sustainability within industrial ecosystems (Ventura et al., 2025). Accordingly, industrial symbiosis may be understood as a decentralized coordination mechanism that partially internalizes environmental externalities through market-based cooperation rather than direct regulatory intervention (Liu et al., 2018).

A substantial body of literature has examined the environmental performance implications of industrial symbiosis, particularly in relation to resource efficiency and lifecycle emission reduction (Savian et al., 2023). The literature identifies three core operational mechanisms through which these benefits are realized. First, material substitution reduces emissions associated with primary resource extraction and processing by replacing virgin materials with secondary resources (Li et al., 2017). Second, energy cascading improves overall energy efficiency by reusing excess energy or waste heat across interconnected processes, thereby reducing fossil fuel consumption (Muñoz Puche et al., 2026), as illustrated by applications such as the co-production of methanol and ammonia integrating green hydrogen within carbon capture and utilization systems (Magson et al., 2025). Third, waste valorization contributes to emission reduction by transforming waste streams into productive inputs, thereby avoiding disposal-related impacts and closing material loops within industrial systems (Yu et al., 2018). Empirical studies confirm that these mechanisms can generate measurable environmental benefits at the system level, particularly in terms of reduced energy consumption and greenhouse gas emissions (Jacobsen, 2006; Neves et al., 2020; Sokka et al., 2011).

Despite these advances, the literature reveals a limited integration between industrial symbiosis research and environmental economics analysis (Bastias et al., 2023). While many studies focus on environmental performance improvements, fewer contributions explicitly examine how these improvements translate into economic efficiency gains or how they interact with policy instruments aimed at emission reduction (Martin et al., 2015). As a result, industrial symbiosis is frequently treated as an environmental management practice rather than as an economically grounded mechanism contributing to optimal resource allocation and emission reduction (Morales & Diemer, 2019).

Another critical issue identified in the literature concerns the measurement of environmental benefits generated through industrial symbiosis (Aissani et al., 2019). Emission reductions often occur indirectly through avoided production processes or reduced demand for primary resources,

which makes them difficult to capture using conventional firm-level environmental accounting approaches (Ismail, 2020). This challenge has led to increasing emphasis on environmental performance indicators capable of reflecting system-level outcomes (Fraccascia et al., 2021b). In particular, greenhouse gas emissions expressed in CO<sub>2</sub>-equivalent terms have become a key metric for evaluating industrial decarbonization strategies, as they enable comparison across alternative production configurations and facilitate alignment with climate policy objectives (Chertow, 2007; Jacobsen, 2006; Neves et al., 2020). Recent literature further highlights the growing use of Life Cycle Assessment in evaluating industrial symbiosis within circular solid waste management, reinforcing its relevance for assessing environmental impacts of inter-industry collaboration (Vahidzadeh et al., 2025).

In addition to environmental performance, environmental economics analysis requires the integration of economic indicators that capture the costs and benefits associated with resource exchange (Morales & Diemer, 2019). Existing studies indicate that cost savings from reduced material inputs, avoided waste management, and improved energy efficiency provide direct incentives for firms to engage in industrial symbiosis (Muñoz Puche et al., 2026; Genç et al., 2019). At the same time, broader societal benefits arise through the reduction of environmental externalities, highlighting the dual economic and environmental nature of industrial symbiosis. The incorporation of indicators such as eco-efficiency and emission abatement cost is therefore essential for linking environmental performance assessment with economic evaluation (Bastias et al., 2023).

Overall, the reviewed literature demonstrates that industrial symbiosis is increasingly recognized as a system-level mechanism for improving resource efficiency and reducing environmental impacts, while also highlighting significant gaps in the integration of environmental performance and economic evaluation. In particular, the relationship between industrial symbiosis activities, measurable environmental outcomes, and economic efficiency remains insufficiently structured. This indicates the need for a comprehensive theoretical framework that explicitly links operational

mechanisms, environmental performance indicators, and economic outcomes in order to clarify the role of industrial symbiosis within industrial decarbonization strategies.

## 2. RESULTS

The framework integrates perspectives on material and energy exchange with economic concepts related to efficiency improvement and externality reduction. In this context, industrial symbiosis is interpreted not only as an environmental management practice but also as an organizational arrangement through which environmental and economic outcomes are jointly produced.

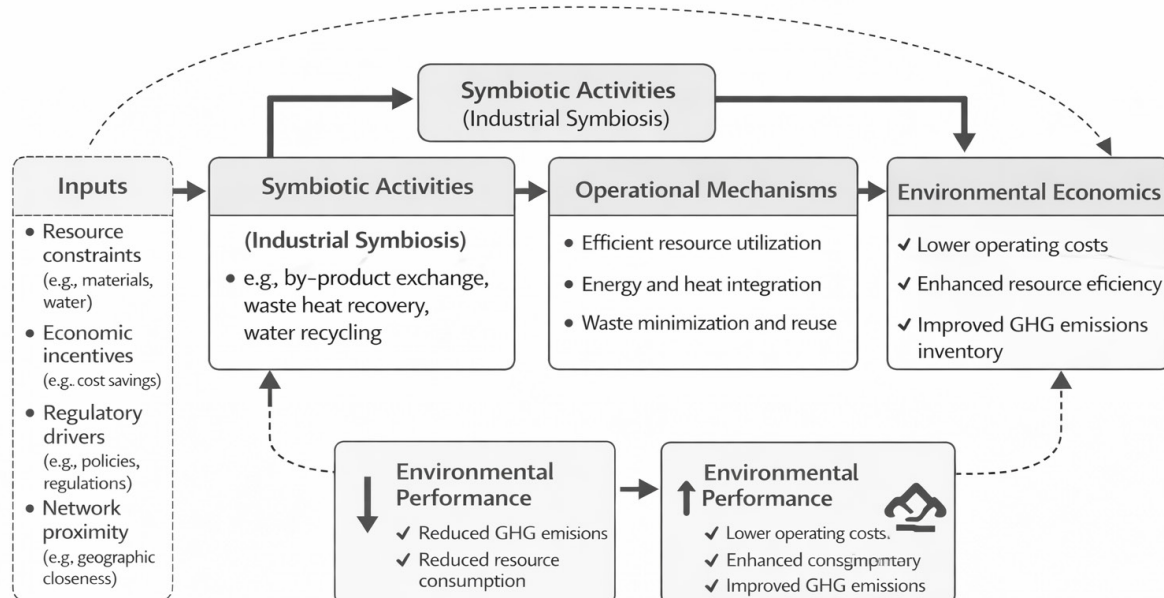
The proposed framework is structured around four interrelated components:

1. **Industrial Symbiosis Activities:** These include exchanges of materials, energy, water, and by-products among industrial actors. Such exchanges transform residual outputs into productive inputs, reducing the demand for virgin resources and additional energy consumption.
2. **Operational Mechanisms:** Environmental improvements occur through three core mechanisms: material substitution, energy cascading, and waste valorization. These mechanisms enable more efficient use of resources and energy across interconnected industrial processes.

3. **Environmental Performance Outcomes:** These outcomes include reductions in resource consumption, decreased energy use, and avoidance of emissions associated with waste treatment and primary production. Greenhouse gas emissions expressed in CO<sub>2</sub>-equivalent terms serve as the primary indicator for evaluating these improvements.
4. **Environmental Economic Outcomes:** These include increased resource efficiency, reduced production costs, and mitigation of environmental externalities. Through these effects, industrial symbiosis aligns private economic incentives with broader environmental objectives.

A key implication of the framework is that emission reductions achieved through industrial symbiosis are primarily systemic rather than technological. Environmental improvements arise from reconfiguring relationships between firms and optimizing resource flows, rather than from introducing entirely new production technologies. This highlights the role of organizational innova-

Source: Author's elaboration based on Arce Bastias et al. (2023) and Vahidzadeh et al. (2025).



**Figure 1.** Conceptual framework for industrial symbiosis contribution to GHG emission reduction

tion as a driver of industrial decarbonization and strengthens the connection between environmental performance assessment and economic evaluation.

The framework, presented in Figure 1, illustrates how enabling conditions, such as resource constraints, economic incentives, regulatory drivers, and network proximity, facilitate symbiotic activities. These activities improve operational mechanisms through enhanced resource efficiency, energy integration, and waste minimization, ultimately leading to improved environmental performance and economic outcomes, and contributing to greenhouse gas emission reduction. The framework represents causal relationships rather than empirical quantification.

By establishing these conceptual linkages, the framework provides a structured basis for assessing industrial symbiosis within industrial decarbonization strategies and supports the integration of environmental and economic evaluation approaches.

This study follows a theory-building approach to integrate existing insights into a coherent analytical structure rather than test predefined hypotheses empirically. Such approaches are particularly relevant in interdisciplinary fields where empirical evidence exists but remains analytically fragmented.

## 2.1. Framework development procedure

The conceptual framework was developed through a structured analytical process consisting of three stages:

- Stage 1: Literature Identification and Theoretical Scope Definition Relevant literature was reviewed to identify core mechanisms linking industrial symbiosis with environmental and economic outcomes.
- Stage 2: Conceptual Categorization of Mechanisms and Outcomes Identified concepts were grouped into four analytical categories: industrial symbiosis activities, operational mechanisms, environmental per-

formance outcomes, and environmental economic outcomes.

- Stage 3: Indicator Integration and Analytical Alignment Environmental and economic indicators were incorporated to operationalize conceptual relationships, ensuring consistency with system-level and life-cycle-based evaluation approaches.

Rather than conducting empirical measurement, the analysis synthesizes these insights to establish a structured conceptual foundation for interpreting industrial symbiosis as a system-level emission reduction mechanism.

## 2.2. Environmental performance indicators

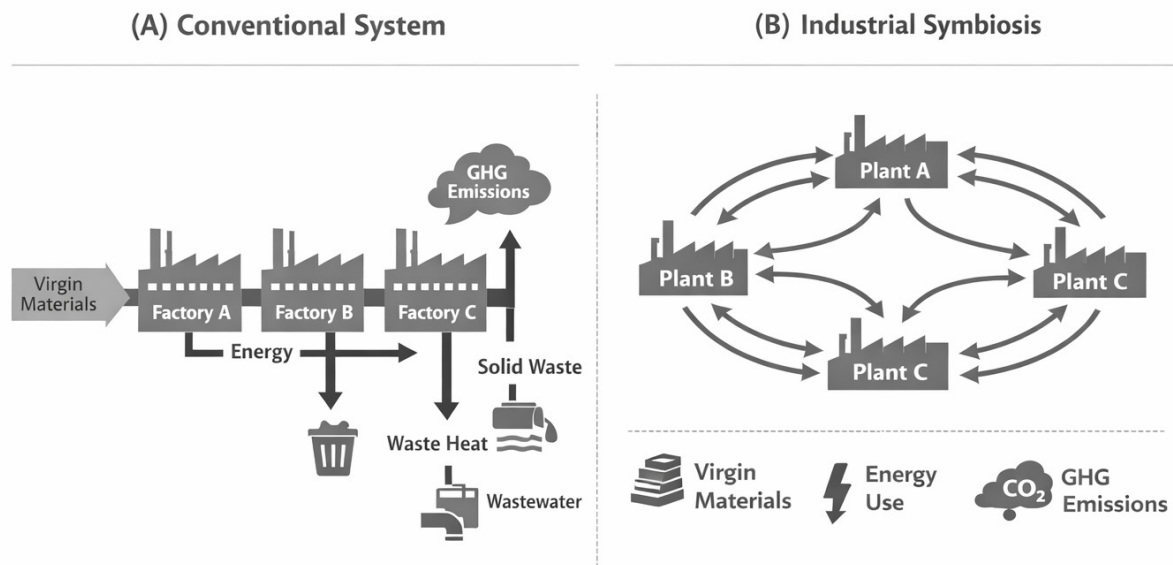
Environmental performance indicators are central tools for evaluating environmental outcomes within the proposed framework. Industrial symbiosis generates environmental benefits primarily through indirect effects such as avoided production processes, reduced energy consumption, and decreased waste treatment requirements.

Greenhouse gas emissions expressed in CO<sub>2</sub>-equivalent terms are adopted as the primary indicator due to their relevance for climate policy and industrial decarbonization assessment. Emission reduction is conceptualized as the difference between emissions associated with conventional production systems and those resulting from symbiotic resource utilization. This approach enables system-level evaluation and comparison across alternative production configurations.

Figure 2 illustrates the emission reduction mechanisms enabled by industrial symbiosis by contrasting a conventional linear industrial system, characterized by high virgin resource consumption and waste generation, with a symbiotic industrial network in which waste streams and by-products are valorized as productive inputs for other processes, thereby reducing virgin material demand, energy consumption, and overall greenhouse gas emissions.

In addition, complementary indicators such as energy intensity and material efficiency are incorpo-

Source: Prepared by the author following the methodological insights of Muñoz Puche et al. (2026) and Genç et al. (2019).



**Figure 2.** Illustration of emission reduction mechanisms via industrial symbiosis

rated to capture broader improvements associated with resource flow optimization.

### 2.3. Economic indicators for environmental economics evaluation

Environmental economics analysis requires the integration of economic indicators that reflect the feasibility and efficiency of industrial symbiosis activities. Economic effects arise through reduced material and energy consumption, avoided waste management costs, and revenues from secondary resource exchanges.

The inclusion of economic indicators allows industrial symbiosis to be evaluated simultaneously in environmental and economic terms. Indicators such as cost savings, eco-efficiency, emission abatement cost, and investment-related measures provide a bridge between environmental performance assessment and economic evaluation.

Table 1 presents the principal economic indicators conceptually incorporated into the analytical framework. Indicators were selected according to three criteria: a) relevance for capturing system-level environmental change, b) compatibility with environmental economics evaluation, and c) frequency of use in industrial symbiosis and life-cycle assessment literature.

These economic indicators provide a robust framework for quantifying the financial viability and overall economic impact of industrial symbiosis initiatives. They bridge the gap between environmental improvements and their monetary benefits, making the case for symbiotic relationships more compelling for industrial stakeholders.

### 2.4. Analytical logic and limitations

The analytical logic of the framework is based on life-cycle thinking, recognizing that environmental impacts occur across interconnected production stages. Industrial symbiosis modifies these relationships by introducing alternative resource pathways that reduce emissions and improve resource productivity.

The theoretical nature of the study implies certain limitations. The framework does not quantify emission reductions or prescribe a universal indicator set but instead provides a conceptual structure for future empirical application. The magnitude of benefits may vary depending on sectoral, technological, and regional conditions.

To sum up, the study develops a conceptual framework explaining industrial symbiosis as a system-level mechanism for greenhouse gas emission reduction based on resource flow optimization. The framework integrates four key components (ac-

**Table 1.** Economic indicators for assessing industrial symbiosis contributions to greenhouse gas emission reduction

No.	Economic indicator	Analytical purpose	Unit	Conceptual interpretation
1	Cost savings	Reduction in input and disposal costs	€/year	Savings from reduced material, energy, and waste management costs (Chebbi et al., 2020; Magnusson et al., 2019)
2	Additional revenue	Economic value of by-product exchange	€/year	Income generated from the sale of by-products in the market (Hatsor & Jelnov, 2024; Herczeg et al., 2018)
3	Net economic benefit	Overall private economic gain	€/year	The overall positive outcome from an industrial symbiosis, representing a favorable business case (Haq et al., 2021; Leiva et al., 2025)
4	Transaction costs	Coordination and implementation costs	€/year	Costs related to negotiation, acquiring knowledge, searching for buyers, logistics, and regulatory burdens in establishing exchanges (Hatsor & Jelnov, 2024; Yazdanpanah et al., 2020)
5	Payback period	Investment attractiveness	Years	Time required to recover initial investment in symbiosis infrastructure (Neves et al., 2020; Yeo et al., 2019)
6	Net present value	Long-term economic viability	€	Discounted value of future net benefits (Yang et al., 2018; Yeo et al., 2019)
7	Internal rate of return	Investment efficiency	%	The discount rate that makes the net present value of a project equal to zero (Harding & Long, 2018; Yang et al., 2018)
8	Emission abatement cost	Cost-effectiveness of emission reduction	€/tCO <sub>2</sub> e	Cost per unit of avoided emissions (Bastias et al., 2023)
9	Eco-efficiency ratio	Economic value relative to environmental impact	€/tCO <sub>2</sub> e	Ratio of an economic variable (e.g., production or revenue) to an environmental variable (e.g., consumption or environmental influence) (Park & Behera, 2014)
10	Avoided externality value	Societal benefit of emission reduction	€/year	The economic value representing the avoided environmental damage to society due to reduced pollution (Wadström et al., 2021)

tivities, operational mechanisms, environmental performance outcomes, and economic outcomes) and demonstrates how environmental and economic benefits are jointly generated. These results provide a structured analytical foundation for evaluating industrial symbiosis within industrial decarbonization strategies and environmental economics analysis.

### 3. DISCUSSION

The conceptual framework and methodological approach developed in this study provide a structured interpretation of industrial symbiosis as a mechanism through which environmental and economic objectives may converge within industrial systems (Fraccascia et al., 2021a).

The environmental performance indicators demonstrate that emission reductions associated with industrial symbiosis are frequently indirect and distributed across multiple stages of production (Aissani et al., 2019). This complexity reinforces the need for system-level analytical approaches capable of capturing interdependencies between

industrial processes and resource flows (Pan et al., 2016). Material substitution reduces upstream emissions related to resource extraction and processing, while energy cascading decreases energy demand and associated emissions in interconnected processes (Li et al., 2017; Savian et al., 2023). Waste valorization further contributes to emission reduction by avoiding disposal-related impacts (Neves et al., 2020). These systemic effects highlight the importance of evaluating industrial symbiosis at the network level rather than at the level of individual firms, as environmental improvements may not be fully observable within conventional firm-level accounting frameworks (Chertow, 2007; Jacobsen, 2006; Martin et al., 2015). At the same time, the indirect nature of these benefits requires methodological approaches capable of capturing avoided impacts across the lifecycle of interconnected processes (Ismail, 2020).

The inclusion of economic indicators provides additional insight into the conditions under which industrial symbiosis becomes economically viable (Morales & Diemer, 2019). In this context, the development of robust monitoring and performance evaluation systems becomes essential for support-

ing decision-making and improving the effectiveness of industrial symbiosis initiatives (Lütje & Wohlgemuth, 2020; Mantese & Amaral, 2016).

In many industrial contexts, emission reductions achieved through resource exchange may occur at lower cost compared to purely technological mitigation options. Industrial symbiosis therefore expands the portfolio of available decarbonization measures by introducing organizational innovation as a complementary pathway to emission reduction (Genç et al., 2019).

Furthermore, the valuation of avoided environmental externalities through indicators such as avoided externality value provides a conceptual link between industrial symbiosis and broader societal benefits associated with emission reduction.

The discussion also suggests that industrial symbiosis contributes to decarbonization by expanding the range of emission reduction mechanisms beyond traditional technological solutions (Johansson et al., 2018). Environmental improvements emerge from the reconfiguration of production relationships and resource flows, indicating that organizational innovation plays an important role in achieving climate objectives (Bilyaminu et al., 2024). This perspective reinforces the importance of integrating industrial ecology insights into environmental economics analysis, particularly in the context of long-term transitions toward climate-neutral industrial systems (Smart et al., 2017).

Compared with previous studies, the findings of this study are consistent with the established view that industrial symbiosis contributes to environmental improvement by enabling resource exchange, reducing waste, and improving the efficiency of material and energy flows. Foundational studies by Chertow (2000) and Ehrenfeld and Gertler (1997) emphasized that industrial symbiosis generates environmental and economic benefits through inter-firm cooperation and the reuse of residual outputs. The present study supports this interpretation but extends it by structuring these benefits within an environmental economics framework that explicitly links symbiotic activities, operational mechanisms, environmental performance outcomes, and economic outcomes.

The findings also correspond with empirical evidence from Jacobsen (2006), Sokka et al. (2011), and Daddi et al. (2017), who demonstrated that industrial symbiosis can generate measurable reductions in resource consumption, energy use, and environmental impacts. Similar to these studies, the present analysis confirms that greenhouse gas emission reduction is not limited to direct emission savings within individual firms but often emerges from avoided production, reduced demand for primary materials, and improved use of secondary resources across the wider industrial network. However, while earlier studies mainly focused on specific cases or life-cycle assessment applications, this study provides a conceptual explanation of how these mechanisms can be interpreted as system-level emission reduction pathways.

The results further align with Martin et al. (2015) and Aissani et al. (2019), who highlighted the methodological difficulty of attributing environmental benefits within industrial symbiosis networks. The present study confirms that emission reductions are frequently indirect and distributed across several stages of production, which makes conventional firm-level environmental accounting insufficient. In this respect, the study reinforces the need for network-level and life-cycle-based evaluation approaches capable of capturing avoided impacts and interdependencies between industrial actors.

In comparison with studies focusing on performance measurement, such as Fraccascia et al. (2021a), Mantese and Amaral (2016), and Lütje and Wohlgemuth (2020), the present study similarly emphasizes the importance of indicators for assessing industrial symbiosis outcomes. Nevertheless, its contribution lies in integrating environmental performance indicators with economic evaluation criteria. By including indicators such as cost savings, eco-efficiency, emission abatement cost, and avoided externality value, the framework developed in this study shows how environmental improvements can be assessed together with economic efficiency and policy relevance.

Finally, the results correspond with broader circular economy studies, including Domenech et al. (2019) and Neves et al. (2020), which identify industrial symbiosis as an important strategy for

supporting resource efficiency and circular industrial development. The present study confirms these conclusions but places stronger emphasis on greenhouse gas emission reduction and the economic interpretation of environmental benefits. Therefore, the main contribution of this study is not the identification of entirely new industrial symbiosis mechanisms, but the development of an integrated conceptual framework that brings together previous findings on material substitution, energy cascading, waste valorization, environmental performance indicators, and economic evaluation within a single analytical structure.

Overall, the analysis demonstrates that industrial symbiosis should be interpreted not only as an environmental management practice but also as an economically meaningful mechanism capable of supporting industrial decarbonization strategies. By linking environmental performance indicators with economic evaluation criteria, the framework developed in this study provides a basis for assessing industrial symbiosis within both environmental and economic decision-making contexts.

## 4. IMPLICATIONS

The framework developed in this study offers policy, industry, and research implications.

Industrial symbiosis should be recognized as a complementary mechanism within industrial decarbonization policy. Policy measures aimed at facilitating industrial coordination, information exchange, and infrastructure development can enhance environmental outcomes without imposing additional regulatory burdens on firms. Clarifying regulatory classifications of secondary resources and by-products can further reduce uncertainty and encourage wider implementation of symbiotic exchanges. The integration of environmental and economic indicators highlights the importance of incorporating system-level performance metrics into environmental policy evalua-

tion. Indicators such as emission abatement cost and eco-efficiency allow policymakers to compare industrial symbiosis with alternative emission reduction strategies on an economic basis.

For industrial actors, participation in industrial symbiosis networks can simultaneously improve environmental performance and economic efficiency. Cost savings resulting from reduced material inputs, improved energy utilization, and avoided waste treatment represent direct economic incentives that can enhance competitiveness under increasing carbon and resource constraints. Industrial symbiosis can be interpreted not only as an environmental initiative but also as a strategic approach to improving operational efficiency and long-term economic resilience. Collaboration and information sharing among firms are crucial enabling conditions for successful symbiotic exchanges. While transaction costs may initially limit participation, long-term economic benefits reflected in indicators such as net economic benefit, payback period, and eco-efficiency may outweigh initial coordination efforts.

The study identifies several directions for future research aimed at strengthening the analytical integration of industrial ecology and environmental economics. Empirical applications of the proposed framework are needed to operationalize environmental and economic indicators in real industrial symbiosis networks. An integrated optimization modeling framework for low-carbon and green regional transitions through resource-based industrial symbiosis could also offer valuable insights. Quantitative assessment of emission abatement costs and eco-efficiency across different industrial sectors would improve comparability between cases and support evidence-based policy evaluation. Future research may also explore the role of digital technologies and data-driven monitoring systems in improving transparency and accuracy in the assessment of network-level environmental performance.

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## CONCLUSION

The aim of this study was to develop a theoretical framework explaining how industrial symbiosis networks contribute to greenhouse gas emission reduction and how these effects can be interpreted within an environmental economics perspective.

The results demonstrate that industrial symbiosis functions as a system-level mechanism of emission reduction based on resource flow optimization, structured through four interrelated components: symbiotic activities, operational mechanisms, environmental performance outcomes, and environmental economic outcomes. The framework shows that emission reductions occur through material substitution, energy cascading, and waste valorization, while environmental performance indicators and economic measures jointly explain how environmental improvements align with economic efficiency.

These findings indicate that industrial symbiosis should be interpreted not only as an environmental management practice but also as an economically relevant coordination mechanism capable of reducing environmental externalities and supporting industrial decarbonization. The study provides a conceptual foundation for future empirical research and supports the integration of industrial symbiosis into environmental policy and decision-making frameworks.

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