

Review

Data-Driven Tools and Methods for Low-Carbon Industrial Parks: A Scoping Review of Industrial Symbiosis and Carbon Capture with Practitioner Insights

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Abstract

Industrial symbiosis and carbon capture are increasingly recognized as critical strategies for reducing emissions and resource consumption in industrial parks. However, existing research remains fragmented across tools, methods, and case-specific applications, providing limited guidance for effective real-world deployment of data-driven approaches. This study addresses this gap through a PRISMA-guided scoping review of 116 publications, complemented by a targeted practitioner survey conducted within the IEA IETS Task 21 initiative to assess practical relevance and adoption challenges. The review identifies a broad landscape of data-driven tools, ranging from high-technology-readiness simulation and optimization platforms to emerging visualization and matchmaking solutions. While the literature demonstrates substantial methodological maturity, the combined evidence reveals a persistent gap between tool availability and effective implementation. Key barriers include fragmented and non-standardized data infrastructures, confidentiality constraints, limited stakeholder coordination, and weak policy and market incentives. Based on the integrated analysis of literature and practitioner insights, the paper proposes a conceptual framework that links tools and methods with data infrastructure, stakeholder governance, policy, and market enablers, and implementation contexts. The findings highlight that improving data governance, interoperability, and collaborative implementation pathways is as critical as advancing analytical capabilities. The study concludes by outlining focused directions for future research, including AI-enabled optimization, standardized data-sharing frameworks, and coordinated pilot projects to support scalable low-carbon industrial transformation.

Keywords: industrial symbiosis; carbon capture; eco-industrial parks; scoping review; data governance; optimization tools; sustainability assessment; stakeholder engagement; circular economy; decarbonization



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1. Introduction

Global climate change remains an urgent concern that demands innovative pathways to reduce greenhouse gas emissions and manage finite natural resources [1]. As populations expand and economic activities intensify, energy, water, and raw materials become increasingly strained, driving the need for sustainable industrial solutions [2]. Recent estimates indicate that worldwide energy demand could reach 15,755 million tons by 2030, underscoring the gravity of the resource challenge [3]. In response, industrial

parks and eco-industrial parks have gained increasing attention as system-level intervention points for coordinating industrial activities, minimizing waste, and enhancing collective competitiveness. By aligning with the United Nations' Sustainable Development Goals, eco-industrial parks leverage industrial symbiosis, defined as data- and exchange-driven collaboration among co-located or networked industries, where materials, energy, water, and by-products are shared to establish more resilient and low-carbon production networks [4,5].

Despite the increasing global focus on eco-industrial parks, limited clarity remains regarding how industrial symbiosis and carbon capture tools are operationalized, integrated, and scaled in real-world industrial settings. Industrial symbiosis has proven effective in reducing pollution and resource dependency [6,7], yet its broader adoption, particularly for carbon mitigation, depends on the availability of robust, data-driven analytical tools and decision-support frameworks. While numerous advanced approaches, including combined heat and power optimization, hydrogen-based multi-energy systems [8], and integrated electricity–heat networks have been piloted in industrial zones worldwide, and guidance on tool selection, implementation pathways, and scalability across heterogeneous industrial contexts remains fragmented [9,10]. According to [11], existing industrial symbiosis tools tend to focus on individual resource streams, leaving a significant research gap in the integrated optimization of energy, water, power, carbon, and waste flows. As a result, practitioners and planners face persistent challenges in selecting appropriate tools that align with both technical requirements and organizational realities.

Recent review studies have contributed valuable classifications of industrial symbiosis tools and conceptual frameworks for eco-industrial parks, yet they predominantly emphasize technical feasibility, policy design, or resource-flow optimization in isolation. Comparatively limited attention has been given to how data-driven tools are adopted, combined, and governed across real-world industrial contexts, particularly when carbon capture is considered alongside industrial symbiosis. Building on prior classification-oriented reviews, such as a review by Lawal and Wan Alwi [11], this study advances the literature by explicitly integrating practitioner perspectives and by examining adoption feasibility, usability, and governance challenges associated with industrial symbiosis–carbon capture tools.

Similarly, research on the systematic integration of carbon capture within industrial symbiosis networks remains at an early stage, despite its potential to substantially reduce greenhouse gas emissions while strengthening economic viability [12,13]. Carbon capture refers to technologies that reduce carbon dioxide (CO₂) emissions from stationary sources through permanent storage or conversion into valuable products, as commonly framed within the Carbon Capture, Utilization, and Storage paradigm [14,15]. In this paper, carbon capture is understood not only as a set of process technologies, such as post-combustion CO₂ removal and catalytic methanation, but also as a data-supported system function enabled through emissions monitoring, optimization, and heat recovery tools. This broader interpretation reflects the growing importance of digital and data-driven infrastructures in industrial decarbonization strategies. This broader interpretation reflects the increasing importance of digital and data-driven infrastructures in enabling integrated industrial decarbonization strategies rather than isolated technology deployment.

To address these gaps, this study adopts a dual-method approach. First, a PRISMA-guided scoping review is conducted to systematically map tools and methods that support the integration of industrial symbiosis and carbon capture in industrial and commercial parks. Second, the review is complemented by a targeted practitioner survey

conducted within the International Energy Agency (IEA) Industrial Energy-Related Technologies and Systems (IETS) Task 21 initiative, capturing empirical insights from technology developers and users with direct experience in applying these tools. The scoping review encompasses data-driven simulation and modeling tools, statistical and econometric methods, optimization frameworks, data collection and management techniques, and decision-support platforms, while the survey provides practical perspectives on usability, maturity, and implementation barriers.

Specifically, this paper addresses the following research question: What data-driven tools and methods are employed to support the integration of industrial symbiosis and carbon capture in industrial and commercial parks, and which technical, organizational, and policy-related factors influence their effective deployment? By systematically synthesizing published evidence and practitioner experiences, this study offers both a structured analytical overview and an empirically grounded assessment of enabling conditions, technology readiness levels, persistent barriers, and real-world performance of industrial symbiosis and carbon capture interventions.

This scoping review helps fill a critical knowledge gap, as existing studies rarely connect tool development with adoption feasibility, despite the growing recognition of eco-industrial parks as key instruments for emissions reduction, economic resilience, and sustainable industrial transformation [16,17]. Moreover, prior research typically emphasizes either high-level policy frameworks or isolated technology case studies, without providing an integrated mapping of tools across data requirements, decision functions, and implementation contexts. By incorporating practitioner survey evidence, this study aligns theoretical potential with operational constraints, thereby offering actionable insights for policymakers, industrial park operators, and researchers seeking scalable pathways toward low-carbon industrial development.

The contributions of this study are threefold. From a theoretical perspective, the paper extends existing industrial symbiosis and carbon capture literature by conceptualizing these domains as an integrated, data-driven ecosystem rather than as parallel or loosely coupled strategies. From a methodological perspective, the study combines a PRISMA-guided scoping review with practitioner survey evidence to link tool development with adoption feasibility. From a practical perspective, the paper provides actionable insights for policymakers, industrial park operators, and technology developers by identifying governance, data, and implementation conditions that shape successful deployment.

The remainder of the paper is structured as follows. Section 2 describes the review protocol and survey design, including eligibility criteria, data extraction, and analytical procedures. Section 3 presents the results of the study, with Section 3.1 reporting the literature review results derived from the PRISMA-guided scoping review and Section 3.2 presenting the practitioner survey results. Section 4 discusses the findings, introduces an integrated conceptual framework for industrial symbiosis and carbon capture deployment, and identifies key barriers and enablers. Section 5 concludes the paper by summarizing contributions, acknowledging limitations, and outlining directions for future research.

Figure 1, which illustrates the overall paper structure and research flow, is provided after the methodological description to support clarity and avoid interrupting the conceptual framing of the introduction.

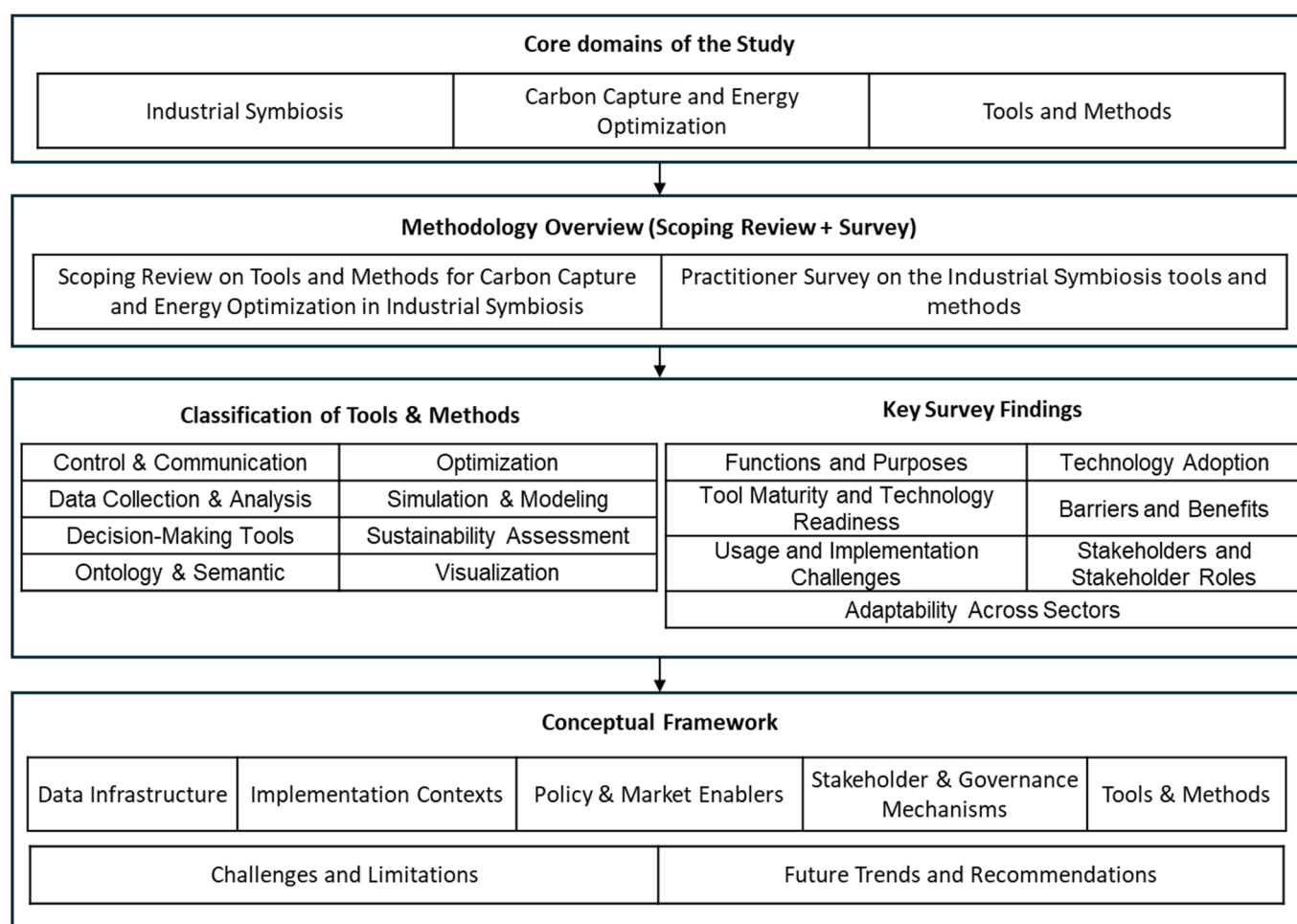


Figure 1. Paper structure and research flow.

2. Materials and Methods

This study employed a dual-methods approach consisting of (i) a structured literature review to examine existing research on industrial symbiosis tools and methods and (ii) a survey of technology providers and users to explore the practices, perceived effectiveness, and challenges in using and implementing these tools. A PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews) approach was adopted because the objective is to comprehensively map concepts, tool types, and research characteristics across a heterogeneous literature base, rather than to estimate intervention effects or perform evidence grading as in a full systematic review. Accordingly, the review process followed elements of the PRISMA extension for scoping review guidelines [18], while the survey design was guided by best practices in mixed-methods research [19].

2.1. Literature Review Protocol

The scoping review aims to map the diverse methods and tools that support the integration of industrial symbiosis and carbon capture in industrial and commercial parks. A scoping review protocol was developed before initiating the review. Although it was not registered in a public database, the protocol was internally reviewed and approved by the research team. The protocol specified objectives, inclusion/exclusion criteria, search strategy, and data synthesis procedures, ensuring methodological rigor and reproducibility (see Table 1). Any modifications to the protocol were documented and justified.

Table 1. Eligibility criteria.

Criteria	Inclusion	Exclusion
Study Focus	Studies on enhancing energy efficiency and sustainability in industrial parks via IS	Studies that do not focus on implementing industrial symbiosis in industrial parks to promote energy efficiency and sustainability
Study Design	Empirical studies, including quantitative, qualitative, and mixed methods, related to optimizing industrial parks	Research lacking primary data or original research on industrial symbiosis
Publication Type	Peer-reviewed articles and conference papers pertaining to industrial parks, energy efficiency	Non-peer-reviewed articles (e.g., editorials, opinion pieces), abstract-only records
Language	Publications written in English	Publications in languages other than English

Table 1 summarizes the eligibility criteria used during screening and final inclusion. To improve transparency of the inclusion logic, the criteria were operationalized as three sequential decision rules applied consistently across records:

- (1) Topical relevance. The study must address industrial symbiosis in industrial or commercial parks and must report a tool, method, or data-driven approach that supports analysis, design, optimization, decision making, assessment, or implementation. Studies focusing on industrial sustainability without an explicit industrial symbiosis focus in an industrial or commercial park context were excluded.
- (2) Evidence type. Empirical studies were included (quantitative, qualitative, or mixed methods). Studies were excluded if they lacked original research content relevant to tools or methods, including editorials, opinion pieces, non-peer-reviewed reports, and abstract-only records.
- (3) Publication constraints. Peer-reviewed journal articles and conference papers written in English were included. Publications in other languages were excluded.

Carbon capture integration was treated as an inclusion-relevant scope element rather than a mandatory requirement. Specifically, studies were included if they addressed industrial symbiosis in parks and either (i) explicitly examined carbon capture or Carbon Capture, Utilization, and Storage integration, or (ii) addressed energy and carbon-related modeling, optimization, monitoring, or assessment functions that support carbon mitigation in industrial symbiosis contexts. This interpretation aligns with the paper’s objective of mapping data-driven tools supporting the integration of industrial symbiosis and carbon mitigation strategies.

A systematic search was conducted in Scopus, Web of Science, and IEEE Xplore, covering publications from database inception to January 2026. The final search was executed in January 2026 and includes all publications indexed up to 18 January 2026. The search string combined keywords related to industrial parks, energy/carbon, and symbiosis. Boolean operators (AND, OR) and filters (English language, peer-reviewed articles) were applied to refine the results. The draft search strategy was reviewed by experts in industrial symbiosis to ensure completeness.

The search string used was as follows:

TI = (energy OR electricity OR heat* OR carbon OR CO₂) AND (“industrial park” OR “commercial park” OR “industrial area” OR “commercial park”) AND (symbiosis OR mutual* OR “eco-industrial” OR “industrial ecology” OR synerg* OR co-* OR integration OR sustainabl* OR ecosystem OR collaboration).

No additional automation tools were used to exclude studies. All records were screened manually based on the eligibility criteria.

Studies were imported into EndNote for reference management, where duplicates were removed. The study selection followed a PRISMA-consistent process comprising identification, screening, eligibility assessment, and inclusion. First, titles and abstracts were screened against the eligibility criteria. Second, full texts were assessed to confirm final inclusion. Third, reasons for exclusion at the full-text stage were documented and summarized in the PRISMA flow diagram categories. Any disagreements were resolved through discussion or by consulting a third reviewer.

In total, 239 records were identified across the databases. After duplicate removal ($n = 67$), 172 unique records remained for title and abstract screening. Of these, 53 records were excluded for failing to meet the eligibility criteria. The remaining 119 records were subjected to full-text assessment, and all were confirmed as meeting the inclusion criteria. Therefore, the final dataset comprises 119 studies (as shown in Table A1 in the Appendix A), which form the basis of the scoping review. The identification, screening, eligibility assessment, and inclusion process are summarized in the PRISMA flow diagram (Figure 2).

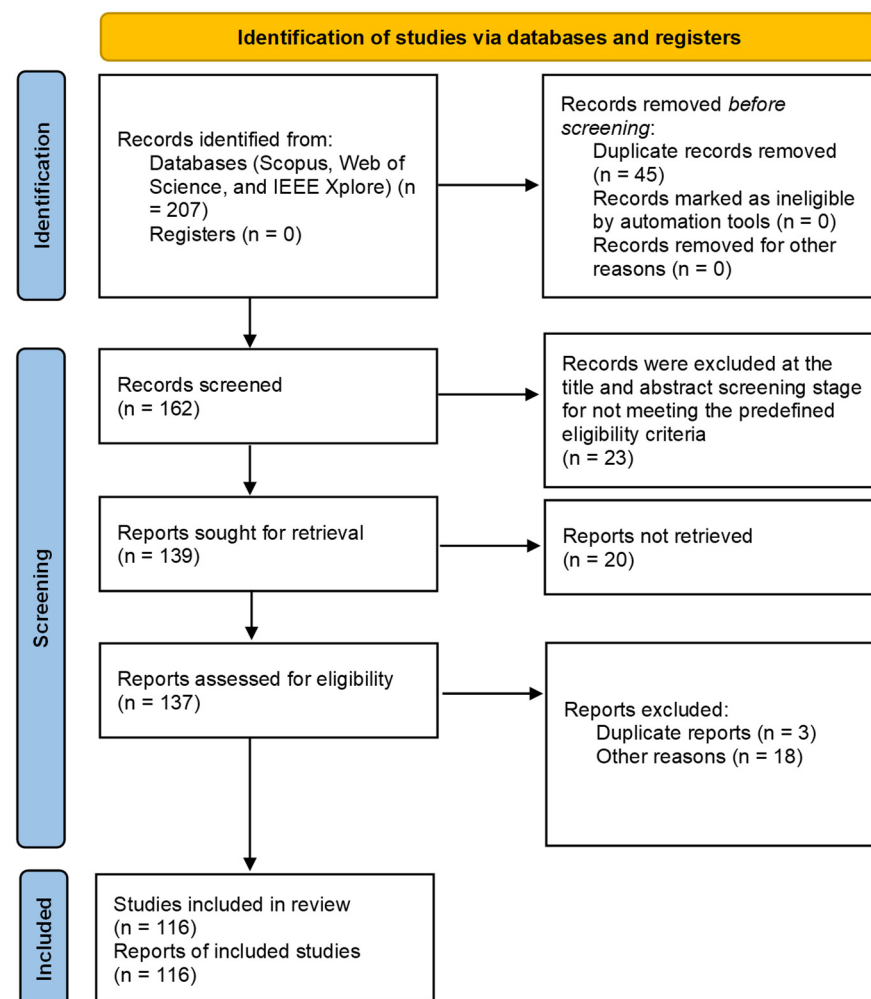


Figure 2. The PRISMA flow diagram.

A standardized data extraction form was piloted on a subset of studies to ensure consistency and comprehensiveness. Two independent reviewers used this form to extract relevant data, including study focus, methodology, key findings, and contextual details. Discrepancies were resolved through discussion, and a third reviewer was consulted

when necessary. Consistent with PRISMA-ScR guidance, no formal risk-of-bias or quality assessment was conducted, as the purpose of the review was mapping and synthesis rather than evidence grading.

The final dataset captured multiple dimensions of industrial symbiosis tools and methods, such as simulation models, econometric analyses, optimization frameworks, data collection instruments, decision-making approaches, and sustainability assessments. Table 2 provides an overview of the data charted.

Table 2. Data items chart.

Category	Sub-Category	Details
Study Characteristics	Publication Details	Author(s), year of publication, journal/conference
	Type of Study	Classification of studies as review or primary research
	Geographical Context	Country or region where the study was conducted or focused
Focus of the Study	Areas of Application	Types of industries or settings (e.g., eco-industrial parks, energy-intensive parks)
	Approaches/Strategies	Proposed approaches for addressing the objectives (e.g., scenario-based optimization)
	Tools/Technologies	Analysis, simulation, and optimization tools (e.g., MATLAB, HOMER)
	Relevant Stakeholders	Policymakers, industries, energy providers, and technology developers
Key Findings	Main Results	Principal outcomes, conclusions, recommendations
	Research Gaps	Underexplored areas and future directions
Methodological Details	Research Designs	Case studies, experiments, or surveys
	Analytical Frameworks	Mathematical models, LCA, MFA, or agent-based simulations

Note: Software tools are reported at the platform or method level as described in the reviewed literature. Specific software version numbers are not consistently reported across primary studies and are therefore not specified.

A thematic analysis identified recurring patterns and trends in the literature, such as common simulation and optimization tools (e.g., Aspen Plus, Mixed-Integer Linear Programming), prevalent industrial settings (e.g., eco-industrial parks), and stakeholder considerations. Contextual analysis examined how these approaches applied to specific industrial scenarios, highlighting unique challenges (e.g., confidentiality in data sharing) and potential benefits (e.g., cost savings, emission reductions). These synthesized results form the basis of the literature review results reported in Section 3.1.

Furthermore, findings were mapped to the research question concerning the diversity of methods/tools for integrating industrial symbiosis and carbon capture, as well as the key factors influencing their success or challenges. The synthesis illuminates frequently used strategies (e.g., simulation models, optimization tools) that can enhance the environmental and economic performance of industrial parks.

2.2. Survey Design and Data Collection

To complement the scoping literature review, a structured practitioner survey was conducted under the IEA IETS Task 21 initiative to investigate the practical use, perceived effectiveness, scalability, and implementation challenges of industrial symbiosis and carbon capture tools. The survey was explicitly designed as an exploratory instrument to contextualize and validate literature-based findings, rather than as a statistically representative study. Its purpose is to capture practitioner perspectives that are typically underreported in academic publications, particularly regarding usability, adoption barriers, and governance-related constraints.

A survey-based approach was selected because industrial symbiosis and carbon capture tools are often developed, tested, and applied by a limited number of highly specialized actors. In such contexts, in-depth expert elicitation is more appropriate than large-sample surveys, as it enables the collection of experience-based insights across the full tool lifecycle, including development, application, and implementation. Therefore, the survey serves a complementary and explanatory role alongside the scoping review.

The survey instrument was developed after completion of the literature review to ensure alignment between the identified tool categories and the survey questions. The full set of survey questions is provided in the Supplementary Materials, and the survey structure closely mirrors the analytical dimensions used in the literature review, enabling systematic triangulation between literature and practitioner evidence.

The survey was structured into six sections:

- Respondent profile, capturing affiliation, position, expertise, years of experience, and role in relation to the tool or method.
- Basic information on tools and methods, including functionality, scope, licensing, and technology readiness level.
- Functions and purpose, covering analytical, modeling, simulation, optimization, and control capabilities.
- Application and implementation, addressing deployment contexts, operational scale, and managed resource types.
- Development and evolution, focusing on adaptability, future development plans, and stakeholder involvement.
- Familiarity and perception of industrial sustainability practices, including perceived benefits, barriers, and organizational priorities.

A summary of the questionnaire structure and question logic is provided in Table 3.

The survey was distributed online, targeting practitioners, researchers, and industry stakeholders with direct experience in industrial symbiosis and carbon capture tools. Participants were selected using purposive expert sampling, targeting individuals actively involved in tool development, application, or evaluation within research institutions and applied industrial projects associated with the IEA IETS Task 21 network. This sampling strategy prioritizes depth of expertise over breadth of representation and aligns with exploratory studies in emerging, highly specialized research domains.

A total of eight respondents completed the survey. Although numerically limited, the participant group demonstrates a high level of domain expertise and diverse roles. Respondents were primarily affiliated with academic and applied research institutions and included senior researchers, PhD researchers, and research associates. Their expertise spans software engineering, system innovation, industrial energy transformation, hydrogen technologies, carbon capture and utilization, methanation, energy optimization, and the facilitation of industrial symbiosis. Participants represent early-, mid-, and senior-career researchers, with experience ranging from less than 5 years to more than 10 years. A detailed demographic summary of respondents' affiliations, positions, expertise, and experience is reported in Table 13 in Section 3.2.

The limited sample size is a recognized limitation of the survey and reflects the current concentration of expertise in industrial symbiosis and in the development of carbon capture tools. The survey is not intended to support statistical generalization; instead, it provides qualitative and descriptive quantitative insights that complement and contextualize the scoping review results.

Each survey required approximately 10–15 min to complete. Responses included a combination of structured multiple-choice questions and open-ended qualitative inputs. To enhance content validity, survey questions were derived directly from categories and

gaps identified in the literature review, ensuring conceptual consistency between the two methods. The survey instrument was reviewed internally by domain experts prior to dissemination to ensure clarity, relevance, and completeness.

Table 3. Structure and thematic focus of the practitioner survey questionnaire.

Questionnaire Section	Focus of the Section and Key Information Collected
Introduction	Industrial symbiosis and carbon capture are pivotal for enhancing efficiency and sustainability in industrial operations. Industrial symbiosis involves the collaborative use of resources among industries to optimize material and energy flows, while carbon capture focuses on technologies to capture and store CO ₂ emissions from industrial processes. This survey is part of the IEA IETS Task 21 initiative and aims to explore the practices and perceived effectiveness of various tools and approaches used in industrial symbiosis and carbon capture within industrial parks. Your insights will help us understand the current state of these practices and inform future research and policy development. The survey is divided into six parts.
Basic information on respondents	Name, affiliation, position, email, expertise, years of experience, and how they familiarize themselves with the tool/method.
Basic information about the tool/method	Name of the tool/method, short description of the tool/method, weblink for the tool/method, related publications/documentation, technology readiness level (TRL) of the method/tool, regions where the tool/method has been tested or used, any similar method/tool, advantages of the tool/method, especially compared to similar methods/tools, shortcomings of the tool/method, especially compared to similar methods/tools.
Functions and purpose of the tool/method	Main functions of the tool/method, any specific requirements or inputs needed for using the tool/method, main results or outcomes achieved by using the tool/method, any specific methods or theories applied in the tool/method, any data/dataset needed as input for using the tool/method, the tool/method data generation capabilities (if any), the tool/method adaptability for use in different industrial sectors, any plans to further develop the functions of the tool/method, Who benefits from the results/outcomes of the tool/method.
Application of the tool/method	Types of industrial parks the tool/method can be used in, scale the tool/method covers, elements the tool/method covers, measurable improvements in sustainability metrics the implementation of this tool/method led to (if any), plans to further extend the application of the tool/method.
Development and implementation of the tool/method	Developers of the tool/method, users of the tool/method, information providers or the need to be involved in using the tool/method, challenges (technical, economic, social, regulatory, etc.) in developing, using, and implementing the tool/method.
Familiarity and perception of industrial sustainability practices	Familiarity with the concept of industrial symbiosis and carbon capture, perceive belief on what industrial symbiosis and carbon capture brings to companies, level of importance on achieving industrial symbiosis and carbon capture, perceive as the main barriers to adopting industrial symbiosis practices in organization, any other tools/methods you believe should be explored for industrial symbiosis and carbon capture, future trends or developments in the field of industrial symbiosis and carbon capture, any case studies or examples of successful implementation of industrial symbiosis or carbon capture to share.

Given the exploratory nature of the survey and the small expert sample, formal statistical reliability testing was not performed. However, several measures were applied to enhance reliability and interpretive robustness. These include standardized question wording, consistent response scales, and cross-validation of practitioner responses against patterns identified in the literature review. Convergence between survey responses and literature findings is explicitly examined in Section 4, thereby strengthening analytical credibility through methodological triangulation.

Survey responses were coded and analyzed using descriptive statistics and thematic analysis. Quantitative responses were summarized using frequency counts and simple association tests where appropriate, while qualitative responses were analyzed to identify recurring themes related to tool usability, adoption barriers, data requirements, and governance challenges. The analytical focus is on pattern identification rather than hypothesis testing, consistent with the survey's exploratory intent.

The survey analysis focuses on the following aspects:

- Alignment between tool functionality and industrial symbiosis and carbon capture objectives.
- Barriers related to data availability, confidentiality, regulation, cost, and interoperability.
- Perceived contributions to resource efficiency and carbon reduction.
- Opportunities for tool enhancement and supporting policy mechanisms.

The survey results are presented in Section 3.2 and interpreted in conjunction with the literature review in Section 4.

3. Results

This section presents the results of the study in two complementary parts, reflecting the dual-method research design. Section 3.1 reports the results of the PRISMA-guided scoping literature review, synthesizing publication trends, geographic distribution, tool and method classifications, implementation contexts, and stakeholder roles based on the analyzed corpus. Section 3.2 presents the practitioner survey results, providing empirical insights into tool usage, perceived maturity, implementation challenges, and adoption conditions in real-world industrial contexts.

3.1. Literature Review Results

Industrial symbiosis has emerged as a vital strategy for enhancing resource efficiency, reducing emissions, and fostering circular economy goals in industrial parks. This section synthesizes findings from a scoping review of 119 studies, capturing broad trends in publication outputs, technological developments, and stakeholder contributions from 2006 to 2025. To improve interpretability, key descriptive patterns are reported with explicit counts and percentages, and each table is accompanied by a short analytical interpretation of what the mapped methods imply for tool maturity, deployment readiness, and remaining research gaps. Emphasis is placed on the evolution of research, the geographic scope of industrial symbiosis initiatives, and the array of tools and methods employed for resource optimization, decision-making, and sustainability assessment.

3.1.1. Evolution of Industrial Symbiosis Research

- Publication Trends

The scoping review indicates a generally upward trajectory in industrial symbiosis publications from 2006 to 2025 (Figure 3). The trend is characterized by a low-volume early phase from 2006 to 2012, followed by accelerated growth after 2013 and a peak in 2021 with 15 studies. This increase reflects the growing recognition of industrial symbiosis as a key approach to mitigating resource scarcity and climate change, while advancing circular economy principles [1]. Notably, the period 2021–2025 accounts for 55 of 119 studies, representing approximately 46.2 percent of the included literature, indicating that the evidence base is recent and rapidly expanding. The scoping review result also shows the following fields that have been prioritized over the years: inter-firm collaborations, waste valorization, and integrated energy solutions that lower environmental impacts and promote economic gains within industrial parks. However, the year-by-year pattern shows fluctuations rather

than linear growth, implying sensitivity to policy cycles, demonstration funding, and national decarbonization programs that tend to drive bursts of applied research.

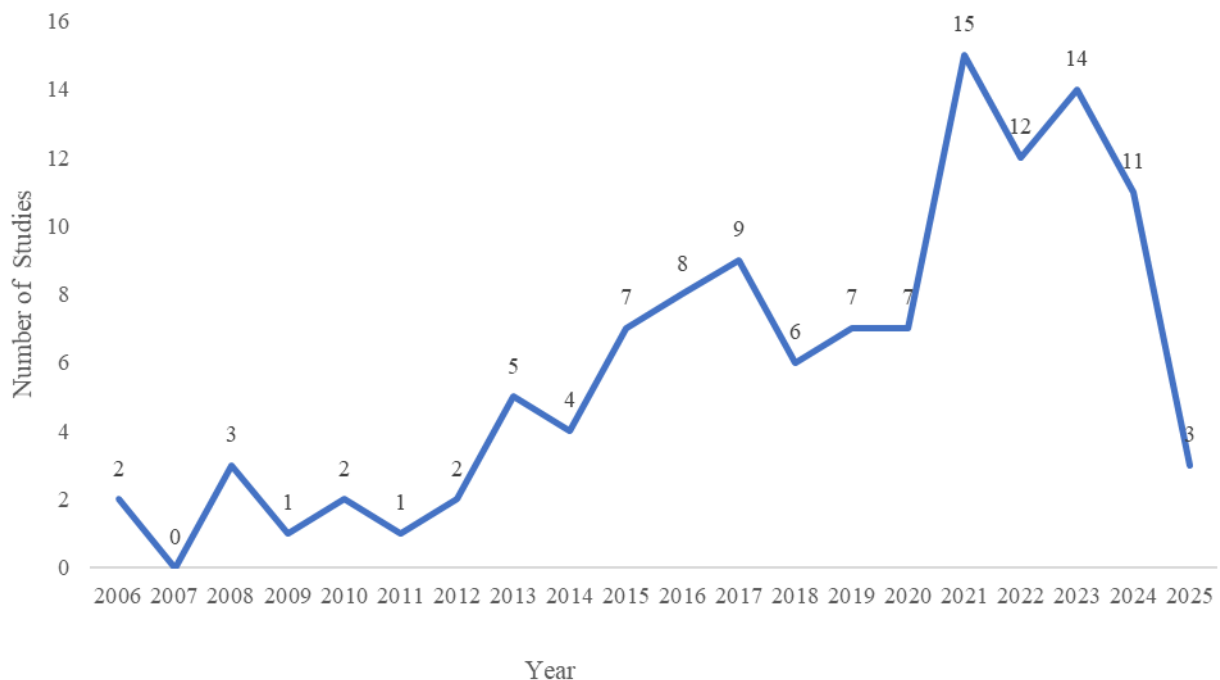


Figure 3. Number of included studies per year, 2006–2025, based on the 119-study scoping review dataset.

Figure 3 shows that annual publications remain low before 2013, then increase markedly, reaching 15 studies in 2021, followed by 12 studies in 2022, 14 studies in 2023, 11 studies in 2024, and 3 studies in 2025. The lower count in 2025 reflects partial-year coverage up to January 2026 rather than a substantive decline in research activity. This concentration of output in recent years suggests that industrial symbiosis tool development has shifted from conceptual framing toward implementation-oriented modeling and assessment, likely influenced by national net-zero targets and eco-industrial park programs. At the same time, the post-2021 fluctuation indicates that the evidence base is shaped by program cycles and case-study availability rather than steady linear growth, which has implications for the transferability of reported results across regions and sectors.

- **Geographic Distribution**

Analysis of the 119 selected studies revealed that 95 reported specific locations. Figure 4 illustrates how China leads in the number of publications. Among the location-reported studies, China accounts for 60, indicating a highly skewed geographic evidence base. This concentration implies that reported tool usage patterns, data availability assumptions, and governance models may disproportionately reflect contexts with stronger state-led eco-industrial park programs and more mature industrial data infrastructures. As highlighted by [2], such systemic conditions—particularly integrated governance structures and coordinated data management—are critical enablers for energy–water–food–carbon nexus implementation in eco-industrial parks, and are not uniformly present across regions. Consequently, evidence on tool deployment barriers in regions with weaker institutional capacity or limited data-sharing mechanisms may be underrepresented in the current literature.

However, industrial symbiosis has also attracted considerable interest across Asia (South Korea, Malaysia, Qatar, Singapore, the Philippines, Japan, Bangladesh, Indonesia, and Vietnam) and Europe (France, Russia, Turkey, Greece, Bosnia and Herzegovina,

Belgium, and Spain), with additional initiatives reported in Australia and Morocco. This geographic concentration suggests that the literature is shaped not only by technical need but also by institutional capacity, availability of industrial data, and sustained public programs that support eco-industrial park experimentation. A further implication is that evidence on tool adoption and governance may be overrepresented in regions with mature park programs and underrepresented in contexts where data access, investment, or institutional coordination are weaker.

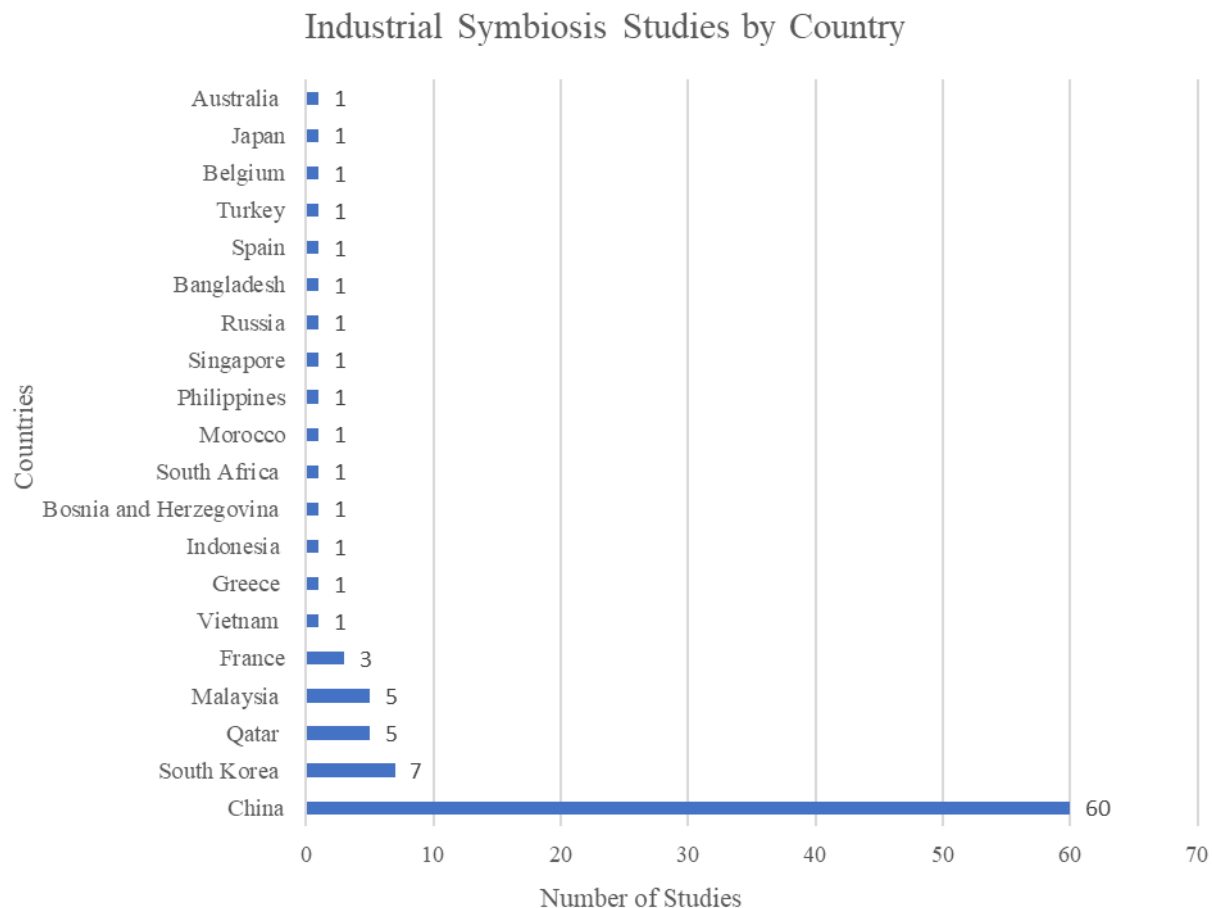


Figure 4. Distribution of included studies by country for the subset of studies reporting a specific study location, n equals 95.

3.1.2. Classification of Tools and Methods Supporting Industrial Symbiosis

The reviewed literature reveals a diverse range of tools and methods aimed at facilitating resource sharing, optimizing energy use, managing data, and informing decision-making in industrial symbiosis. These technologies span from simulation platforms and econometric models to optimization frameworks, data analysis instruments, decision-support systems, and sustainability assessment techniques. Where the included studies explicitly report software, solvers, or named methods, frequency patterns are synthesized qualitatively in the narrative to distinguish dominant tool families from underrepresented capabilities, rather than treating all tools as equally prevalent. Across the mapped tool landscape, two cross-cutting patterns are apparent. First, a substantial share of methods emphasize planning, optimization, and performance assessment. Second, comparatively fewer studies operationalize interoperability, semantic integration, or governance-oriented digital mechanisms, even though these factors are repeatedly identified as barriers to real-world implementation. This imbalance indicates that methodological maturity in analytical

optimization has advanced more rapidly than the socio-technical mechanisms required for large-scale deployment.

To provide a clearer conceptual overview, Figure 5 groups these methods into three overarching clusters. Analytical and Optimization tools include simulation and modeling platforms, optimization frameworks, and econometric approaches that help design and optimize industrial symbiosis systems. Data and Decision Support tools encompass data collection and communication techniques, decision-making frameworks, control tools, and ontology-based approaches that ensure real-time monitoring, coordination, and structured knowledge management. Evaluation and Visualization tools include sustainability assessment and visualization techniques that quantify environmental, social, and economic impacts while illustrating flows and synergies across actors. References to each table (Tables 3–11) in this section offer an overview of methodologies and their industrial applications. Across the optimization-oriented literature summarized in Tables 3–5, MILP and related mathematical programming formulations recur across multiple case studies as the dominant family of approaches for park-level coordination, whereas ontology-based and semantic interoperability methods appear only sporadically, highlighting a structural gap between analytical tool development and deployment-oriented data integration.

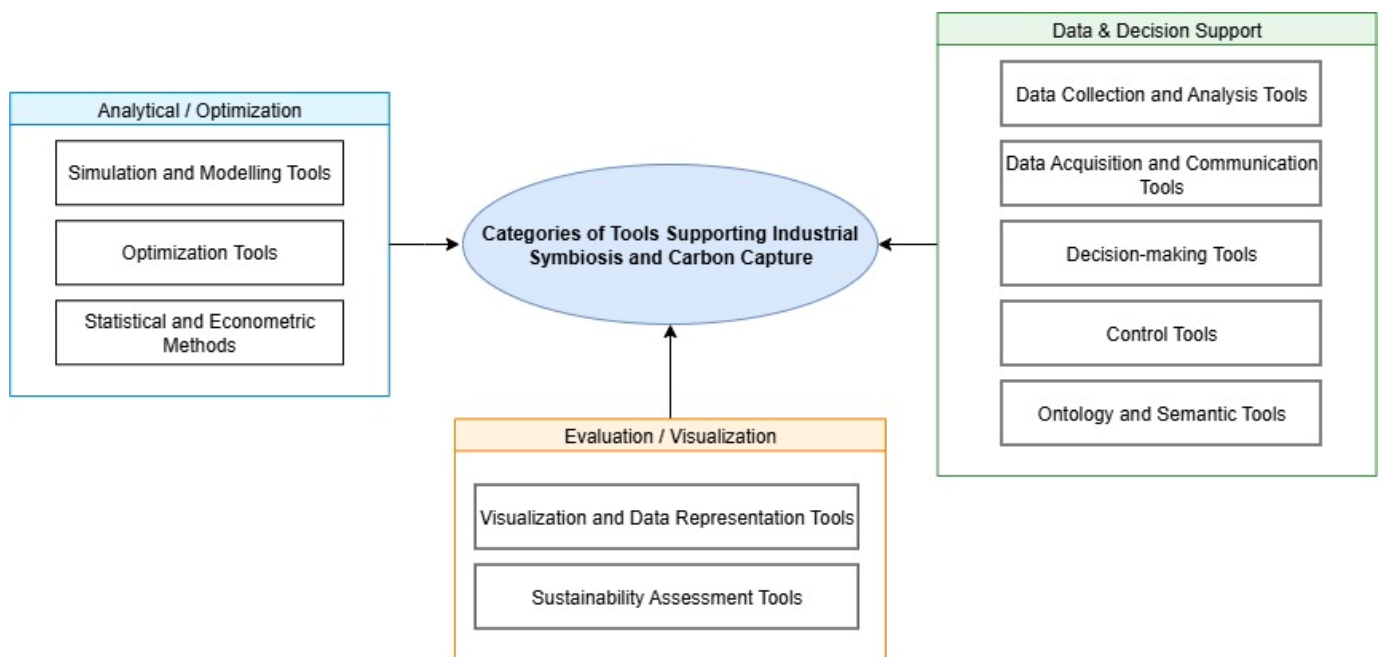


Figure 5. Classification of Data-Driven Tool Categories Supporting Industrial Symbiosis and Carbon Capture in Industrial Parks.

Table 4. Simulation and modeling tools used to analyze energy, material, and carbon flows in industrial symbiosis and eco-industrial park studies.

Method/Software Platform	Function	Example Application	Relevance to Industrial Symbiosis (IS)/Carbon Capture (CC)
HOMER	Energy system simulation	Microgrids, energy planning	Supports planning of hybrid IS systems and emission reduction
EnergyPLAN	Energy planning and modeling	Microgrids, waste heat recovery	Optimizes park-level energy and waste-heat symbiosis
EMB3Rs	Waste heat recovery simulation	Industrial energy optimization	Facilitates industrial energy exchanges and IS integration

Table 4. *Cont.*

Method/Software Platform	Function	Example Application	Relevance to Industrial Symbiosis (IS)/Carbon Capture (CC)
Aspen Plus	Simulates industrial/energy processes	Biorefinery scenarios, ECR optimization, chemical processes	Models energy/material flows in IS; potential to embed CC pathways
Aspen HYSYS	Process design and monitoring	GTL, ammonia, mass, and energy balances	Simulates process-level energy flows, supporting IS resource optimization
ProSimTM	Thermal efficiency and recovery analysis	Thermal efficiency, heat recovery	Assesses recovery options relevant to cross-company IS
AVEVA PRO/II	Steady-state process simulation	ALPG system performance	Optimizes steady-state performance; applicable to IS utilities
MATLAB	Dynamic simulation and optimization	Power flow, GRG algorithm, park-level microgrids	Supports IS microgrid design and testing carbon-reduction strategies
Vensim	System dynamics simulation	Dynamic system behavior over time	Analyses feedback and long-term IS development dynamics
Monte Carlo Simulation	Uncertainty modeling	Probabilistic outcomes, system behavior	Captures variability in IS systems and CC scenarios
RTDS Simulation Platform	Real-time grid simulation	Power system validation	Validates IS-integrated grid control with carbon implications
Digsilent PowerFactory	Grid modeling and analysis	Power system operation, uncertainty handling	Models IS-integrated grid networks and renewable flows
AnyLogic	Simulation environment	Mixed energy–production scheduling in eco-industrial parks	EIP eco-industrial park-level energy–production validation
SimaPro (ReCiPe)	LCA-based simulation tool	Pollution–carbon synergy evaluation in an industrial park	Environmental impact and synergy modeling
LEAP	Scenario-based energy and emission modeling	Zhejiang and Shandong eco-industrial parks	Decarbonization pathways

Note: Software tools are reported at the platform or method level as described in the reviewed literature. Specific software version numbers are not consistently reported across primary studies and are therefore not specified.

Table 5. Statistical and econometric methods applied to evaluate policy impacts and performance of industrial symbiosis and eco-industrial parks.

Method/Software Platform	Function	Example Application	Relevance to Carbon Capture (CC)/Eco-Industrial Parks (EIPs)
Econometric software	Supports statistical and econometric analysis	Regression and model validation in EIP studies	Supports evaluation of EIP policy impacts on emissions
Multiple Linear Regression (MLR)	Model relationships between variables	Incorporating climate change data into energy analyses	Helps quantify links between industrial activity, climate factors, and emissions
Welch’s T-test (95% CI)	Validates models	Applied in CC-VRES validation	Confirms reliability of emission reduction results
Linearity Tests	Assesses variable relationships for models	Assessing need for nonlinear modeling	Ensures correct choice of statistical models for emissions data
J-Tests	Verify econometric model appropriateness	Regression models in EIP performance studies	Identifies statistically valid links between policies and emission outcomes

Table 5. Cont.

Method/Software Platform	Function	Example Application	Relevance to Carbon Capture (CC)/Eco-Industrial Parks (EIPs)
Significance Tests	Test's reliability of estimated coefficients	Regression models in EIP performance studies	Identifies statistically valid links between policies and emission outcomes
Difference-in-Differences (multi-period, staggered, spatial variants)	Evaluates causal and spillover effects of EIP policies on emissions and efficiency	Multi-period DID: long-term CO ₂ reduction in EIPs; Staggered DID: phased adoption of EIP policies; Spatial DID: spillover effects across cities; NDEP policy evaluation across 282 Chinese cities (DID + Spatial DID)	Provides robust evidence of EIP policy effectiveness, spatial spillovers, and emission-reduction outcomes
Tobit regression (with DDF-DEA)	Econometric analysis of bounded efficiency scores	Green-development efficiency; Zero-Waste City and synergy determinants in a chemical industrial park	Links policy/structure factors to efficiency outcomes

Note: Software tools are reported at the platform or method level as described in the reviewed literature. Specific software version numbers are not consistently reported across primary studies and are therefore not specified.

Table 6. Optimization methods and tools used for resource allocation, energy integration, and emission reduction in industrial symbiosis systems.

Method/Software Platform	Function	Example of Applications	Relevance to Industrial Symbiosis (IS)/Carbon Capture (CC)
LP/MILP	Optimize energy, resources, costs	Sustainable clusters, heat recovery, hybrid power	Widely used in eco-industrial parks; supports emission cuts via symbiosis
MINLP	Model nonlinear energy–resource systems	Trigeneration, heat exchangers, EWFC networks	Reduces hot utility; relevant for CC–energy integration
Solvers (GAMS, CPLEX, BARON, AIMMS, LINGO, What'sBest)	Platforms for MILP/MINLP	System design, CO ₂ , and cost integration	Enable model implementation in IS/CC
Multi-Agent EMS and Bi-level Optimization	Distributed and hierarchical decision-making	BESS in microgrids, shared scheduling	Balance industrial and CC goals in eco-industrial parks
Heuristic and Metaheuristic Methods (PSO, GA, NSGA-II, AMPSO, IGA)	Find near-optimal solutions	Microgrid planning, storage, and demand response	Flexible when exact models not feasible
Stochastic and Decomposition-Based Optimization	Manage uncertainty, improve efficiency	Stochastic prog., dual decomp., FISTA	Strengthen IS/CC robustness under variability
Pricing and Scheduling Models	Optimize power use and operations	TOU tariffs, peak–valley pricing, sizing energy islands	Cut costs and support low-carbon operations
Total Site Analysis (TSA) and Pinch Analysis	Improve park-wide efficiency	Heat integration, waste-to-resource	Reduce fuel use and emissions for CC
Park-level Integrated Energy Systems	Coordinate energy at eco-industrial park scale	System-wide planning	Basis for sustainable CC at park level
IBM ILOG CPLEX (Constraint Programming)	CP/Discrete optimization for schedule–resource coordination	Energy–production co-scheduling in an eco-industrial park (WSC 2024)	Aligns production with onsite energy → IS efficiency and emissions cuts
Gurobi (MILP Solver)	Large-scale MILP for integrated energy design and operation	Electricity–heat co-optimization with PV/wind/CO ₂ HP and storage (IFEEA 2024)	Designs low-carbon IES layouts in eco-industrial parks (symbiosis across utilities)

Table 6. *Cont.*

Method/Software Platform	Function	Example of Applications	Relevance to Industrial Symbiosis (IS)/Carbon Capture (CC)
Excel Solver	Multi-objective optimization in spreadsheet environment	Industrial-structure adjustment under pollutant/CO ₂ constraints (JCP 2024)	Helps derive SCMPR pathways at park level (IS + decarbonization)
ACTA (Automated Composite Table Algorithm)	Targeting + network synthesis for resource allocation	CO ₂ allocation network and fresh-CO ₂ minimization in a chemical eco-industrial park (PSEP 2024)	Directly supports carbon symbiosis/utilization across plants

Note: Software tools are reported at the platform or method level as described in the reviewed literature. Specific software version numbers are not consistently reported across primary studies and are therefore not specified.

Table 7. Data collection and analysis tools supporting monitoring, modeling, and decision-making in industrial symbiosis and carbon-related applications.

Method/Tool	Function	Example of Applications	Relevance to Industrial Symbiosis (IS)/Carbon Capture (CC)
Surveys and Interviews	Capture both quantitative and qualitative data	Collecting data on energy consumption, environmental performance, and operational efficiency	Identifying resource and energy patterns for IS
Literature Review	Collect and synthesize existing information	Gathering knowledge on energy and operational efficiency	Supports understanding of industrial processes and symbiotic opportunities
Least Squares Regression	Quantifies load-curve impacts	Modeling energy demand patterns	Evaluating energy flows for IS
Correlation and Regression Analysis	Map relationships between variables	Studying link between policies and competitiveness	Informing policy-driven IS strategies
Sensor-Based Monitoring	Real-time data collection	Measuring energy and material flows	Enables continuous improvement in eco-industrial strategies
EV Data Logging	Collect operational data from electric vehicles	Tracking energy use in industrial processes	Supports real-time optimization in IS
SCADA Measurements	Automated monitoring of processes	Real-time tracking of energy or material flows	Facilitate continuous improvement in eco-industrial strategies
Industrial Data Collection and Preprocessing	Collects and harmonizes FDLI-level data across industries	Pollution-carbon synergy modeling in an eco-industrial park (SCMPR tool)	Provides empirical inputs to support IS optimization under dual-carbon goals

Table 8. Decision-making methods used for scenario analysis, stakeholder coordination, and planning in industrial symbiosis contexts.

Method/Software Platform	Function	Example of Application	Relevance to Industrial Symbiosis (IS)/Carbon Capture (CC)
Performance Metrics	Assess optimization effectiveness	Energy costs, storage, emissions, and scheduled-job ratio	Quantifies gains from IS-oriented coordination in parks
Sensitivity Analysis	Test impact of parameter changes	Varying heat-to-electric storage investment ratio and tracking capacity/NPV response	Identify critical decision factors
Scenario Analysis	Explore varying assumptions	Load-ratio scenarios and external-waste-heat scenarios (park-wide); decarbonization pathway scenarios at eco-industrial park scale	Guide eco-industrial planning

Table 8. *Cont.*

Method/Software Platform	Function	Example of Application	Relevance to Industrial Symbiosis (IS)/Carbon Capture (CC)
Game Theory	Model stakeholder strategies	Resource-sharing interactions	Enable fair, cooperative strategies
Cooperative Game Theory (Maali's Method)	Determine fair cost allocations	Allocating cost savings fairly among multiple companies	Encourages equitable collaboration in IS
WAR GUI	Assess environmental impact	Evaluating potential environmental risks of processes	Supports sustainable decisions
Inherent Safety Index (ISI) Calculation	Measure process safety	Industrial operation risks	Ensure safe IS frameworks
Steam System Composite Curves	Analyze steam generation and recovery	Optimizing steam systems	Improves energy efficiency

Note: Software tools are reported at the platform or method level as described in the reviewed literature. Specific software version numbers are not consistently reported across primary studies and are therefore not specified.

Table 9. Visualization and data representation tools used to communicate resource flows and system interactions in industrial symbiosis.

Method/Software Platform	Function	Example of Application	Relevance to Industrial Symbiosis (IS)/Carbon Capture (CC)
GIS/ArcGIS	Map spatial data and analyze distribution	Mapping energy potential, eco-industrial park layouts	Optimizes eco-industrial park design and resource allocation
e!Sankeys	Visualize resource flows	Depicting carbon flow diagrams	Illustrate resource/carbon flows for optimization
Maps/Network Maps	Represent locations and infrastructure	Showing eco-industrial park locations, energy infrastructure	Supports planning and management of industrial networks
Network Diagrams	Illustrate interconnections between sectors	Mapping sectoral interconnections	Clarify IS linkages
Grassman/Energy Utilization Diagrams (EUDs)	Analyze energy and exergy flows	Energy/exergy tracking	Identify efficiency/recovery options
GCCs/SSSPs	Visualize heat integration	Heat integration for Total Site Analysis (TSA)	Optimize heat recovery and integration
GEPHI	Visualize networks	Symbiosis network mapping	Reveal network structures and relationships
Network Allocation Diagrams (NADs)	Optimize allocation	Carbon distribution optimization	Ensure fair, efficient allocation
Sankey/Energy-flow diagrams	Visualize multi-energy conversions and transfers	Park-level energy-flow depiction for baseline vs. optimized waste-heat integration	Clarifies cross-process exchanges and recovery benefits in IS

Note: Software tools are reported at the platform or method level as described in the reviewed literature. Specific software version numbers are not consistently reported across primary studies and are therefore not specified.

- **Simulation and Modeling Tools**

Simulation and modeling platforms enable the design and validation of industrial symbiosis scenarios under realistic conditions [12]. Table 4 provides a list of commonly adopted tools, such as HOMER [20–22]. Other energy simulation and modeling tools identified in studies include EnergyPLAN [23] and EMB3Rs [24], which addresses microgrids, energy planning, and waste-heat recovery.

Mathematical models capture multi-energy systems, allowing users to explore constraints, optimize resource allocation, and simulate real-time operations [25,26]. These models also address the interactions within energy–water–food–carbon (EWFC) systems [2] and industrial parks, including energy generation, storage, demand, and balance [27]. They are crucial for integrating renewable energy sources into energy systems [28], analyzing energy consumption and savings in industrial chains [29]. Additionally, they play a key role in evaluating resource utilization and economic benefits in industrial symbiosis [30,31].

Table 10. Ontology-based and semantic tools supporting data interoperability and knowledge representation in industrial symbiosis systems.

Method/Software Platform	Function	Example of Application	Relevance to Industrial Symbiosis (IS)/Carbon Capture (CC)
Protégé	Create, visualize, and edit ontologies	Developing domain and application ontologies for eco-industrial parks	Enables structured representation of processes and resource flows
Apache Jena Fuseki	Publish and store ontologies locally	Hosting ontologies for eco-industrial systems	Provides accessible ontology databases for eco-industrial park knowledge management
SPARQL/RDF Query Language	Retrieves data efficiently from ontology databases	Querying RDF-formatted ontologies for energy and resource information	Facilitates data-driven decision-making in IS
Agent Communication Language (ACL)	Facilitates communication between agents in decentralized systems	Information exchange in decentralized Energy Management Systems (EnMS)	Supports coordination and interaction among multiple industrial agents

Note: Software tools are reported at the platform or method level as described in the reviewed literature. Specific software version numbers are not consistently reported across primary studies and are therefore not specified.

Table 11. Sustainability assessment methods used to evaluate environmental, economic, and social performance of industrial symbiosis and carbon-related systems.

Method/Software Platform	Function	Example of Application	Relevance to Industrial Symbiosis (IS)/Carbon Capture (CC)
Life Cycle Assessment (LCA)	Evaluates the impact of supply chains and IS	Comparing IS systems to non-symbiotic baselines; life-cycle-based synergy evaluation (LCA-SE) to quantify pollution–carbon synergy in industrial parks	Evaluates environmental benefits and potential carbon reductions
Material Flow Analysis (MFA)	Map material flows and identify IS opportunities	Measuring resource savings and waste reduction	Supports resource efficiency and circularity
Social Impact Assessment (SIA)	Evaluate social consequences of industrial decisions	Assessing job creation and community health impacts	Ensures social sustainability in eco-industrial park
Sustainability Metrics (e.g., SWROIM)	Assess performance	Evaluating sustainability performance of industrial entities	Provides integrated sustainability assessment
Logarithmic Mean Divisia Index (LMDI)	Decompose changes in carbon emissions	Analyzing sources of carbon emission changes	Supports understanding of emission dynamics in IS networks
Data Envelopment Analysis (DEA)	Measure efficiency	Assessing operational efficiency in industrial parks; DDF-DEA combined with Tobit regression to analyze green-development efficiency and policy determinants	Identifies performance gaps and best practices
Ward’s Hierarchical Clustering	Group similar industrial parks	Analyzing eco-efficiency patterns across parks	Supports benchmarking and comparative analysis

Table 11. Cont.

Method/Software Platform	Function	Example of Application	Relevance to Industrial Symbiosis (IS)/Carbon Capture (CC)
Social Network Analysis (SNA)	Identify key nodes and vulnerabilities	Mapping IS network interactions	Enhances resilience and connectivity in IS networks
Remote Sensing	Detect renewable energy potential	Identifying wind and solar resources	Supports planning for renewable integration and carbon reduction
Steam System Composite Curves	Visualize steam generation, consumption, and recovery	Optimizing steam networks in industrial parks	Improves energy efficiency and resource recovery
Specialized Software (SimaPro, Slack-Based DEA)	Enhance precision in modeling and analysis	LCA modeling and eco-efficiency analysis	Enables detailed sustainability and carbon-related assessments
Decoupling and Coordination Models (Tapio, CCD)	Track decoupling and coordination status	Applied to park-level analysis of pollution–carbon–economy co-benefits	Monitors progress towards synchronized IS and carbon goals

Note: Software tools are reported at the platform or method level as described in the reviewed literature. Specific software version numbers are not consistently reported across primary studies and are therefore not specified.

Recent studies also applied simulation environments such as AnyLogic to test energy–production scheduling in eco-industrial parks [32], while life cycle tools such as SimaPro (ReCiPe) were used to evaluate pollution–carbon synergies [33]. Similarly, LEAP was employed to simulate decarbonisation pathways in Zhejiang and Shandong eco-industrial parks [34,35].

Process simulators optimize industrial and energy systems. For example, Aspen Plus is employed to simulate biorefinery scenarios [36], optimize energy conversion systems (ECR) [37], analyze system performance [38], and simulate chemical processes to obtain data on waste heat and heating demand for plants and communities [39]. Aspen HYSYS is used to simulate various industrial processes, collect data on mass and energy flows, contaminant concentrations, and economic parameters, and monitor water usage and contaminants in processes like GTL and ammonia production [40]. Meanwhile, ProSimTM analyzes the performance of thermal systems, focusing on thermal efficiency and heat recovery [41], while AVEVA PRO/II is a steady-state simulator used to optimize process performance, like modeling the ALPG system [42].

Programming environments like MATLAB and Vensim support dynamic or real-time validations [43]. MATLAB, for example, is used to simplify complex models, such as fitting transportation costs into a simplified formulation [37], and to simulate power flow forecasting and charging processes using MATLAB/Simulink [44]. Additionally, MATLAB supports optimization techniques like the Generalized Reduced Gradient (GRG) algorithm [39] and is applied in the simulation and analysis of park-level microgrids [45]. On the other hand, Vensim simulates and analyzes the dynamic behavior of systems over time [43]. Moreover, Monte Carlo simulation approaches [8], RTDS Simulation Platforms [12], and Digisilent PowerFactory handle uncertainties and grid complexities [46].

Collectively, the simulation and modeling tools listed in Table 3 reflect a strong emphasis on engineering feasibility and performance estimation. Their value lies in enabling scenario exploration and techno-economic assessment, but they typically assume that high-quality process and energy flow data are available and shareable across firms. This assumption becomes a limiting condition for adoption in industrial symbiosis settings where data confidentiality and heterogeneous data formats are common.

Carbon capture modeling gap. Despite the prominence of process simulation tools for emissions and material-flow modeling, relatively few studies explicitly simulate carbon

capture technology pathways, such as absorption, adsorption, amine scrubbing, membrane separation, or oxy-fuel combustion, as integrated subsystems within industrial symbiosis networks. Catalytic methanation appears as a carbon capture-related pathway, but other capture options are rarely modeled in industrial symbiosis contexts. This gap suggests that future tool development and review synthesis should more systematically connect carbon capture technology representation to industrial symbiosis toolchains and data requirements.

- Statistical and Econometric Methods

Statistical and econometric methods are used to evaluate initiatives like eco-industrial parks (EIPs) and their impact on emissions and environmental outcomes (as shown in Table 5). Studies employ econometric software to support statistical and econometric analysis [47], while tools like Multiple Linear Regression (MLR) incorporate climate change data for augmentation [42]. Methods such as Welch's *t*-test (95% confidence interval) validate models like CC-VRES [42], while linearity tests justify the use of nonlinear models by assessing variable relationships [47]. J-tests ensure appropriate model specifications [47], and Significance Tests determine the reliability of model coefficients [47].

Difference-in-Differences (DID) methods, including multi-period [48], staggered [49], and spatial approaches, measure the causal effects of eco-industrial parks on emissions and their spillover impacts [50]. These methods deliver statistically robust evidence on how and whether eco-industrial park policies meet greenhouse gas reduction objectives. Consistent with this, spatial DID and DID have been applied to assess the effect of China's National Demonstration Eco-Industrial Parks on urban carbon-emission efficiency across 282 cities [51], while Tobit regression has been used (with DDF-DEA) to examine green-development efficiency and policy drivers at park and enterprise levels [34].

The econometric toolset indicates that a policy-evaluation stream has matured alongside the development of engineering tools. Unlike simulation-based studies, which often focus on technical feasibility, econometric studies can support causal inference into the effects of eco-industrial park designation and related policies. However, these studies typically operate at aggregated spatial or sectoral levels and therefore provide limited operational guidance on tool selection, system integration design, or data governance mechanisms required for firm-level adoption.

- Optimization Tools

Linear Programming (LP) and Mixed-Integer Linear Programming (MILP) are optimization methods for solving complex problems, especially in energy systems (shown in Table 6). Multi-period and successive MILP models address time-dependent operational and utility decisions [5]. MILP is widely used to minimize energy costs, design sustainable clusters, optimize energy networks, and reduce GHG emissions through energy symbiosis [52]. It also evaluates the economic benefits of energy exchanges in eco-industrial parks and integrates renewable energy, achieving up to 97% potential emission reduction [53]. Furthermore, MILP supports the design of cost-efficient hybrid power systems and enhances both economic and environmental performance [54]. MILP is also applied to determine optimal solutions and operating strategies for multi-energy systems [55]. These models are commonly solved using GAMS, IBM ILOG CPLEX, and LINGO [56]. For MINLP problems, GAMS combined with the BARON solver is frequently employed [57]. AIMMS provides solvers such as CONOPT for NLP and MILP optimization [58,59]. Meanwhile, What's Best! by LINDO Systems integrates with Microsoft Excel to handle objectives such as profit maximization, cost minimization, and energy/CO₂ integration in eco-industrial parks [60].

Mixed-Integer Nonlinear Programming (MINLP) extends optimization capabilities to highly complex energy systems, including renewable integration in eco-industrial parks [4] and sustainable energy–water–food–carbon networks [2]. MINLP applications include optimizing heat and material stream integration in a natural gas industrial park—achieving a 30.5% reduction in hot utility consumption [53], and minimizing total annualized costs in trigeneration and heat exchanger networks where fuel input deviations significantly increased costs [3].

Multi-agent Energy Management Systems (EMS) and consensus-based algorithms optimize Battery Energy Storage Systems (BESS) in DC microgrids within industrial parks [61]. Bi-level optimization frameworks model decision-making processes involving two levels with conflicting objectives [13], while the Bi-level Fuzzy Programming Model incorporates flexibility and uncertainty into these objectives [10].

Heuristic and metaheuristic methods address complex energy optimization problems. Particle Swarm Optimization (PSO) is used for energy dispatch [62], storage allocation [63], and management strategies for large users [64]. Variants like the Improved Second-Order Oscillating PSO [26] and Adaptive Modified PSO (AMPSO) [65] enhance microgrid operation planning. Genetic algorithms (GA), including improved GA (IGA) [66] and NSGA-II for multi-objective problems [67], optimize operating schedules and tackle multi-objective energy challenges. Recent 2025 evidence further illustrates the continued relevance of multi-objective optimization for eco-industrial park restructuring. In particular, an NSGA-II-based multi-objective optimization framework was applied in [68] to evaluate trade-offs between economic output, carbon mitigation, and pollution reduction in a real eco-industrial park, demonstrating how optimization supports simultaneous decarbonization and waste-management strategies at the park scale.

Stochastic and decomposition-based methods handle uncertainty and boost efficiency: stochastic programming manages renewable and demand variability, dual decomposition simplifies problems, and FISTA speeds up real-time optimization [27]. Meanwhile, the electricity pricing strategies include peak–valley and time-of-use models, which reduce microgrid costs in industrial parks [69,70]. An optimal sizing scheme further determines equipment parameters for new energy islands [1].

Total Site Analysis (TSA) improves park-wide systems by assessing energy use, savings, and cross-process heat integration [15]. Analysis optimizes energy efficiency, heat exchange, and resource use, supporting carbon planning, thermal management, and waste-to-resource strategies [71]. Additionally, park-level integrated energy systems determine economical and environmentally sustainable energy plans for industrial parks [17].

In line with these trends, IBM ILOG CPLEX has been applied as a constraint programming solver for mixed energy production scheduling in eco-industrial parks [32], Gurobi has been used to optimize integrated electricity–heat systems [72], Excel Solver has supported multi-objective structural adjustment under pollution–carbon constraints [73], and ACTA (Automated Composite Table Algorithm) has enabled CO₂ allocation network design [74]. Complementing these solver-centered approaches, [75] develops a nonlinear programming model in Python for peer-to-peer multi-energy trading in an eco-industrial park and implements ADMM as a decentralized coordination mechanism to clear the thermal energy market under network and storage constraints, highlighting the role of distributed optimization in preserving privacy while improving overall system performance.

The dominance of MILP and related optimization formulations indicates that industrial symbiosis research strongly prioritizes optimal resource allocation and cost minimization under constraints. However, optimization models typically embed strong assumptions about coordination, centralized decision authority, and data availability. In practice, adoption depends on governance arrangements that enable data sharing and agreement on

objective functions, which are rarely modeled explicitly. This gap implies that future work should integrate optimization formulations with interoperability and governance mechanisms, especially when carbon capture is introduced as an additional coupled subsystem.

- **Data Collection and Analysis Tools**

Effective industrial symbiosis depends on rich and reliable datasets. Table 7 reveals how surveys, interviews, and literature reviews capture both quantitative and qualitative dimensions of energy consumption, environmental performance, and operational efficiency [76]. Least squares regression quantifies load-curve impacts [69], while correlation and regression analyses map the relationship between eco-industrial park policies and enterprise competitiveness [77].

Some studies employ sensor-based monitoring, EV data logging [44], and SCADA measurements to facilitate real-time optimization [78] thereby enabling continuous improvements in eco-industrial strategies. In addition, multi-source industrial and pollutant datasets have been collected and preprocessed to calibrate optimization models for pollution–carbon synergy pathways [73].

Data collection and monitoring tools highlight that industrial symbiosis tools are conditional on data accessibility and standardization. The literature increasingly recognizes the role of real-time monitoring and integrated datasets, yet many studies treat data as an available input rather than as a governance and interoperability challenge. This pattern strengthens the interpretation that data infrastructure is not a secondary implementation detail but a central determinant of whether advanced modeling and optimization tools can be deployed in practice.

- **Decision-Making Tools**

Decision-making tools use data as input but are primarily designed for modeling scenarios or decision-making (as shown in Table 8). For instance, performance metrics assess key factors (e.g., energy costs, electricity exchange, storage levels, and emissions) to determine the effectiveness of optimization approaches [8]. Eco-industrial park studies have also applied performance metrics such as energy-utilization ratio and scheduled-job ratio to compare scheduling strategies [32]. Sensitivity analysis is conducted to understand how changes in parameters like electricity prices, energy storage usage, and investment costs impact the economic performance of different scenarios [79]. Sensitivity analysis has also been used to test the effect of storage investment ratios on integrated energy systems in the eco-industrial parks [72]. Scenario analysis explores the effects of varying assumptions and conditions on energy consumption, economic growth, and network design [80,81]. Furthermore, scenario analysis has also been used to evaluate different load-ratio cases, external waste-heat utilization, and decarbonization pathways at the park scale [35,82].

Additionally, Game Theory [64] and Cooperative Game Theory (Maali's Method) [83] are utilized to analyze strategic decision-making among agents and determine fair cost allocations in scenarios involving multiple stakeholders. The Shapley value calculation is also used in cooperative game theory to allocate cost savings among participating companies [59]. Furthermore, the WAR GUI and Inherent Safety Index (ISI) calculation assess the environmental impact and safety of processes [36], while steam system composite curves offer insights into steam generation and recovery opportunities within utility systems [15].

Decision-oriented methods represent a bridge between technical optimization and stakeholder negotiation because they explicitly surface trade-offs, uncertainty, and fairness. However, their practical impact depends on whether stakeholders accept shared metrics and whether decision authority is sufficiently coordinated. This suggests that decision-

support value is highest when combined with governance mechanisms that legitimize data sharing and collective action.

- Data Acquisition and Communication Tools

Data acquisition systems gather live information from industrial assets, including PV inverters and storage modules [25,62]. Communication networks allow real-time feedback to optimize algorithms, yielding coordinated energy flows that minimize operational costs and lessen ecological footprints. These systems underscore the transition toward digitalized, interconnected industrial frameworks necessary for comprehensive symbiosis [25,62].

- Control Tools

Control solutions handle real-time dispatch, load balancing, and energy flow coordination. Model Predictive Control (MPC) forecasts near-future demand to refine plant scheduling [62], and multi-agent systems (MAS) distribute control intelligence among autonomous components [84]. Such approaches to safeguard grid stability and resilience when intermittent renewables supply a significant share of the industrial park's energy [84,85].

- Visualization and Data Representation Tools

GIS-based tools are widely used in the reviewed literature to map renewable energy potential [86], analyze eco-industrial park distribution [49], and link energy consumption with spatial data [87]. In the reviewed studies, ArcGIS is commonly employed to identify PV-suitable roofs, analyze network data [46], assesses heat sources and industrial–urban symbiosis configurations [88], and evaluates industrial parks' water and solar potential [76]. GIS-based visualization is also used to illustrate supplier–customer energy exchanges [58]. Tools such as e!Sankey are applied to depict carbon flows in industrial symbiosis systems [16]. In addition, spatial maps are used to show eco-industrial park locations and energy infrastructure [89], while network diagrams illustrate sectoral interconnections [31].

Advanced tools like Grassman and Energy Utilization Diagrams (EUDs) analyze energy/exergy flows [38], while Grand Composite Curves (GCCs) and Site Source–Sink Profiles (SSSPs) visualize heat integration for Total Site Analysis (TSA) [15,53]. GEPHI visualizes IS networks [90], and Network Allocation Diagrams (NADs) optimize carbon distribution [71]. Park-wide multi-energy flows have also been represented with Sankey-style energy-flow diagrams to compare cases and communicate system operation [82].

Visualization tools shown in Table 9 are essential for stakeholder engagement and early-stage opportunity identification because they make exchange relationships intelligible. Their limitation is that visualization alone rarely resolves confidentiality constraints or produces implementable operating strategies. This suggests a need for hybrid toolchains that connect visualization to optimization and to secure data-sharing mechanisms.

- Ontology and Semantic Tools

Ontology-based approaches (shown in Table 10) build a shared vocabulary and data structure for eco-industrial systems. Protégé is used for creating, visualizing, and editing domain and application ontologies [91,92]. Apache Jena Fuseki serves as a local host for publishing and storing these ontologies, while the SPARQL Protocol and RDF Query Language enable efficient data retrieval from RDF-formatted ontology databases [91]. Additionally, Agent Communication Language (ACL) supports communication and information exchange between agents in decentralized Energy Management Systems (EnMS) [84].

Ontology and semantic tools directly address interoperability and structured data exchange, yet they remain less prominent in the overall tool landscape than simulation and optimization. This imbalance indicates that the literature may overinvest in analytical

sophistication relative to the socio-technical prerequisites for tool integration, particularly common data models and governance for shared semantics.

- Sustainability Assessment Tools

Sustainability assessment tools/methods (shown in Table 11) cover the environmental, social, and economic impacts of industrial symbiosis projects. Life Cycle Assessment (LCA) quantifies the environmental impacts of supply chain stages and evaluates the benefits of industrial symbiosis systems compared to non-symbiotic baselines [7] and has also been extended through life-cycle-based synergy evaluation (LCA-SE) to measure joint pollution–carbon effects at the industrial-park scale [33].

Meanwhile, Material Flow Analysis (MFA) maps material flows, identifies industrial symbiosis opportunities, and measures resource savings and waste reduction [81]. Social dimensions are addressed through Social Impact Assessments (SIA), which evaluate the consequences of supply chain options, including job creation and community health impacts [93]. Sustainability Metrics, including the Sustainability Weighted Return on Investment Metric (SWROIM), assess economic, environmental, and social performance [40].

Advanced analysis methods include the Logarithmic Mean Divisia Index (LMDI) for decomposing carbon emission changes [94,95], and Data Envelopment Analysis (DEA) to measure the efficiency of industrial entities [96]. Recent applications combine DDF-DEA with Tobit regression to evaluate green-development efficiency and to identify structural and policy determinants, while Tapio decoupling and coupling-coordination degree (CCD) models have been applied to assess coordination between economic growth, pollution reduction, and carbon mitigation at the park scale [34].

Recent 2025 studies further extend sustainability assessment from retrospective evaluation toward implementation-relevant quantification. In particular, [97] proposes an evaluation framework to quantify the carbon emission reduction potential of industrial symbiosis in industrial parks by distinguishing different symbiosis modes, such as waste reuse, energy cascade, and infrastructure sharing, and validating their approach through a real industrial park case study. This work illustrates how sustainability assessment methods can support prioritization of industrial symbiosis pathways rather than only ex-post performance comparison.

Moreover, Ward's Hierarchical Clustering Method groups industrial parks with similar industrial structures to analyze eco-efficiency patterns [98]. Social Network Analysis (SNA) identifies key nodes and vulnerabilities in industrial symbiosis networks [90], often supported by tools like UCINET 6 Software. Remote sensing aids in identifying renewable energy potential, such as wind and solar resources [42]. Steam System Composite Curves visualize steam generation, consumption, and recovery [52]. Specialized software such as SimaPro for LCA modeling [52] and the Slack-Based DEA Model for eco-efficiency analysis [98] enhances precision and depth in evaluating eco-industrial park systems.

Sustainability assessment methods strengthen claims of environmental and economic value, but they often remain retrospective or evaluative rather than prescriptive. This limits their direct utility for tool selection and operational deployment. A practical implication is that assessment methods should be increasingly coupled with decision-support pipelines that translate evaluation outputs into implementable investments and operating strategies under real-world governance constraints.

- Additional Methods and Tools

Other tools and methodologies applied to industrial symbiosis studies are identified (shown in Table 12). Java-based applets, for example, provide user interfaces for interacting with systems like J-Park Simulator (JPS), while sensor and actuator networks collect real-time data and implement decisions [91]. Advanced programming tools, such

as the Digsilent Programming Language (DPL), enable custom algorithm development for simulation automation [46]. Geographic insights are obtained through GIS tools like ArcGIS for mapping plants and communities [39]. Material analysis is enhanced by Thermo-Gravimetric/Differential Thermal Analysis (TG/DTA) to measure CO₂ content in fly ash and X-ray Powder Diffraction (XRD) to identify mineral transformations [99]. Energy system models, such as the gas turbine combined system and thermodynamic property equations (Peng-Robinson, Steam Table, Redlich–Kwong), assess efficiency and working fluid properties [38]. Data storage and processing are facilitated by a central database for company data management [6] and Big Cloud Moving Smart Technologies for advanced analysis [100]. Real-time operations leverage an IoT Management Platform connected via Power Optical Fiber and 5G networks [100]. Interfaces such as human–machine systems allow operators to monitor and control microgrid performance [25]. Decision support tools include Multi-Criteria Decision Making (MCDM) for evaluating trade-offs among solutions [5], and Adversarial Autoencoders (AAE) and SHAP explanations for analyzing energy models and reducing data dimensionality [42].

Table 12. Supporting computational and digital tools complementing core modeling and optimization methods in industrial symbiosis research.

Method/Software Platform	Function	Example of Application	Relevance to Industrial Symbiosis (IS)/Carbon Capture (CC)
Java-based Applets	Provide user interfaces for interacting with systems	Interacting with systems like JPS	Enhance accessibility and interaction in IS
Sensor and Actuator Networks	Collect real-time data and implement decisions	Process monitoring and automation	Support real-time optimization
Digsilent Programming Language (DPL)	Develop custom algorithms for simulation	Automating energy or process simulations	Enable tailored modeling
GIS Tools (ArcGIS)	Obtain geographic insights	Mapping plants and resources	Support spatial planning and resource allocation
Thermo-Gravimetric/Differential Thermal Analysis (TG/DTA)	Measure material properties	Measuring CO ₂ content in fly ash	Assess carbon/material changes
X-ray Powder Diffraction (XRD)	Identify mineral transformations	By-product analysis	Support material efficiency
Energy System Models (Gas turbine combined systems, Thermodynamic equations: Peng-Robinson, Steam Table, Redlich–Kwong)	Assess energy efficiency and fluid properties	Energy system performance in eco-industrial parks	Optimize energy use and emissions
Central Database	Store and process data	Industrial park database	Facilitate coordinated data management and analysis
Big Cloud Moving Smart Technologies	Advanced data storage and analysis	Processing large-scale industrial data	Enhance data-driven decisions in IS
IoT Management Platform (via Power Optical Fiber and 5G)	Enable real-time monitoring and control	Managing microgrid operations	Improve system coordination
Human–Machine Interfaces (HMI)	Monitor and control system performance	Operator supervision of microgrids	Improve operational management and response
IoT Management Platform (via Power Optical Fiber and 5G)	Enable real-time monitoring and control	Managing microgrid operations	Support operational efficiency and energy system coordination
Human–Machine Interfaces (HMI)	Monitor and control system performance	Operator supervision of microgrids	Improve operational management

Table 12. Cont.

Method/Software Platform	Function	Example of Application	Relevance to Industrial Symbiosis (IS)/Carbon Capture (CC)
Multi-Criteria Decision Making (MCDM)	Evaluate trade-offs among solutions	Resource allocation decisions	Guide optimal choices
Adversarial Autoencoders (AAE) and SHAP explanations	Analyze and reduce data dimensionality	Energy model interpretability	Improve decision support

Note: Software tools are reported at the platform or method level as described in the reviewed literature. Specific software version numbers are not consistently reported across primary studies and are therefore not specified.

3.1.3. Implementation Contexts in Industrial Symbiosis

The successful implementation of industrial symbiosis depends on diverse operational contexts, ranging from eco-industrial parks and conventional industrial parks to specialized sectors such as petrochemicals, agriculture, and fisheries. Each of these contexts presents unique opportunities and challenges, influencing the effectiveness, scalability, and adaptability of industrial symbiosis frameworks.

- **Eco-Industrial Parks**

Eco-industrial parks [101–103] incorporate collaborative waste management, shared utilities, and synergy-based optimization to reduce emissions. Empirical research employs scenario-based modeling, DID analyses, and cooperative game theory to affirm the effectiveness of eco-industrial parks in reducing CO₂ and SO₂ while fostering economic growth [47,104]. Studies also highlight that CO₂ reduction incentives in algae-based eco-industrial parks can enhance both environmental performance and cost savings through improved cooperation and optimization [10].

- **Industrial Parks**

Studies in industrial parks, for instance, Refs. [105–107] are increasingly incorporating symbiosis-driven frameworks. Relevant case studies in industrial parks involve multi-energy system optimization [5], carbon mitigation programs, and integrated energy systems [70]. Multi-objective approaches combine renewables with energy storage to cut costs and emissions [67]. Simulation tools like HOMER or Aspen Plus, as well as MILP-based methods, help design feasible system architectures that align with regulatory and financial constraints.

- **Other Industrial Sectors**

Industrial symbiosis principles are adapted to other industrial areas [108,109] such as agriculture, petrochemicals, fisheries, and beyond [26]. Tools such as Catalytic methanation, for instance, utilize CO₂-rich off-gases for green fuel production [42], while electrocoagulation of industrial effluents demonstrates synergy potential in fish processing [110]. Such applications confirm that industrial symbiosis can be tailored to different sectoral challenges, from specialized chemical routes to wastewater valorization.

The literature indicates that tool choice is shaped by the maturity of park infrastructure, the availability of shared utility systems, and the feasibility of data sharing across firms, which jointly influence whether advanced optimization and simulation can move beyond feasibility analysis toward deployment.

3.1.4. Key Stakeholders in Industrial and Eco-Industrial Parks

The successful deployment of industrial symbiosis relies on the involvement of numerous stakeholders. While not always explicitly stated in the literature, they are key

contributors to the development and operation of sustainable, innovative industrial ecosystems. Figure 6 illustrates these stakeholder groups, clustered into Core Industrial Park Operators, Policy and Finance Enablers, Technology and Knowledge Enablers, and Oversight and Beneficiaries, with industries positioned at the center as the hub of exchanges. Each group contributes distinct resources, incentives, or oversight to collective resource management and innovation [1,15].

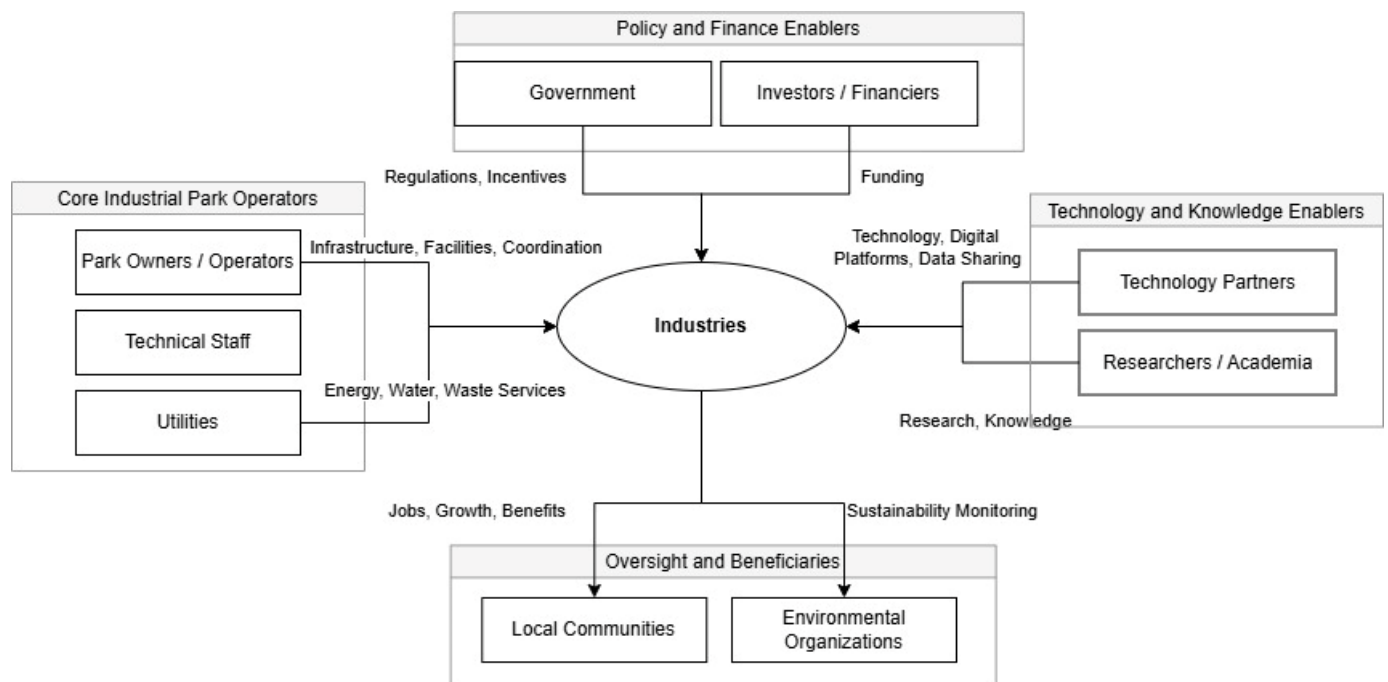


Figure 6. Key relationships among stakeholders in industrial and eco-industrial parks.

Government agencies establish environmental standards and offer incentives, while utilities ensure the provision of consistent service. Industrial park owners and operators provide infrastructure, facilities, and coordination, enabling industries to function and exchange resources. Technology partners deliver digital platforms, technologies, and data-sharing solutions, supporting innovation and monitoring. Investors and financiers advance funding for park development, while researchers and academia contribute knowledge and pilot new industrial symbiosis and carbon capture technologies. Environmental groups and local communities emphasize sustainability outcomes, accountability, and shared benefits, including job creation and economic growth. Technical staff (e.g., engineers, technicians, energy managers, consultants) build and maintain systems to ensure efficient park operations.

These stakeholders operate in a highly interconnected ecosystem. For example, government bodies influence industries and park operators through environmental policies and financial incentives, while utilities and technology developers provide essential services and digital infrastructures for monitoring and coordination. Researchers often collaborate with companies and park owners to test innovative symbiosis or carbon capture solutions, while communities and environmental groups exert legitimacy and social pressure, shaping public perception and adoption. These layered and reciprocal relationships highlight that effective industrial symbiosis depends not only on individual stakeholder actions but also on structured collaboration across clusters where infrastructure, finance, technology, and societal oversight converge.

3.2. Survey Results

To complement the findings from the literature review, a survey was conducted to capture real-world experiences and practitioner insights on industrial symbiosis and carbon capture tool adoption. This section presents key results from the survey, focusing on how industry professionals perceive, use, and evaluate these tools in operational contexts.

3.2.1. Practitioner Background and Perceptions of Industrial Symbiosis and Carbon Capture

A total of eight participants with diverse professional backgrounds participated in the survey, providing both quantitative and qualitative input. Although the sample size is limited, the respondents represent highly specialized expertise directly involved in tool development, evaluation, or application, which aligns with the exploratory objective of the survey. Respondent backgrounds are summarized in Table 13.

Of the eight respondents, three are senior researchers with more than ten years of experience, two are mid-career researchers with five to ten years of experience, and three are early-career researchers with less than five years of experience. This distribution indicates that the survey captures perspectives across different career stages rather than being dominated by a single experience group.

Regarding carbon capture, six out of eight respondents identified regulatory compliance, carbon credits or carbon pricing, and market reputation as key motivations for adoption, while four respondents also referenced financial support mechanisms such as subsidies or grants. At the same time, three respondents expressed uncertainty about the relevance of carbon capture to their current organizational context. This divergence suggests that while carbon capture is recognized as strategically important, its perceived applicability remains uneven across organizations, reflecting differences in regulatory exposure, investment capacity, and technology readiness. These patterns are consistent with prior studies highlighting the role of economic and regulatory drivers in adoption [42], as well as the inhibiting effects of cost and technical uncertainty [49].

In addition to carbon capture, the survey explored each respondent's perceptions of industrial symbiosis (as shown in Table 14). Six respondents (75 percent) identified cost savings and resource sharing as primary benefits, and four respondents (50 percent) highlighted new revenue from by-products. Several respondents referenced established cases such as Kalundborg Symbiosis, indicating that concrete examples play an important role in legitimizing industrial symbiosis practices. Conversely, five respondents (62.5 percent) identified high initial costs and limited awareness as significant barriers. This pattern reinforces the literature's emphasis on trust-building, demonstrable benefits, and supportive policy environments as prerequisites for wider adoption [8].

These findings indicate that practitioner support for industrial symbiosis and carbon capture is strongly conditioned by tangible economic incentives and visible success cases, rather than by abstract sustainability goals alone. The coexistence of strong perceived benefits and persistent uncertainty highlights a gap between conceptual attractiveness and operational readiness, which mirrors patterns observed in the literature review.

Table 13. Professional background, expertise, and experience of practitioner survey respondents (N = 8).

Category	Expertise Areas	Years of Experience	Involvement with Tools
Software and Systems	Software Engineering (2 respondents)	<5 years	Main developers
	System Innovation for Transformative Change	>10 years	Heavy user
Energy and Processes	Hydrogen, CCU, Industrial Energy Transformation	5–10 years	Some experience
	Energy Optimization, Process Integration	>10 years	Some experience

Table 13. *Cont.*

Category	Expertise Areas	Years of Experience	Involvement with Tools
Carbon Capture and Storage	Carbon Capture and Storage, Energy Systems, Economics	<5 years	Heavy user
	Methanation, CCU, Carbon Capture	>10 years	Main developer
Sustainability and Industrial Symbiosis	Industrial Symbiosis, Renewables in Processes	<5 years	Some experience

Table 14. Familiarity with and perceived benefits of industrial symbiosis and carbon capture among survey respondents (N = 8).

Respondent ID	Familiarity with CC	Importance of CC	Benefits of CC	Familiarity with IS	Importance of IS	Benefits of IS	Barriers to IS	Case
1	Somewhat familiar	Unknown	Carbon credits/pricing; Compliance	Unsure	Unknown	Cost savings; Revenue from by-products	Lack of knowledge/awareness	–
2	Somewhat familiar	Unknown	Credits/pricing; Compliance; Market reputation; Tax incentives; Subsidies	High	High	Cost savings; By-products; Shared resources; Tax incentives; Subsidies	Technological limitations	Kalundborg Symbiosis
3	Very familiar	Not relevant	Subsidies; Market reputation; Grants	Not relevant	Not relevant	Grants; Technical assistance; Shared resources; By-products	Government research institute context	–
4	Very familiar	High	Credits/pricing; Compliance; Grants; Technical assistance	High	High	Cost savings; By-products; Shared resources; Technical assistance	Technological limitations; Lack of awareness	–
5	Very familiar	High	Credits/pricing; Compliance; Market reputation; Grants	High	High	By-products; Cost savings; Shared resources; Grants	Lack of awareness; High initial costs	–
6	Somewhat familiar	Not relevant	Credits/pricing; Compliance; Tax incentives	Not relevant	Not relevant	Cost savings; Shared resources; Technical assistance	High initial costs	ICEIS project
7	Very familiar	Very high	Credits/pricing; Compliance; Operational efficiency; Reputation; Tax/Subsidies...	Unsure	Unknown	Cost savings; By-products; Shared resources; Tax, Subsidies; Grants...	Not specified	–
8	Somewhat familiar	Moderate	Credits/pricing; Compliance; Market reputation; Tax incentives; Subsidies	High	High	Cost savings; By-products; Shared resources; Tax incentives; Tech. assist.	High costs; Lack of awareness; Insufficient network	Conceptual studies only

Note: CC: carbon capture; IS: industrial symbiosis (Source: survey data).

3.2.2. Tools and Methods Overview

Survey participants reported the functions, maturity levels (TRLs), and usage contexts of tools they develop or use for industrial symbiosis and carbon capture. Among the eight respondents, two reported using tools at TRL 9, two reported tools at TRL 6, one reported TRL 4, one reported TRL 5, and two selected “other” or were uncertain. These results indicate that practitioners engage with tools across a wide maturity spectrum rather than converging on a single readiness level.

Table 15 summarizes each tool’s purpose, strengths, limitations, TRL, and tested regions. Tools such as System Dynamics and Aspen Plus are well-established and widely cited in the literature (TRL 9), while others, such as the Symbiosis Tool and Zukunftsbild Oberösterreich, remain at pilot or demonstration stages (TRL 4–6). Only one respondent (12.5 percent) described a specific carbon capture technology (catalytic methanation), whereas the remaining respondents focused on modeling, planning, or visualization tools.

This imbalance suggests that, in practice, methodological and planning tools are more commonly used than dedicated carbon capture technologies at the industrial park level, reflecting the early deployment stage of CC technologies in symbiosis contexts.

Table 15. Functions, technology readiness levels, and reported limitations of industrial symbiosis and carbon capture tools based on practitioner input (N = 8).

Tool	Main Purpose	Strengths	Limitations	TRL	Usage Context/Tested Regions
Symbiosis Tool	Visualize flows, support IS matchmaking	Simple, web-based, collaborative	Limited modeling	4–6	Denmark (IS projects)
System Dynamics	Model feedback loops and system interactions	Captures complexity, supports scenarios	Requires expertise	9	Global (policy, planning)
Zukunftsbild Oberösterreich	Regional resource flow visualization	Integrates multiple components	High data needs	6	Upper Austria (regional planning)
Aspen Plus	Process simulation (material and energy flows)	Detailed insights, widely used	Specialist skills required	9	Global (industry and academia)
Total Site Heat Integration	Cross-plant energy optimization	Site-wide efficiency	Data-intensive	N/A	Industrial parks/clusters
Catalytic Methanation	CO ₂ -to-SNG conversion	Innovative, flexible	Not yet scaled	5	Austria (pilot projects)
Fact Sheets	Document inputs/outputs	Simple, entry-level	Low detail, varied quality	Not specified	Multiple EU sites (early IS)

The distribution of TRLs and tool types indicates a clear usability–depth trade-off. High-TRL tools such as Aspen Plus and System Dynamics offer analytical rigor but require specialized expertise and extensive data, which constrains accessibility. In contrast, lower-TRL tools such as the Symbiosis Tool and Fact Sheets lower entry barriers but provide limited analytical depth. This trade-off explains why practitioners often combine multiple tools rather than relying on a single integrated solution.

Several respondents noted plans to expand tool functionality, including extending modeled flow types, enabling automated facility comparisons, and incorporating sustainability metrics beyond energy balances [63]. This forward-looking orientation suggests that practitioners recognize current tool limitations and actively seek hybrid solutions that balance usability and analytical capability, consistent with prior findings that industrial symbiosis tools must remain adaptable to heterogeneous sectoral and organizational contexts [46]. The diversity of tools corroborates literature findings that industrial symbiosis implementation typically relies on a combination of detailed simulation and simpler, entry-level instruments for early-stage data collection and matchmaking [36,90].

3.3. Application and Implementation Contexts

Most surveyed tools address multiple scales in industrial parks, from individual processes to entire facilities, integrating external networks. Table 16 also describes the entities that developed each tool and the typical user profiles. Many participants stated that universities or research institutions initiate the tools' development, reflecting a strong research-driven impetus behind these solutions [53]. However, successful adoption often depends on collaboration between diverse stakeholders (industrial park operators, technology providers, and local authorities) who must collectively resolve technical, social,

and economic constraints, consistent with prior findings on stakeholder coordination and governance in industrial symbiosis systems [9].

Table 16. Overview of industrial symbiosis and carbon capture tools reported in the practitioner survey, including developers, users, and application contexts (N = 8).

Tool Name	Adaptation Across Sectors (Yes/No)	Explanation or Key Constraints	Application Scale and Elements Covered	Developers (and Main Users)	Development Challenges
Symbiosis Tool	Maybe	Expanding to multiple flow types and improved optimization	Industrial parks (general, specialized), addresses electricity, heat, water; synergy from process to entire park	Research institutions; used by park operators, facility owners	Difficulty in data collection; limited proven case studies
System Dynamics	Yes	Generic but models are often context-specific	Whole-park symbiosis; synergy with external systems; addresses technical and decision-making integration	Tech/service providers, research institutions	Low initial interest from companies (complex system thinking)
Zukunftsbild Oberösterreich (Vision UA)	Yes	Encourages diverse sectors, not tied to a single industry	Covers entire park's symbiosis with external networks (electricity/district heating); addresses electricity, heat, carbon, material	Research institutions	Reluctance to share data; preference for quick fixes over systemic changes
Aspen Plus/Process Modeling	Yes	Widely used in chemical and energy-intensive industries	Broad park-level or multi-process modeling for electricity, heat, carbon, materials	Not clearly stated; often research and park operators	Data quality issues, specialized training requirements
Total Site Heat Integration	Yes	Sector-independent, general methodology	Typically addresses heat flows at process and park scale, synergy among multiple plants	Research institutions; used by park operators and facility owners	Requires thermo-economic modeling and advanced technical expertise
Catalytic Methanation	Yes	Works with CO ₂ -rich off-gases if free of catalyst poisons	Scales from individual industrial process to synergy with external networks; addresses electricity, carbon, water	Research institutions and technology providers; used by operators	Uncertainties in upscaling; pilot-level demonstration
Technology Fact Sheet/Process Fact Sheet	Yes	Universal format for different processes/technologies	Industrial park or single-process coverage; addresses electricity, heat, carbon, water, materials	Research institutions; used by facility owners, operators	Low industry engagement; confidentiality concerns

(Source: survey data).

Table 17 below details the specific barriers that survey respondents face when using or implementing the tools. Data confidentiality, limited standardization, and user acceptance were identified as the most frequently cited constraints, reported by at least five respondents. In contrast, purely technical limitations were mentioned less consistently. In some cases, tool outputs may require significant operational changes (e.g., rescheduling machine operations), prompting reluctance or skepticism among facility owners [56]. Participants also noted that certain tools remain largely illustrative, lacking in actionable detail if sufficient or reliable data are unavailable. These survey-based observations align with earlier studies emphasizing that data-sharing frameworks, trust among stakeholders, and practical feasibility are decisive factors in scaling industrial symbiosis beyond pilot or demonstration stages [54].

The predominance of organizational and data-related barriers over purely technical ones reinforces the conclusion that tool maturity alone is insufficient for successful deployment. Even high-TRL tools may remain underutilized when governance arrangements, data-sharing agreements, and incentive structures are weak, a pattern consistently reported in the industrial symbiosis literature. This finding underscores that industrial symbiosis

tools operate at the intersection of technical optimization and organizational change, and their effectiveness depends on both dimensions.

Table 17. Reported utilization and implementation challenges of industrial symbiosis and carbon capture tools from the practitioner survey (N = 8).

Tool/Methods	Utilization Challenges in Using the Tool	Implementation Challenges
Symbiosis	Difficulty obtaining reliable data; limited case studies	Adjusting schedules; convincing operators of tool-derived changes
System Dynamics	Complexity in system thinking; low initial interest	Unclear
Zukunftsbild Oberösterreich	Lack of standardization; not ready for independent use	Actors prefer quick solutions rather than systemic transformations
Aspen Plus/Process modeling	Data quality issues; results largely illustrative	Data-driven but may not yield immediately actionable conclusions
Total Site Heat Integration	Requires thermo-economic model; advanced technical knowledge	Not indicated
Catalytic Methanation	Scale-up assumptions are uncertain	Dependent on the reliability of model parameters
Fact Sheet/Process Sheet	Low industry engagement; confidentiality concerns	Not indicated

Sources: survey data.

The mixed-methods survey reveals that industrial symbiosis and carbon capture tools vary in maturity, ranging from early-stage (TRL 4–6) platforms focused on visualization or data gathering, to advanced simulators (TRL 9) capable of rigorous process optimization. Despite strong practitioner interest in decarbonization and resource efficiency, adoption remains uneven due to cost constraints, data confidentiality, and the need for cross-organizational coordination, echoing patterns identified in earlier empirical and review-based studies. These insights reflect a tension between the promise of industrial symbiosis, highlighted by established examples like Kalundborg, and the real-world complexities of adopting tools that require extensive data inputs and cross-functional collaboration.

4. Discussion

This section interprets and synthesizes the findings presented in Section 3, moving beyond descriptive results to examine their implications for tool adoption, integration, and governance in industrial symbiosis and carbon capture. Section 4.1 compares practitioner survey evidence with literature-based findings, highlighting convergences, divergences, and adoption gaps across tools and methods. Section 4.2 develops an integrated conceptual framework that explains how tools, data infrastructure, stakeholder governance, policy and market enablers, as well as implementation contexts interact as a socio-technical system. Section 4.3 translates these insights into future research directions and actionable recommendations, focusing on data governance, policy support, technological integration, and long-term system evolution.

4.1. Comparison Between Surveyed Tools and Literature

The literature review highlights a wide spectrum of tools and methods used to advance industrial symbiosis and carbon capture initiatives—ranging from visualization platforms (e.g., Symbiosis Tool, Zukunftsbild Oberösterreich) to process-level simulations (e.g., Aspen Plus) and systemic modeling approaches (e.g., System Dynamics, Total Site Heat Integration). Survey insights, though derived from a small sample, illuminate adoption-

related and organizational challenges that are only weakly reflected in the predominantly technology-oriented academic literature.

4.1.1. Tool Maturity Versus Adoption Feasibility

As shown in Table 18, tools like Aspen Plus and System Dynamics are consistently rated at TRL 9 in both literature and practice. However, survey respondents flagged challenges related to complexity and usability. Aspen Plus, while widely used for modeling CO₂ absorption and process-level emissions, remains only weakly integrated with broader industrial symbiosis networks, largely due to its specialization and high data requirements. This suggests that high TRL alone is not a sufficient indicator of deployment readiness in multi-actor industrial symbiosis contexts. Similarly, System Dynamics offers strong capabilities for simulating long-term feedback and stakeholder behaviors but requires conceptual expertise and user engagement, which can hinder practical uptake.

Table 18. Overview of the tools/methods.

Tool/Method	Tool Type (Function)	TRL in the Literature	TRL in Survey	Barriers (Literature)	Barriers (Survey)
Aspen Plus	Process simulation	9	9	Requires expertise and detailed input data	Illustrative outputs not easily actionable
Symbiosis Tool	Visualization/analysis	Not discussed	4–6	—	Limited modeling; low industry engagement
System Dynamics	System-level modeling	9	9	Complex setup, domain expertise needed	Low initial interest; hard to implement
Zukunftsbild Oberösterreich	Resource flow visualization	Not available	6	Data-intensive; limited uptake in studies	Not standardized; preference for quick fixes
Total Site Heat Integration	Pinch-based optimization	Mentioned (TSA)	N/A	Requires advanced technical data	Not reported
Catalytic Methanation	Carbon capture technology modeling	5–6	5	Upscaling uncertainty	Pilot stage; stability of parameters required
Technology Fact Sheet	Data logging/screening	Not assigned	Not assigned	Generic; lacks analytical capacity	Confidentiality; inconsistent quality

Adapted from [2,15,16,23,24,36,38,41,42,71,86–88,90,93,111–115].

In contrast, tools such as the Symbiosis Tool and Zukunftsbild Oberösterreich provide early-stage visualization and resource flow analysis and are perceived as easier to use by practitioners. However, their lower TRLs, limited standardization, and restricted analytical depth constrain their use beyond exploratory or communicative purposes. Survey evidence thus reveals an engagement–depth trade-off that is largely implicit in the literature but becomes explicit in practice: tools that are easy to engage with often lack decision-grade analytical power, while analytically rigorous tools face adoption barriers.

4.1.2. Diffusion Gaps and Accessibility Constraints

Conversely, tools like Total Site Heat Integration and Catalytic Methanation are well represented in academic studies but were rarely cited by survey respondents. This discrepancy suggests a diffusion lag between research visibility and practical uptake, likely driven by advanced technical requirements, reliance on thermo-economic modeling, or sensitivity to operating conditions. These characteristics may disproportionately limit accessibility for small and medium-sized enterprises, which often lack dedicated modeling expertise and data infrastructures.

Technology Fact Sheets, while commonly used for screening and data logging, were noted in both sources as constrained by low automation, inconsistent quality, and confidentiality concerns. This reinforces the observation that data governance and standardization,

rather than algorithmic sophistication, often constitute the primary bottlenecks for real-world implementation.

4.1.3. Functional Coverage and Integration Gaps Across Industrial Symbiosis and Carbon Capture

To deepen the interpretation, this paper also assessed how each tool supports specific integration challenges across industrial symbiosis and carbon capture domains. Aspen Plus and ProSimTM are suited for detailed mass and energy simulation but face barriers due to user skill requirements. System Dynamics excels in long-term planning and behavioral modeling but depends heavily on facilitation. Visualization tools like Symbiosis Tool and Zukunftsbild are useful for initiating industrial symbiosis opportunities, but lack optimization functions. Catalytic Methanation represents a novel carbon capture pathway but remains pilot-scale. Fact Sheets enable quick screenings but suffer from limited analytical depth. These patterns indicate that no single tool currently supports end-to-end integration from opportunity identification to operational decision-making.

Both literature and practice emphasize the importance of robust data systems. Most high-fidelity tools assume access to accurate, high-resolution datasets, reinforcing the need for data-sharing protocols and interoperable infrastructures. Stakeholder collaboration emerges as a parallel requirement: System Dynamics relies on participatory modeling, while visualization tools facilitate cross-actor communication. However, these socio-technical prerequisites are rarely embedded directly within tool designs, contributing to the observed gap between technical potential and adoption feasibility.

4.1.4. Hybrid Toolchains and Design Trade-Offs for Industrial Symbiosis and Carbon Capture

The comparison in Table 18 also reveals growing interest in hybrid approaches. Combining System Dynamics with pinch analysis or integrating Aspen Plus with Catalytic Methanation enables multi-functional toolchains that link planning, optimization, and carbon utilization. While conceptually promising, such hybrid configurations introduce new integration challenges related to data compatibility, workflow alignment, and knowledge transfer. Addressing these challenges will require modular architectures and interoperable design standards rather than further tool specialization.

Ultimately, high-fidelity tools such as Aspen Plus offer analytical precision but are constrained by cost, data intensity, and training demands. Lighter tools, such as the Symbiosis Tool and Fact Sheets, lower entry barriers but lack decision-grade depth. This persistent trade-off suggests that future tool development should prioritize modularity, interoperability, and cross-domain compatibility rather than incremental analytical sophistication alone.

To illustrate these dynamics, five representative tools highlight recurring patterns. Aspen Plus enables detailed CO₂ simulation but requires specialized expertise. System Dynamics supports complex industrial symbiosis planning but depends on facilitation. The Symbiosis Tool provides intuitive visualization but limited analytical strength. Catalytic Methanation remains promising yet immature at scale. Fact Sheets offer accessible entry points but limited decision support. These examples demonstrate that tool selection is fundamentally a socio-technical decision shaped by organizational readiness, data availability, and coordination capacity, not merely by technical capability.

4.1.5. Synthesis of Literature–Practice Gaps

This study identifies misalignments between literature and practice across four core dimensions (Table 19). In terms of technology readiness and complexity, research emphasizes advanced simulators and optimization-heavy tools, while practice reveals uneven adoption driven by cost and expertise constraints. In usability and engagement, the literature

prioritizes capabilities, whereas practitioners favor simplicity and transparency. In data requirements and governance, the literature often assumes standardized datasets, while practice confronts confidentiality and fragmentation. In policy and implementation drivers, research highlights regulatory frameworks, whereas practitioners prioritize operational feasibility. Collectively, these gaps explain why tool availability has outpaced effective deployment in industrial symbiosis and carbon capture contexts.

Table 19. Key gaps between literature and practice across four core dimensions.

Dimension	From: Literature Perspective	Gap and Magnitude	To: Practice Perspective
Technology Readiness and Complexity	Emphasis on advanced simulators, high TRL, and optimization-heavy tools	Large: Research maturity outpaces adoption; tools are complex, costly, and require specialized expertise	Mixed TRL adoption with cost and expertise barriers
Usability and Engagement	Capabilities prioritized; limited focus on ease-of-use	Moderate–Large: Tools stress advanced features, but practitioners need simple, transparent, user-friendly solutions	Preference for simple, intuitive tools
Data Requirements and Governance	Assumes robust, standardized datasets	Large: Literature expects open, reliable data, while practice faces confidentiality issues and inconsistent standards	Confidentiality issues; inconsistent data standards
Policy and Implementation Drivers	Strong focus on policy frameworks and pricing mechanisms	Moderate: Policy seen as main enabler in research, but practice prioritizes short-term feasibility and cost	Policy signals weaker; operational feasibility dominates

Overall, the comparison indicates that bridging literature–practice gaps will require integrated, user-centered, and governance-aware approaches rather than further expansion of standalone analytical tools. This insight provides a direct foundation for the integrated conceptual framework developed in the following subsection.

4.2. Conceptual Framework-Integrated Pathway for Industrial Symbiosis and Carbon Capture

Existing literature tends to focus on either industrial symbiosis or carbon capture separately. Some focus on eco-industrial park policies, data systems, or specific technical tools, but they do not integrate these areas into a comprehensive model. The comparative analysis in Sections 3.1 and 3.2 demonstrates that this fragmentation contributes directly to the observed gap between tool availability and effective deployment. Therefore, this study presents an integrated framework that brings together industrial symbiosis and carbon capture within a single model, connecting tools, data, stakeholders, policies, and real-world settings.

The proposed integrated conceptual framework unifies five interdependent elements: (i) Tools and Methods, (ii) Data Infrastructure, (iii) Stakeholder and Governance Mechanisms, (iv) Policy and Market Enablers, and (v) Implementation Contexts. Rather than treating these elements as independent layers, the framework conceptualizes industrial symbiosis and carbon capture as a socio-technical system in which analytical capabilities, organizational arrangements, and policy conditions co-evolve. The framework underscores circular, iterative interactions in which technical innovations (e.g., simulation, optimization, carbon capture) are enabled by robust data systems and guided by collaborative governance, while supportive policies and market instruments spur adoption in diverse implementation contexts. This integrative perspective directly addresses the literature–practice misalignments identified in Section 4.1. The five core elements are outlined below.

- Methods and Tools

The reviewed literature identifies a broad spectrum of simulation platforms, econometric models, optimization algorithms, data analysis tools, and sustainability assessments. It encompasses a broad spectrum of technical tools from advanced simulation platforms (e.g., Aspen Plus, HOMER) and optimization algorithms (e.g., MILP, MINLP) to statistical methods (e.g., MLR, DID analyses) and sustainability assessments (e.g., LCA, MFA). They form the technical backbone for designing synergy pathways, quantifying resource savings, and predicting economic and environmental outcomes. However, the analysis in Section 4.1 shows that high analytical sophistication does not automatically translate into adoption readiness. Tools and methods are most effective when embedded within data infrastructures and governance arrangements that support cross-organizational coordination, rather than when deployed as standalone optimization engines.

- **Data Infrastructure**

Effective industrial symbiosis relies on accurate, real-time information about energy use, waste streams, and operational parameters. Data collection methods (e.g., sensor networks, SCADA), communication protocols, and integrated databases facilitate continuous monitoring and model-driven decision-making. This dimension draws on information systems and cyber-physical systems perspectives, which link digital representations to physical industrial processes.

Survey and literature evidence jointly indicate that data availability, confidentiality, and interoperability constitute binding constraints on tool deployment. Fragmented data ownership, incompatible formats, and limited data-sharing agreements frequently prevent advanced tools from being operationalized, even when analytical capability exists. Accordingly, data infrastructure is positioned in the framework not as a supporting layer, but as a central enabling condition for industrial symbiosis and carbon capture integration.

- **Stakeholder and Governance Mechanisms**

The success of eco-industrial parks and industrial symbiosis initiatives depends not purely on technical solutions but also on effective human collaboration and group efforts. Diverse stakeholders in eco-industrial parks include government bodies, utilities, park owners, companies, investors, and communities. Their collaboration is essential for trust-building, data-sharing agreements, and equitable cost-benefit distribution. Governance structures range from bilateral contracts to cooperative frameworks guiding joint investments in energy or waste exchange projects.

Empirical insights from the survey highlight persistent challenges related to limited stakeholder engagement, resistance to change, and unclear decision authority. Drawing on institutional economics, organizational theory, and social network analysis, the framework emphasizes governance arrangements as mechanisms to overcome fragmented incentives and firm-level self-interest that otherwise inhibit collaboration. This explicitly links tool effectiveness to institutional design rather than to technical performance alone.

- **Policy and Market Enablers**

Industrial symbiosis advances more swiftly with supportive financial and regulatory instruments such as carbon pricing, tax incentives, transparent permitting processes, and environmental standards. These measures encourage facility owners to adopt advanced tools for resource exchange and carbon capture while reducing risks associated with pioneering new synergy strategies. Clear environmental standards and streamlined permitting processes also play a vital role. Survey findings confirm that the lack of financial incentives and weak regulatory support are major barriers to implementation.

Carbon pricing mechanisms, such as carbon taxes and emissions trading schemes, are particularly important because they internalize environmental costs and make collaborative resource use economically attractive. In this framework, policy instruments are

conceptualized as dynamic drivers that shape not only adoption incentives but also the design priorities of tools and data infrastructures. Real-world cases, such as Kalundborg Symbiosis, illustrate how aligned policy support and municipal involvement can sustain long-term cooperation and innovation [116].

- **Implementation Contexts**

Industrial symbiosis tools must be tailored to each setting, whether eco-industrial parks, conventional industrial parks, or specialized sectors (petrochemical, agricultural, wastewater). Factors like unique local conditions, resource availability, and market drivers influence the feasibility and scope of carbon capture and symbiosis-based resource sharing. This reflects contingency theory and socio-ecological systems thinking, which recognize that technical solutions must be embedded within their environmental and institutional settings. The framework therefore rejects a one-size-fits-all implementation logic and instead emphasizes context-sensitive configuration of tools, governance mechanisms, and policy instruments.

The conceptual model places these five elements in a circular, iterative relationship (as shown in Figure 7). Tools and Methods transform raw operational data into analytical insights through the Data Infrastructure. These insights inform stakeholder negotiation and coordination, supported by Governance Mechanisms. Policy and Market Enablers act as external but integral forces that shape incentives and constraints. Implementation Contexts both condition and are reshaped by these interactions, creating feedback loops that continuously adjust technical strategies and organizational behavior. This dynamic structure explains why static tool assessments are insufficient and why adaptive, modular, and governance-aware approaches are required for scaling industrial symbiosis and carbon capture.

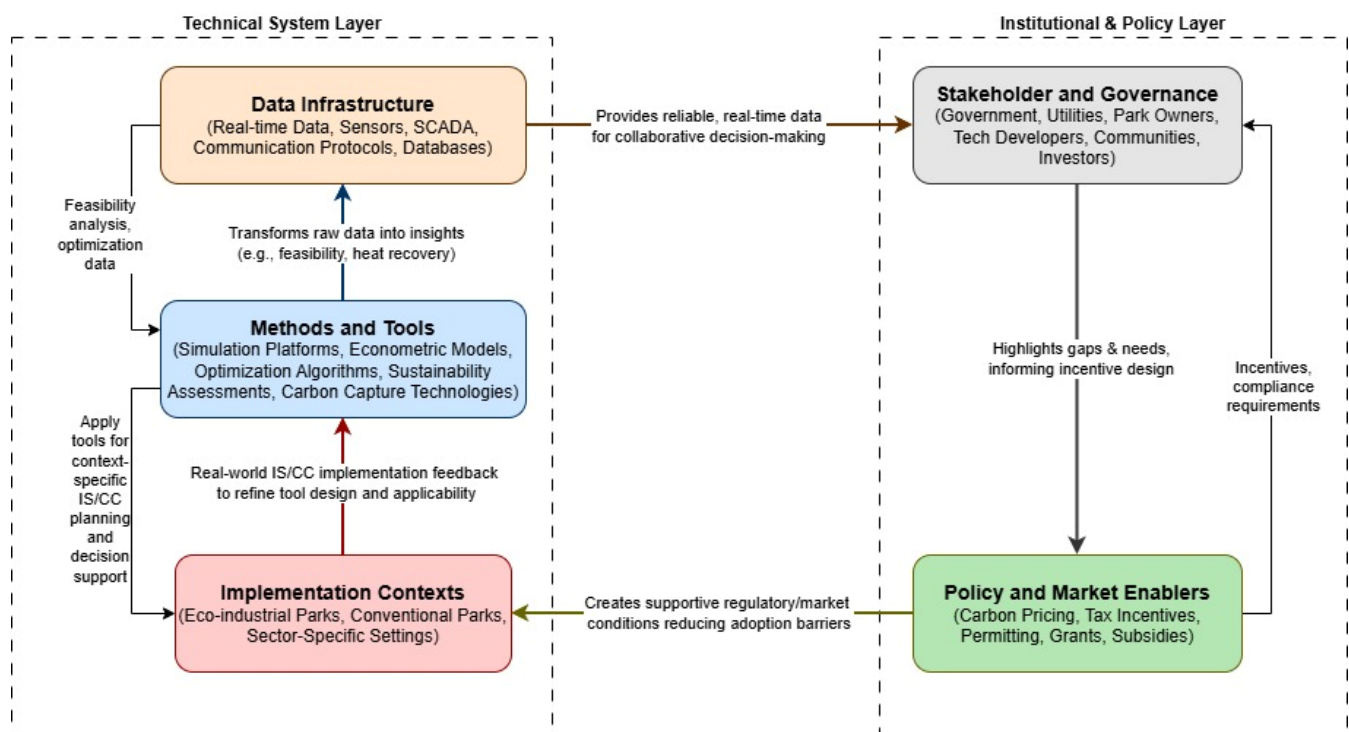


Figure 7. Integrated framework for industrial symbiosis and carbon capture deployment. This Figure integrated conceptual framework for industrial symbiosis and carbon capture deployment, illustrating the iterative interactions among tools, data infrastructure, governance mechanisms, policy enablers, and implementation contexts.

While the framework is conceptual, it can be operationalized using measurable indicators such as technology readiness levels, data accessibility metrics, and stakeholder collaboration indices. These indicators provide practical guidance for assessing implementation feasibility, benchmarking tool maturity, and tailoring deployment strategies across different industrial settings. Future empirical studies can use the framework to systematically compare outcomes across contexts rather than evaluating tools in isolation.

This framework also aligns with theoretical underpinnings in socio-technical systems thinking and institutional economics. It reflects the core principles of the multi-level perspective in sustainability transitions, where technological innovations (e.g., simulation, optimization tools) interact with stakeholder governance and policy environments across niche, regime, and landscape levels. Moreover, the feedback loops in our framework match with innovation diffusion theory, offering a lens to explore how industrial symbiosis and carbon capture tools spread through industrial networks. By integrating technical, organizational, and policy dimensions, the framework advances existing conceptualizations that focus on single layers of the industrial symbiosis ecosystem.

From a scientific perspective, the framework provides a foundation for studying interactions between technology, policy, and industrial collaboration in decarbonizing industrial systems. It supports the development of integrated decision-support systems, hybrid optimization pipelines, and longitudinal analyses of industrial symbiosis evolution.

From a practical perspective, the framework offers a strategic roadmap for policy-makers, industry leaders, and technology developers. By aligning analytical tools with governance structures and policy incentives, stakeholders can design implementation pathways that move beyond pilot projects toward scalable, durable industrial symbiosis and carbon capture solutions. This positioning reinforces the framework as the central integrative contribution of the study rather than a descriptive summary of prior results.

4.3. Future Directions and Recommendations

The findings from this scoping review and survey confirm that while technological advances in industrial symbiosis and carbon capture offer significant potential, their adoption remains hindered by systemic challenges. These include fragmented data-sharing frameworks, high initial investment and training costs, confidentiality risks, and weak market-driven or regulatory incentives. As demonstrated in Sections 4.1 and 4.2, these barriers are not isolated technical issues but reflect misalignments across tools, data infrastructures, governance arrangements, and policy environments. To overcome these barriers and accelerate the integration of industrial symbiosis and carbon capture, a multi-faceted strategy is required, addressing both technical and socio-economic dimensions.

- **Strengthening Data Governance and Interoperability**

A fundamental barrier to industrial symbiosis adoption is the lack of standardized data-sharing frameworks and interoperable platforms [117]. Many industries operate with proprietary software and closed data ecosystems, making it difficult to integrate various modeling tools, simulations, and optimization techniques. Additionally, confidentiality concerns often discourage companies from sharing operational data, further limiting collaboration.

Consistent with the conceptual framework, data infrastructure should be treated as a strategic enabler rather than a secondary implementation issue. Establishing standardized data-sharing protocols and encouraging the development of interoperable platforms can enhance data accessibility and integration across industrial networks. Trusted third-party intermediaries could facilitate secure data exchange, ensuring that companies can collaborate without risking proprietary information leaks [118]. Future tool development should prioritize modular data interfaces that allow advanced simulation and optimization tools,

such as Aspen Plus, pinch analysis, and AI-driven simulators, to interoperate within shared digital environments rather than functioning as isolated applications.

- **Expanding Public–Private Partnerships and Funding Mechanisms**

The high upfront costs of industrial symbiosis technologies, carbon capture systems, and workforce training pose significant financial barriers, particularly for small and medium-sized enterprises (SMEs). Many companies are hesitant to invest in industrial symbiosis tools due to uncertain returns on investment, long payback periods, and a lack of policy incentives supporting capital-intensive projects [118]. Additionally, the technical expertise required to implement industrial symbiosis solutions remains a limiting factor in widespread adoption.

To address these challenges, public–private partnerships should be designed as long-term capability-building mechanisms rather than short-term funding instruments. To overcome these constraints, stronger public–private partnerships (PPPs) are essential. Governments can play a key role by introducing targeted funding mechanisms, tax incentives, and low-interest financing to support industries adopting carbon capture and industrial symbiosis solutions [119]. In addition, coordinated training initiatives involving industry consortia, research institutions, and technology providers are needed to reduce skills gaps and enable organizations to operationalize advanced tools identified in the literature.

- **Advancing Socio-Technical and Longitudinal Research**

Despite the increasing emphasis on industrial symbiosis, many policy frameworks remain reactive rather than proactive, failing to accommodate the long-term evolution of industrial symbiosis ecosystems [117]. Furthermore, while short-term technical assessments of industrial symbiosis are common, there is a lack of longitudinal research that evaluates the economic, social, and environmental impact of industrial symbiosis networks over time [120]. Without such insights, policymakers and industry leaders lack the data necessary to refine and scale industrial symbiosis initiatives effectively.

Future research should therefore prioritize longitudinal and comparative studies that explicitly examine the co-evolution of technologies, stakeholder behavior, and policy frameworks. Tracking industrial symbiosis initiatives over extended periods can reveal how governance arrangements, data infrastructures, and incentive structures influence sustained adoption [116,121]. Integrating behavioral and organizational research is also essential to understand resistance to participation and to design incentive mechanisms that align firm-level decision-making with collective system benefits [122].

- **Leveraging AI and Real-Time Data Analytics for Smart Industrial Symbiosis**

The complexity of industrial symbiosis arises from the simultaneous management of multiple resource flows, such as electricity, heat, water, and carbon capture, which are highly dynamic and interconnected [123]. Traditional simulation tools, while effective, often require manual intervention and extensive data processing, limiting real-time optimization and decision-making [124,125].

AI-driven meta-optimization and machine learning approaches offer a pathway to operationalizing the integrated framework proposed in Section 4.2. By combining real-time IoT sensor data with predictive analytics, industrial parks can develop adaptive decision-support systems that continuously adjust resource flows in response to operational conditions and policy signals [126]. Such systems can enhance waste heat recovery, improve carbon capture efficiency, and stabilize multi-energy systems, thereby translating analytical potential into actionable operational control [127,128].

- **Strengthening Policy Support and Market Incentives**

A major challenge to the widespread adoption of industrial symbiosis is the absence of strong regulatory frameworks and financial incentives that encourage industries to participate in industrial symbiosis and carbon capture initiatives [118]. Without clear economic drivers, many industries remain reluctant to invest in these technologies, limiting their adoption [129].

Policy instruments should therefore be designed to reinforce collaborative behavior and long-term system optimization rather than isolated compliance. Governments can promote adoption through mandatory reporting of industrial resource exchanges, strengthened carbon pricing mechanisms, and direct financial incentives such as tax credits, carbon credits, and emissions trading schemes [130,131]. In parallel, voluntary certification programs and benchmarking schemes developed by industry associations can complement regulation by recognizing high-performing industrial symbiosis initiatives and reducing information asymmetries among stakeholders.

5. Conclusions

Industrial symbiosis and carbon capture play a central role in enabling sustainable and resource-efficient industrial ecosystems. This study contributes by systematically clarifying why the growing body of data-driven tools has not yet translated into widespread, effective deployment. Through a combined PRISMA-guided scoping review and practitioner survey, the paper bridges academic tool development with real-world implementation experience and provides an integrated perspective on industrial decarbonization and circular economy support.

The findings reveal a clear convergence between literature and practice around data governance as a decisive enabling condition. Both sources consistently identify data availability, confidentiality, interoperability, and standardization as binding constraints, even in the presence of technically mature tools. While the literature documents a rich portfolio of high-TRL simulators, optimization frameworks, and system-level models, practitioner evidence shows that technical sophistication alone does not ensure adoption, particularly when tools are costly, complex, or poorly aligned with organizational workflows. In this regard, stakeholder collaboration and transparent, visualization-supported decision processes emerge as necessary complements to analytical rigor.

At the same time, important divergences persist. Practitioner insights emphasize operational disruption, resistance to change, and organizational readiness as primary barriers, whereas academic studies tend to prioritize policy instruments and regulatory design. This mismatch highlights a persistent misalignment between technology-centric research agendas and the socio-technical realities of industrial implementation. Addressing this gap requires closer integration of organizational, behavioral, and governance considerations into tool design and evaluation.

By integrating evidence from both literature and practice, this study develops an integrated conceptual framework that links tools and methods with data infrastructure, stakeholder governance, policy and market enablers, as well as implementation contexts. The framework demonstrates that effective industrial symbiosis and carbon capture depend on coordinated evolution across these dimensions rather than isolated advances in analytical capability. It provides a structured basis for assessing implementation feasibility, benchmarking tool maturity, and designing context-sensitive deployment strategies.

Several limitations should be acknowledged. The practitioner survey is based on a small expert sample and is not statistically representative, and the scoping review focuses on peer-reviewed English-language publications, which may underrepresent emerging practices in non-English or gray literature. Nevertheless, the triangulation of methods

strengthens the robustness of the conclusions by combining systematic literature synthesis with direct practitioner insight.

Future research should pursue clearly defined and non-generic directions. These include (i) the development of interoperable and modular toolchains that connect simulation, optimization, and visualization through shared data standards; (ii) longitudinal empirical studies that track adoption, learning, and performance of industrial symbiosis initiatives over time; and (iii) AI-enabled decision-support systems that integrate real-time data with adaptive optimization under uncertainty. Equally important is the investigation of governance mechanisms and incentive structures that enable data sharing and sustained collaboration across industrial actors.

In conclusion, the study shows that the main bottleneck in industrial symbiosis and carbon capture is not the lack of tools, but the lack of integration across technical, organizational, and institutional layers. By addressing these interdependencies, future research and practice can move beyond isolated pilots toward scalable, durable low-carbon industrial transformations.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/en19030755/s1>, reference [132] is cited in the Supplementary Materials.

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Abbreviations

The following abbreviations are used in this manuscript:

ACL	Agent Communication Language
ACTA	Automated Composite Table Algorithm
AI	Artificial Intelligence
AMPSO	Adaptive Modified Particle Swarm Optimization
BESS	Battery Energy Storage Systems
CC	Carbon Capture
CCD	Coupling-Coordination Degree
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CCUS	Carbon Capture, Utilization, and Storage
CI	Confidence Interval
CO ₂	Carbon Dioxide
CP	Constraint Programming
CPS	Cyber-Physical Systems
DC	Direct Current

DDF-DEA	Directional Distance Function Data Envelopment Analysis
DEA	Data Envelopment Analysis
DID	Difference-in-Differences
DPL	Digsilent Programming Language
ECR	Energy Conversion Systems
EIP	Eco-Industrial Park
EIPs	Eco-Industrial Parks
EnMS	Energy Management Systems
EUDs	Energy Utilization Diagrams
EV	Electric Vehicle
EWFC	Energy–Water–Food–Carbon
FISTA	Fast Iterative Shrinkage-Thresholding Algorithm
GA	Genetic Algorithm(s)
GCCs	Grand Composite Curves
GHG	Greenhouse Gas
GIS	Geographic Information System(s)
GRG	Generalized Reduced Gradient
GTL	Gas-to-Liquids
GUI	Graphical User Interface
HMI	Human–Machine Interfaces
IEA	International Energy Agency
IETS	Industrial Energy-Related Technologies and Systems
IGA	Improved Genetic Algorithm
IS	Industrial Symbiosis
ISI	Inherent Safety Index
LCA	Life Cycle Assessment
LCA-SE	Life-Cycle-Based Synergy Evaluation
LEAP	Long-range Energy Alternatives Planning
LMDI	Logarithmic Mean Divisia Index
LP	Linear Programming
MAS	Multi-Agent Systems
MCDM	Multi-Criteria Decision Making
MFA	Material Flow Analysis
MILP	Mixed-Integer Linear Programming
MINLP	Mixed-Integer Nonlinear Programming
MLR	Multiple Linear Regression
MPC	Model Predictive Control
NADs	Network Allocation Diagrams
NLP	Nonlinear Programming
NPV	Net Present Value
NSGA-II	Non-dominated Sorting Genetic Algorithm II
PPPs	Public–Private Partnerships
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PRISMA-ScR	PRISMA Extension for Scoping Reviews
PSO	Particle Swarm Optimization
PV	Photovoltaic
RDF	Resource Description Framework
RTDS	Real-Time Digital Simulator
SCADA	Supervisory Control and Data Acquisition
SDGs	Sustainable Development Goals
SHAP	Shapley Additive Explanations
SIA	Social Impact Assessment
SMEs	Small and Medium-Sized Enterprises
SNA	Social Network Analysis

SNG	Synthetic Natural Gas
SO ₂	Sulfur Dioxide
SPARQL	SPARQL Protocol and RDF Query Language
SSSPs	Site Source–Sink Profiles
SWROIM	Sustainability Weighted Return on Investment Metric
TG/DTA	Thermo-Gravimetric and Differential Thermal Analysis
TOU	Time-of-Use
TRL	Technology Readiness Level
TSA	Total Site Analysis
UA	Upper Austria
XRD	X-ray Powder Diffraction

Appendix A

Table A1. Reviewed 119 articles.

Ref.	Article Title	Publication Year	Publication Type
[133]	Energy evaluation of combined heat and power plant eco-industrial park (CHP plant EIP)	2006	Journal Article
[6]	Industrial Symbiosis as an Integrated Business/Environment Management Process: The Case of Ulsan Industrial Complex	2006	Conference Proceedings
[112]	A regional synergy approach to energy recovery: The case of the Kwinana industrial area, Western Australia	2008	Journal Article
[38]	System study of combined cooling, heating and power system for eco-industrial parks	2008	Conference Proceedings
[41]	Case study of energy systems with gas turbine cogeneration technology for an eco-industrial park	2008	Journal Article
[108]	Applying heat integration total site based pinch technology to a large industrial area in Japan to further improve performance of highly efficient process plants	2009	Journal Article
[54]	Optimization of a waste heat utilization network in an eco-industrial park	2010	Journal Article
[134]	MW-rated power electronics for sustainable and low carbon industrial revolution	2010	Conference Proceedings
[43]	Eco Industrial Parks for Water and Heat Management	2011	Book
[95]	Regional energy-related carbon emission characteristics and potential mitigation in eco-industrial parks in South Korea: Logarithmic mean Divisia index analysis based on the Kaya identity	2012	Journal Article
[71]	Holistic carbon planning for industrial parks: A waste-to-resources process integration approach	2012	Journal Article
[84]	Energy management and dynamic optimisation of eco-industrial parks	2013	Conference Proceedings
[103]	Modeling and optimization of material/energy flow exchanges in an eco-industrial park	2013	Conference Proceedings
[29]	Optimal energy distribution for eco-industrial park in extreme arid areas of Xinjiang based on the statistics method	2013	Conference Proceedings
[85]	An architecture for a microgrid-based eco industrial park using a Multi-Agent System	2013	Conference Proceedings
[16]	Analysis of low-carbon industrial symbiosis technology for carbon mitigation in a Chinese iron/steel industrial park: A case study with carbon flow analysis	2013	Journal Article
[99]	Two-step accelerated mineral carbonation and decomposition analysis for the reduction of CO ₂ emission in the eco-industrial parks	2014	Journal Article
[81]	Methods for assessing the energy-saving efficiency of industrial symbiosis in industrial parks	2014	Journal Article

Table A1. Cont.

Ref.	Article Title	Publication Year	Publication Type
[135]	Integration of renewable energy sources in industrial parks: Medicoool european demonstration project	2014	Journal Article
[136]	GRID4EU-Nice Grid project: How to facilitate the integration of Distributed Energy Resources into the local grid?	2014	Conference Proceedings
[102]	Systematic allocation of cost savings among energy systems in an eco-industrial park	2015	Journal Article
[106]	Feasibility of heat recovery for district heating based on Cloud Computing Industrial Park	2015	Conference Proceedings
[21]	Efficient hybrid renewable energy system for industrial sector with on-grid time management	2015	Conference Proceedings
[76]	Research on Regional Energy Planning Practice in Industrial Park Mode-Taking the Civil-Military Integration Industrial Park of Mianyang as an Example	2015	Conference Proceedings
[31]	Comprehensive functions of eco-industrial park in conserving energy and improving ecology	2015	Conference Proceedings
[30]	Ecological Network Analysis for Carbon Metabolism of Eco-industrial Parks: A Case Study of a Typical Eco-industrial Park in Beijing	2015	Journal Article
[80]	Fuzzy optimization of a waste-to-energy network system in an eco-industrial park	2015	Journal Article
[14]	On the systematic carbon integration of industrial parks for climate footprint reduction	2016	Journal Article
[83]	An optimization-based negotiation framework for energy systems in an eco-industrial park	2016	Journal Article
[104]	Assessing the performance of carbon dioxide emission reduction of commercialized eco-industrial park projects in South Korea	2016	Journal Article
[137]	Greenhouse Gas Mitigation in Chinese Eco-Industrial Parks by Targeting Energy Infrastructure: A Vintage Stock Model	2016	Journal Article
[107]	Planning of hybrid power system for local industrial park in extreme arid and power shortage area	2016	Conference Proceedings
[77]	Model of eco-industrial park development as a tool for fostering energy efficient economy	2016	Conference Proceedings
[39]	A novel methodology for the design of waste heat recovery network in eco-industrial park using techno-economic analysis and multi-objective optimization	2016	Journal Article
[92]	Towards intelligent thermal energy management of eco-industrial park through ontology-based approach	2016	Conference Proceedings
[10]	Carbon dioxide reduction incentive for eco-industrial parks using bilevel fuzzy programming	2017	Conference Proceedings
[98]	Eco-efficiency assessment of coal-fired combined heat and power plants in Chinese eco-industrial parks	2017	Journal Article
[15]	Carbon dioxide and heat integration of industrial parks	2017	Journal Article
[111]	On the simultaneous integration of heat and carbon dioxide in industrial parks	2017	Journal Article
[23]	Regional energy planning—An example of Suzhou Industrial Park	2017	Conference Proceedings
[66]	Coordinated heat and power dispatch of industrial park microgrid considering distributed heating and indoor comfort constraint	2017	Conference Proceedings
[138]	P2P trading strategies in an industrial park distribution network market under regulated electricity tariff	2017	Conference Proceedings
[101]	Embodied carbon emission analysis of eco-industrial park based on input-output analysis and ecological network analysis	2017	Conference Proceedings

Table A1. *Cont.*

Ref.	Article Title	Publication Year	Publication Type
[91]	Knowledge management of eco-industrial park for efficient energy utilization through ontology-based approach	2017	Journal Article
[58]	Challenges of value creation in Eco-Industrial Parks (EIPs): A stakeholder perspective for optimizing energy exchanges	2018	Journal Article
[110]	Industrial Fish Wastewater Treatment by Electrocoagulation Processes Powered by Solar Energy	2018	Conference Proceedings
[89]	Exploring Greenhouse Gas-Mitigation Strategies in Chinese Eco-Industrial Parks by Targeting Energy Infrastructure Stocks	2018	Journal Article
[88]	Co-benefit potential of industrial and urban symbiosis using waste heat from industrial park in Ulsan, Korea	2018	Journal Article
[64]	Industrial Park Energy Trading and Management Based on Game Theory	2018	Conference Proceedings
[53]	Multi-level energy integration between units, plants and sites for natural gas industrial parks	2018	Journal Article
[9]	Renewable energy in eco-industrial parks and urban-industrial symbiosis: A literature review and a conceptual synthesis	2019	Journal Article
[109]	Economic Evaluation of Micro-Grid System in Commercial Parks Based on Echelon Utilization Batteries	2019	Journal Article
[55]	Site wide heat integration in eco-industrial parks considering variable operating conditions	2019	Journal Article
[46]	Modelling the technical influence of randomly distributed solar PV uptake on electrical distribution networks	2019	Conference Proceedings
[139]	Clean Energy Configuration and Application for Mingzhu Industrial Park	2019	Conference Proceedings
[7]	Life cycle assessment of reduction of environmental impacts via industrial symbiosis in an energy-intensive industrial park in China	2019	Journal Article
[87]	Smart solutions shape for sustainable low-carbon future: A review on smart cities and industrial parks in China	2019	Journal Article
[28]	A model for renewable energy symbiosis networks in eco-industrial parks	2020	Conference Proceedings
[45]	Research on Economic Dispatching and Collaborative Optimization of Industrial Park Micro-grid with Solar-Battery-Charge	2020	Conference Proceedings
[12]	Application of AC/DC Hybrid System in Industrial Park Scenario	2020	Conference Proceedings
[52]	Evaluating the environmental benefit of energy symbiosis networks in eco-industrial parks	2020	Conference Proceedings
[5]	Optimal Design of Eco-Industrial Parks with coupled energy networks addressing Complexity bottleneck through an Interdependence analysis	2020	Journal Article
[25]	Toward a Global Green Smart Microgrid: An Industrial Park in China	2020	Journal Article
[62]	Integrated energy coordinated control system of industrial park and its application	2020	Conference Proceedings
[60]	Synthesis of Sustainable Carbon Negative Eco-Industrial Parks	2021	Journal Article
[78]	Power quality improvement of small hydropower plant located in the industrial area	2021	Conference Proceedings
[22]	Power Capacity Planning on Integrated Multi-Energy System of the Industrial Park	2021	Conference Proceedings
[40]	Sustainable energy-water-food nexus integration and optimisation in eco-industrial parks	2021	Journal Article
[44]	State of Charge Optimization-based Smart Charging of Aggregate Electric Vehicles from Distributed Renewable Energy Sources	2021	Conference Proceedings

Table A1. *Cont.*

Ref.	Article Title	Publication Year	Publication Type
[65]	Research and Simulation of Dual-level Optimal Scheduling of Industrial Park Microgrid Considering Flexible Load	2021	Conference Proceedings
[93]	A New Strategy for Collective Energy Self-consumption in the Eco-Industrial Park: Mathematical Modeling and Economic Evaluation	2021	Conference Proceedings
[17]	Research on Planning and Operation of Distributed Integrated Energy System in Industrial Park	2021	Conference Proceedings
[57]	Multi-objective Optimization of an Integrated Energy-Water-Waste Nexus for Eco-Industrial Park	2021	Journal Article
[56]	Distributed Demand Response of the Integrated Energy System in an Industrial Park	2021	Conference Proceedings
[100]	Intelligent Energy Planning and Design of Industrial Park under New Power System	2021	Conference Proceedings
[13]	Distribution LMP-Based Demand Management in Industrial Park via a Bi-Level Programming Approach	2021	Journal Article
[140]	Optimal Sizing of Hybrid Energy Storage in Industrial Park Integrated Energy System	2021	Conference Proceedings
[61]	Optimal Operation Of Battery Energy Storage System In Industrial Park	2021	Conference Proceedings
[27]	Fast Distributed Stochastic Scheduling for A Multi-Energy Industrial Park	2021	Conference Proceedings
[50]	Does China's National Demonstration Eco-Industrial Park Reduce Carbon Dioxide and Sulfur Dioxide-A Study Based on the Upgrading and Transformation Process	2022	Journal Article
[96]	Research on efficiency measurement of information industry chain integration based on multiple structures and its application in carbon management industrial park	2022	Journal Article
[105]	Application of Photovoltaic Products in Carbon Reduction in Shanghai Industrial Park	2022	Conference Proceedings
[37]	Industrial park heat integration considering centralized and distributed waste heat recovery cycle systems	2022	Journal Article
[113]	Performance Assessment of an Eco-Industrial Park: a Strategic Tool to Help Recovering Energy and Industrial Waste	2022	Journal Article
[4]	Optimising renewable energy at the eco-industrial park: A mathematical modelling approach	2022	Journal Article
[49]	Contributing to carbon peak: Estimating the causal impact of eco-industrial parks on low-carbon development in China	2022	Journal Article
[48]	Carbon emission reduction effects of eco-industrial park policy in China	2022	Journal Article
[86]	Renewable Energy Potential Mapping of Industrial Area in Central Java	2022	Conference Proceedings
[67]	Optimal Configuration of Hybrid Energy Storage System Catered for Low-Carbon Smart Industrial Park	2022	Conference Proceedings
[79]	Research on the Scenario Design and Business Model Analysis of Source-Grid-Load-Storage Collaboration for Zero-Carbon Big Data Industrial Park	2022	Conference Proceedings
[70]	Economic optimization operation strategy for industrial park integrated energy system	2022	Conference Proceedings
[63]	A study on the energy storage scenarios design and the business model analysis for a zero-carbon big data industrial park from the perspective of source-grid-load-storage collaboration	2023	Journal Article
[24]	Market integration analysis of heat recovery under the EMB3Rs platform: An industrial park case in Greece	2023	Conference Proceedings

Table A1. Cont.

Ref.	Article Title	Publication Year	Publication Type
[94]	Carbon Emission Prediction and the Reduction Pathway in Industrial Parks: A Scenario Analysis Based on the Integration of the LEAP Model with LMDI Decomposition	2023	Journal Article
[2]	Sustainable energy-water-food nexus integration and carbon management in eco-industrial parks	2023	Journal Article
[3]	Global Energy Integration for Industrial Parks Incorporating Centralized Trigeneration and Interplant HEN	2023	Journal Article
[26]	Research on Optimal Dispatching Method of Integrated Energy Network in Agricultural Industrial Park Considering Demand Response	2023	Conference Proceedings
[1]	System Architecture Design of Heat-Electricity Energy Internet for a High Energy Consumption Industrial Park in Chongqing	2023	Conference Proceedings
[8]	Coordination optimization of hydrogen-based multi-energy system with multiple storages for industrial park	2023	Journal Article
[36]	High-value Chemicals Production via Eco-industrial Park: Heat Integration, Safety, and Environmental Analysis	2023	Journal Article
[59]	Peer-to-Peer Trading for Multi-Utility Energy Systems in Eco- Industrial Park	2023	Journal Article
[20]	The possibility of applying combined heat and power microgrid model for industrial parks. A case study for Dong Nam industrial park in Vietnam	2023	Conference Proceedings
[47]	Nonlinear Effects of Eco-Industrial Parks on Sulfur Dioxide and Carbon Dioxide Emissions—Estimation Based on Nonlinear DID	2023	Journal Article
[90]	An integrated framework for industrial symbiosis performance evaluation in an energy-intensive industrial park in China	2023	Journal Article
[69]	Energy Storage Configuration Optimization Method for Industrial Park Microgrid Based on Demand Side Response	2023	Conference Proceedings
[34]	Green development and co-benefits analysis of a typical chemical industrial park under pollution and carbon reduction and zero-waste city policies	2024	Journal Article
[114]	Symbiosis: A Web-Based Decision Support Tool for Achieving Symbiosis in Industrial Parks	2024	Conference Paper
[42]	Towards mega-scale decarbonized industrial park (Mega-DIP): Generative AI-driven techno-economic and environmental assessment of renewable and sustainable energy utilization in petrochemical industry	2024	Journal Article
[51]	Does Industrial Symbiosis Improve Carbon Emission Efficiency? Evidence from Chinese National Demonstration Eco-Industrial Parks	2024	Journal Article
[74]	An automated approach for carbon integration in industrial park	2024	Journal Article
[73]	Realizing synergy between pollution reduction and carbon mitigation in industrial parks: From model development to tool application	2024	Journal Article
[33]	Synergetic effect evaluation of pollution and carbon emissions in an industrial park: An environmental impact perspective	2024	Journal Article
[82]	Enhancing the waste heat utilization of industrial park: A heat pump-centric network integration approach for multiple heat sources and users	2024	Journal Article
[32]	Mixed Energy and Production Scheduling in an Eco-Industrial Park	2024	Conference Paper
[127]	Integrated optimization modelling framework for low-carbon and green regional transitions through resource-based industrial symbiosis	2024	Journal Article
[72]	A Study of Practical Cases Regarding the Synergy of Electricity and Heat in Industrial Parks	2024	Conference Proceedings
[68]	Achieving synergy between pollution reduction and carbon mitigation in the eco-industrial park: a multi-objective optimization framework	2025	Journal Article

Table A1. Cont.

Ref.	Article Title	Publication Year	Publication Type
[75]	Optimisation Framework of Multi-Energy Peer-to-Peer Trading with Hybrid Market Models in Eco-industrial Parks	2025	Journal Article
[97]	Evaluation of carbon emission reduction potential of industrial symbiosis in industrial parks	2025	Journal Article

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