

Thematic Proceedings

Advancing Industrial Symbiosis: From Learning and Awareness to Cross-Sectoral Action

WG3 workshop & confence
Piraeus, May 26, 2026



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Content

1	Digital Technology Watch Platforms for Industrial Symbiosis: A Systematic Landscape Review of Capabilities, Governance, and Impact Evidence	7
2	Business Liaison Coordinators as Institutional Actors for Awareness-Raising, Monitoring and Governance of Industrial Symbiosis: Evidence From the Vet System in Kosovo	15
3	Measuring the Progress: A Performance Ranking of European Union Countries in the Circular Economy Era	25
4	Mapping Industrial Symbiosis for Circular Economy Transition: Comparative Insights Across Countries	35
5	Bridging the Education Gap in Industrial Symbiosis for North Macedonia's Alignment With the EU Green Agenda	45
6	Policy-Driven Technological Innovation in Industrial Symbiosis: A Patent-Based Global Analysis (1971–2024)	53
7	Educational Leadership and Institutional Learning in Advancing Industrial Symbiosis Awareness in Higher Education	61
8	Key social and cultural factors influencing Industrial Symbiosis (IS) implementation	69
9	Legal and Political Barriers to Industrial Symbiosis Development	77
10	Navigating the Symbiotic Transition: A Cross-Sectional Analysis of ESRS E5 Adoption in the European Automotive Industry	83
11	Cross-Sectoral Fermentation Pathways for Sustainable Production	91
12	Industrial symbiosis and entrepreneurship Croatian case studies	99
13	Measuring What Matters: Knowledge and Competencies in CE and IS	109
14	Monitoring and Evaluating Awareness Impacts in Circular Economy Transitions: Bridging the Knowledge–Action Gap through Digital Tools and Industrial Symbiosis	117
15	Urban Waste Repurpose under the Concept of Industrial Symbiosis	125
16	Analyzing Barriers to Industrial Symbiosis Adoption Using DEMATEL: KPI-Oriented Insights	133
17	Turning by-products into partnerships: Albania's debut on Industrial Symbiosis	141

Digital Technology Watch Platforms for Industrial Symbiosis: A Systematic Landscape Review of Capabilities, Governance, and Impact Evidence

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ABSTRACT

Industrial symbiosis depends on firms making real commitments to exchange resources across organizational and sectoral boundaries, not simply recognizing that such exchanges are possible (Chertow, 2000). In particular, the phenomenon of digital “technology watch” platforms has become a standard means for creating this recognition. However, the question of what exactly facilitates coordination cost savings, what exactly facilitates the willingness to share sensitive information through the platform’s governance mechanisms, and what exactly demonstrates the effectiveness of the platform’s facilitated recognition in leading to meetings, feasibility studies, pilot projects, and actual exchanges remains poorly specified. This paper suggests a systematic review of the landscape of digital technology watch platforms for industrial symbiosis from January 2000 to January 2026. The timeframe is extensive for a few reasons. First, the first platforms were often built as directories or registries or project support tools that influenced subsequent platforms but were not necessarily documented or published in peer-reviewed journals. Second, the period from 2000 to 2026 allows for a comprehensive overview of the evolution of the phenomenon. Finally, the timeframe searched follows the PRISMA 2020 reporting guidelines with a clear protocol for searching, screening,

and extraction (Page et al., 2021). Relevant studies are those that describe a digital system that facilitates at least one function for progressing from recognition to action, including technology watch/scanning, knowledge curation, opportunity identification or matchmaking, brokerage workflow support (initiation of contact, confidentiality arrangements, feasibility coordination), or monitoring/reporting of outcomes.

For each platform, we create a capability stack and a governance profile. Governance is evaluated through a structured checklist grounded in information security management system requirements, with a focus on aspects such as confidentiality, access control, data minimization, verification and auditability, and the allocation of responsibility in the event of claims being contested (International Organization for Standardization, 2022). Impact evidence is graded through an outcome hierarchy that distinguishes between promotional claims and engagement metrics, behavioral metrics, conversion metrics, and outcomes.

This synthesis yields: (1) a taxonomy of platform generations and types from 2000 to 2026, (2) a governance and trust checklist that links platform design to participation constraints, and (3) a targeted evaluation agenda that makes “awareness to action” quantitatively tractable for auditing by practitioners and policymakers.

KEYWORDS

Industrial Symbiosis • Technology Watch • Digital Platforms • Data Governance • Systematic Review • Impact Evaluation

INTRODUCTION

Industrial symbiosis (IS) is based upon the exchange of residual resources such as waste heat, by-products, or secondary raw materials among firms, facilitated across organizational and sectoral boundaries (Chertow, 2000). While the technical potential for such exchanges is well known, the long-standing issue is how to move from abstract awareness, through feasibility work, to actual commitment (Paquin & Howard-Grenville, 2012). Digital technology watch and matchmaking have been found to be a critical policy and business instrument for addressing information asymmetry, facilitating connections, and making symbiosis opportunities visible (Domenech et al., 2019; Fraccascia et al., 2019).

However, the work of the platform is often seen as an end. Thus, the level of registrations, visits to the platform, and the number of synergies published is commonly reported as an indicator of success, while the more pertinent issues are less well examined, such as what technical functionality is effective at reducing coordination costs, what features are effective at incentivizing firms to disclose operationally sensitive information, and what evidence is there that the awareness-raising work of the platform is effective at leading to feasibility work, agreements, and actual exchanges (Aid et al., 2017; Fraccascia et al., 2019). Moreover, the digitalization of the platform raises important issues regarding information security, data sovereignty, and trust,

especially where the platform is third-party managed or funded through time-limited public funds (International Organization for Standardization [ISO], 2022).

Previous reviews offer important foundational elements. Aid et al. conducted a systematic review on IS platform and data needs in 2017 but focused mainly on data points and promotional measures. Another study by Kristoffersen et al. developed a taxonomy on platform types and critical success factors in 2021, but the longitudinal landscape and the outcome hierarchy were not about governance. Other studies have discussed the implications of digital technologies on the enabling of IS from a circular economic perspective (Domenech et al., 2019; Neves et al., 2020). This paper fills the gaps by presenting a systematic landscape review on digital technology watch platforms for IS from 2000 to 2026. It has three objectives: to propose a taxonomy on platform generations, to propose a checklist on governance and trust based on information security management standards, and to evaluate the evidence on impacts using an outcome hierarchy that differentiates between engagement measures and verified symbiosis outcomes. This study thus contributes to an auditable understanding of the practical outcomes of digital technologies and clearly identifies the types of evidence that should be demanded by policymakers and practitioners.

METHODOLOGY

Review Design

The research design conformed to the PRISMA 2020 guidelines for systematic reviews (Page et al., 2021). Given the diverse and dynamic nature of digital information systems (IS) platforms, a landscape mapping methodology was adopted as an alternative to a meta-analysis of effect sizes. Three key research questions

Search Strategy and Selection

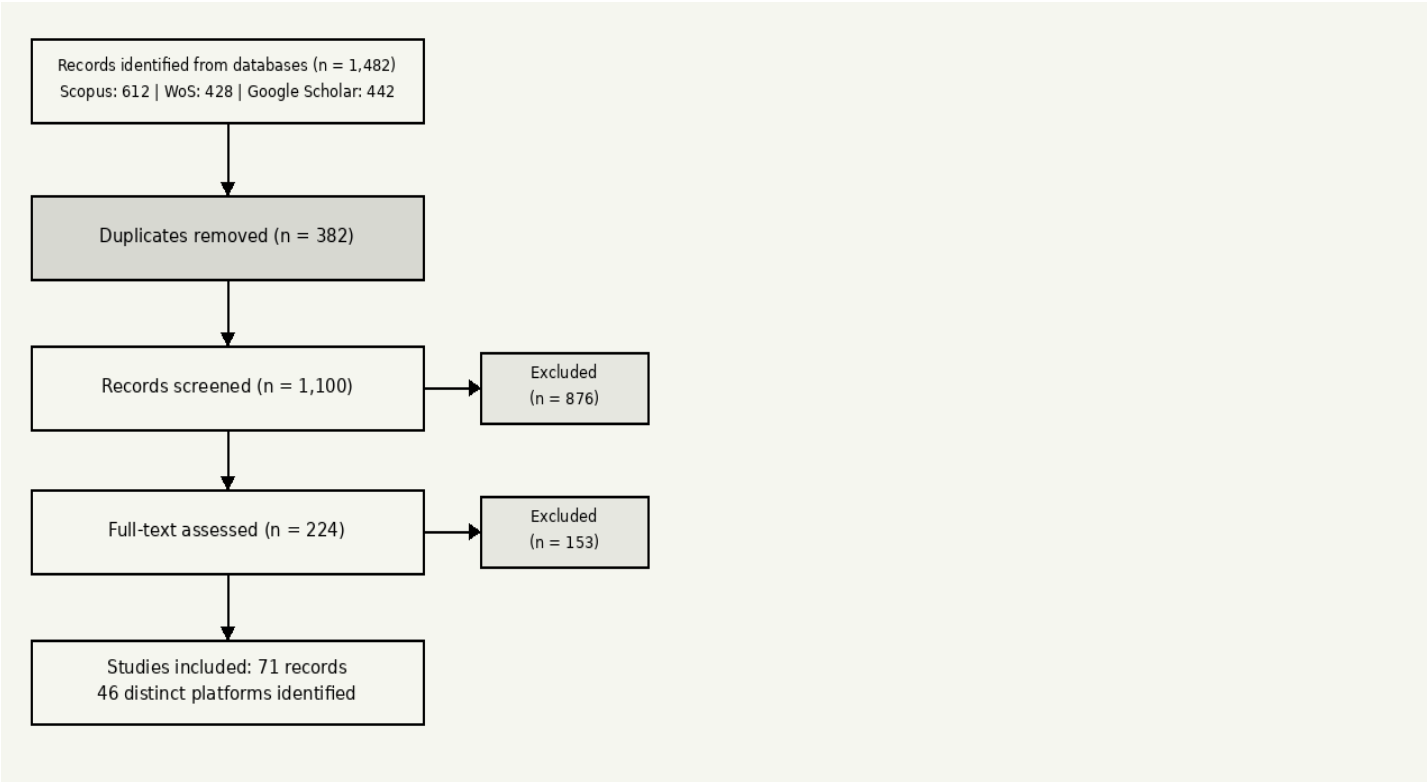
Three bibliographic databases were searched: Scopus, Web of Science Core Collection, and Google Scholar. Searching was done between the 10th and 20th of February 2026. The search period ranged from January 2000 to January 2026. The search strategy combined terms related to industrial symbiosis, digital platforms, and technology watch functions. Backward and forward citation chasing of the review articles by Aid et al. (2017) and Kristoffersen et al. (2021) were additional components of the search. Eligible documents for the review were articles, conference papers, chapters, policy documents, and articles published in English, discussing the application of digital platforms for at least one func-

were addressed by the research design: (a) What types and generations of digital technology-watch platforms have been identified between 2000 and 2026? (b) What technical and/or governance attributes do these platforms exhibit? (c) What types and levels of impact evidence do they support?

tion of industrial symbiosis, such as technology watch, knowledge curation, opportunity identification, brokerage workflow, or outcome monitoring.

A total of 1,482 documents were obtained after the search. After eliminating duplicates, there were 1,100 documents screened based on titles and abstracts, followed by full text screening. A total of 224 documents passed the full text screening. However, after full text screening, there were 153 documents that were excluded. A total of 71 documents remained, describing 46 different digital platforms. Figure 1 shows the PRISM flow diagram.

Figure 1 PRISMA 2020 flow diagram summarizing the systematic review process (Source: Author)



Data Extraction and Synthesis

A data extraction tool in a structured format was used to collect bibliographic data, platform identity and scope, platform generation and type, capability stack, governance profile, and evidence of impact. Data synthesis combined descriptive statistics and qualitative comparative analysis. Evidence of impact was graded

using a four- level outcome hierarchy, consisting of: (1) promotional and engagement metrics, (2) behavioral indicators, (3) conversion indicators, and (4) verified symbiosis outcomes (Aid et al., 2017; Lombardi & Laybourn, 2012).

RESULTS

Platform Generations and Types

The platform typology has revealed that there are four major generations, as depicted inTable 1. Generation 1 includes directory and registry platforms, which make up 30% of the market. This generation includes static databases with map-based interfaces that provide matching functionality. Generation 2 includes match-making engines, which make up 28% of the market. This generation provides matching functionality that includes materials type, quantity, and location. There has

been significant development in this generation through European Union Horizon 2020 projects. Generation 3 includes workflow enabled brokerage platforms that make up 24% of the market. This generation provides the functionality to make contact, ensure confidentiality, and conduct feasibility. Generation 4 includes integrated ecosystem platforms that make up 18% of the market. This generation is the most advanced..

Table 1 Taxonomy of Digital IS Platform Generations (Source: Author)

Generation	Type	Key Features	Share
Gen 1	Directory & Registry	Static databases; map interfaces; manual matching; offline broker contact	30%
Gen 2	Matchmaking Engine	Algorithm-assisted matching; material/location filters; basic scoring	28%
Gen 3	Workflow Brokerage	Structured workflows; confidentiality tools; feasibility coordination; messaging	24%
Gen 4	Integrated Ecosystem	Multi-source data integration; analytics; API connectivity; real-time monitoring	18%
Generation	Type	Key Features	Share

Capability Stacks

An analysis of capability stacks reveals a smooth transition from the prevalence of basic functionalities to the scarcity of more advanced capabilities (Table 2). For example, data entry and search functionalities are ubiquitous and can be found in almost all platforms (approximately 98%). Approximately 70% of the platforms offer some form of opportunity identification or matchmaking capabilities, although these vary significantly in terms of sophistication. Monitoring and reporting functionalities are present in 40% of the

platforms, but only in the form of dashboards showing user numbers and potential savings. More structured brokerage workflow’s support, including Non-Disclosure Agreement (NDA) templates, inquiry forms, and feasibility tracking, is present in only 33% of the platforms. Active technology surveillance, or scanning and alerting new technologies, is present in only 22% of the platforms. Data integration from external sources using APIs or feeds is present in only 15% of the platforms, mainly Generation 4 systems.

Table 2 Platform Capability Adoption Rates (Source: Author)

Capability	Description	Adoption
Data Entry & Search	Basic input forms, search, browse	98%
Opportunity Identification	Matching algorithms, material/location filters	70%
Monitoring & Reporting	Dashboards, KPIs, usage statistics	40%
Brokerage Workflow	Contact forms, NDA templates, feasibility tracking	33%
Technology Watch	Automated scanning, tech alerts, case updates	22%
External Data Integration	API connectivity, ERP integration, real-time feeds	15%

Governance Profiles and Trust Mechanisms

With regards to the different governance models that can be identified within the sample, a significant degree of variation can be noted. Initiatives that are funded or managed by public actors such as regional agencies, research organizations, or European Union projects represent 61% of the sample. On the other hand, private enterprises represent 24%, while public-private partnerships represent 15%. With regards to access control, 45% of the platforms offer free access to basic information, while registration is required to access detailed information. On the contrary, 55% of the platforms restrict access to registered users, with

permissions depending on the roles of the users. Furthermore, the adoption of role-based access control to differentiate firms, brokers, and administrators can be noted within Generation 3 and Generation 4 platforms to the extent of 42%. With regards to the handling of data and the confidentiality of information, the following findings can be noted. While 50% of the platforms document their data handling practices, only 15% of the platforms reference information security standards such as ISO/IEC 27001 (ISO, 2022). Data verification mechanisms can be noted within only 18% of the platforms, while the

remaining platforms rely on self-reported information. European platforms were more likely to report compliance with data protection legislation, which is likely a

consequence of European Union legislation (European Commission, 2020).

Table 3 Platform Governance Profiles (Source: Author)

Dimension	Category	%	Notes
Ownership	Public/publicly funded	61%	Agencies, EU projects
	Private company	24%	Commercial models
	Public-private partnership	15%	Mixed governance
Access Control	Open access (basic info)	45%	Registration for detail
	Registered users only	55%	Role-based options
Data Handling	Clearly documented	50%	Anonymization, rules
	Vague or absent	50%	No clear documentation
ISO 27001 Ref.	Explicit mention	15%	Mostly European
Verification	Present	18%	Rare; advanced only

Evidence of Impact

When examined through the lens of the outcome hierarchy, a strong level of attrition can be observed from engagement to verified outcomes, as shown in Table 4. All platforms surveyed (100%) report Level 1 promotional and engagement metrics such as the number of registrations or the number of listed synergies. Approximately 60% report Level 2 behavioral metrics such as the number of inquiries, messages, or brokerage meetings. Only 33% report Level 3 conversion metrics such as the number of instances where contacts result in formal agreements. Verified Level 4 symbiosis metrics such as the quantified resource or emission

benefits or economic benefits are reported for only 26% of the platforms within the context of established programs. Even in the presence of reported verified outcomes, it can be difficult to determine the attribution to the platform itself as opposed to the broader IS programs or pre-existing relationships. This points to a critical gap in the effectiveness of platforms, as while platforms are ubiquitous and their effectiveness can be clearly tracked through engagement metrics, there is limited evidence to support their distinct contribution to resource exchanges (Aid et al., 2017; Fraccascia et al., 2019).

Table 4 Outcome Hierarchy and Evidence Quality (Source: Author)

Level	Description	Reporting %	Example Indicators
1: Engagement	Visibility metrics, user counts	100%	Registrations ; listed synergies ; page views
2: Behavioral	Actions indicating interest	60%	Enquiries; meetings; feasibility studies
3: Conversion	Formal commitments	33%	Signed agreements; implementation starts
4: Verified	Quantified impacts	26%	Tons diverted; CO ₂ reduced; economic savings

DISCUSSION

The Awareness-to-Action Gap: Partial Success

This review shows that digital platforms can make a significant contribution to reducing information asymmetry and improving the visibility of potential symbiosis opportunities, particularly in regions with policy support (Chertow, 2000; Domenech et al., 2019).

Directory and matchmaking platforms can increase the number of potential partners, while workflow-enabled and integrated platforms can improve the structure of interactions. These recent developments can be considered to address some of the major areas of the

awareness-to-action gap by reducing search costs and improving standardized information on materials and processes. However, most of these platforms still do not offer the full potential of the awareness-to-action process to verify transactions. This can be seen from the fact that most platforms did not adopt brokerage workflow features or offer adequate monitoring capabilities to overcome the awareness-to-action

gap. This shows that most of these platforms can only offer improvements to visibility. In regions with active brokers and program staff, the use of digital platforms can offer improvements to the awareness-to-action process, while in regions with less brokerage capacity, the use of digital tools may not be adequate to overcome the awareness-to-action gap (Fraccascia et al., 2019; Paquin & Howard-Grenville, 2012).

Governance Gaps and Trust Deficits

From this analysis, there is a moderate, though limited, focus on trust and data protection. While many platforms recognize confidentiality issues and provide some basic access controls, only a small percentage (15%) utilize Information Security Management Systems in line with ISO/IEC 27001 (ISO, 2022). For companies considering sharing data like waste composition, production amounts, and capacity per location, these gaps could have a significant impact on the widespread engage-

ment of companies (Fraccascia et al., 2019). Another area with diffuse information is data quality and verification, with many platforms relying on self-reported data without any verification process in place. Adding a more definitive governance checklist, including aspects such as confidentiality, verification, dispute resolution, and communication of standards, could help build more confidence among users and funders.

Platforms Within Policy Ecosystems

European and international policy measures are progressively emphasizing the importance of digitalization for the circular economy, as well as the coordination of information systems (IS) (European Commission, 2020; Neves et al., 2020). However, such measures rarely specify the type of impact that should be delivered by evidence platforms, or how they should be integrated with economic, regulatory, and infrastructural instruments. Studies suggest that platform effectiveness

is maximized if integrated into a broader ecosystem, where there are effective intermediaries, a favorable environment, and stable funding for brokerage (Lombardi & Laybourn, 2012; Paquin & Howard-Grenville, 2012). On the other hand, stand-alone platforms without institutional support seem successful in attracting users but fail to deliver significant outcomes (Aid et al., 2017; Kristoffersen et al., 2021).

Implications for Practice and Policy

For platform developers, the results highlight the need to build stacks that cover the entire continuum from awareness to action with particular attention to brokerage workflows and monitoring (Kristoffersen et al., 2021; Yazan & Fraccascia, 2020). Transparent and easy-to-use governance systems, including privacy policies, role-based access control, and the application of well-established security standards, should be thought of as enablers of participation rather than obstacles to

be overcome. With respect to policymakers and funders, the outcome hierarchy represents a useful tool to demarcate expectations and guide the procurement of evaluations. Requests for funding should encourage platforms to collect not only behavioral and conversion outcomes but also verified outcome measures alongside engagement metrics, as well as sound attribution methods (European Commission, 2020).

CONCLUSIONS

This systematic review of digital technology watch platforms for industrial symbiosis collected 71 records from 2000 to 2026. The findings include the following. First, the review introduces a taxonomy of four generations of industrial symbiosis platforms: directories, matchmaking engines, workflow-enabled platforms, and integrated ecosystem platforms. Second, the review of platform governance demonstrates mode-

rate levels of confidentiality and access control. There is limited systematic integration of information security standards. Only 15% of platforms mentioned the use of the ISO/IEC 27001 standard. Third, the review introduces a hierarchy of four levels of outcomes, demonstrating the dominance of impact reporting at the engagement level. Only 26% of platforms provided verified symbiosis outcomes along with quantified

environmental and economic benefits.

This review is significant for several reasons. First, the review provides a significant contribution to the field of industrial symbiosis. The taxonomy of industrial symbiosis platforms will provide practitioners with a useful tool for benchmarking and improving the design of the platforms. Second, the hierarchy of outcomes will provide policymakers with an auditable hierarchy to evaluate whether publicly funded platforms have met their objectives. Third, the review's governance checklist bridges the gap between information security management principles and the specific trust issues of industrial symbiosis data exchange. Overall, the review's tools will allow policymakers to make the shift from the use of activity as a proxy for impact to actual

outcomes from the use of digital intermediaries.

However, the review's contribution must be tempered by the following caveats. First, the review is limited to English-language platforms only. There is the possibility that relevant platforms have been published in other languages. Second, the review is limited to the present time. The rapid development of digital technologies suggests that some of the features of the platforms may have been underreported in existing literature. Third, the hierarchy of outcomes is based on the platforms' reporting of outcomes. There is the possibility of reporting bias in the hierarchy. Further studies need to focus on the use of quasi-experiments to study the effects of various features of the platforms. These include confidentiality tools and matchmaking engines.

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Business Liaison Coordinators as Institutional Actors for Awareness-Raising, Monitoring and Governance of Industrial Symbiosis: Evidence From the Vet System in Kosovo

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ABSTRACT

Industrial Symbiosis (IS) is being promoted more and more inside EU policy frameworks as an essential instrument for resource efficiency, cross-sectoral cooperation and the green transition. Accordingly, its successful implementation requires organized stakeholder participation, institutional capabilities and evidence-based monitoring together with awareness-raising strategies.

The research presents the findings of an internal assessment carried out as part of the project “Quality Assurance for the Work of Business Liaison Coordinators (BLCs)”, which was funded and carried out by the Ministry of Education, Science and Research of the Republic of Austria.

The assessment examines how BLCs function as institutional intermediaries operating between vocational education and training (VET), enterprises and public authorities, contributing to governance, communication and awareness processes relevant to Industrial Symbiosis. Moreover, the study assesses the project’s contribution to improving work-based learning (WBL), VET-business collaboration, learning communities, with a focus on monitoring awareness impact and institutional learning. The evaluation system uses outcome-oriented measures, including stakeholder comprehension, participation levels, coordination

effectiveness and sustainability of collaboration models and it is in line with ETF and EU quality assurance approaches. Acknowledging the complexity of the topic a mixed-method approach was adopted, containing desk research, surveys, semi-structured interviews and comparative case studies. All the data was gathered from project documents and important stakeholders, such as BLCs, VET school management, VET teachers, in-company instructors, businesses, policy makers and business associations. In addition, 10 pilot VET schools responded to two electronic questionnaires and two schools with distinct performance characteristics were chosen to serve as case studies.

The findings suggest that BLCs play a significant role in fostering structured communication, supporting feedback mechanisms and enabling evidence-based adjustments to cooperation practices.

By doing so they help strengthen institutional awareness, enhance policy coherence and build governance capacity all of which are essential conditions for advancing Industrial Symbiosis and other cross-sector partnerships.

Finally, the report closes with policy-relevant recommendations for improving monitoring frameworks, institutional capacity and assessing awareness impact within VET-led IS support systems.

KEYWORDS

Industrial Symbiosis • VET • Awareness Impact Monitoring • Governance and Institutional Capacity • Stakeholder Engagement; WBL • BLC

INTRODUCTION

Industrial Symbiosis (IS) is increasingly recognized within EU and OECD policy frameworks as a strategic mechanism to optimize resource use, promote circular economy principles and accelerate the green transition (OECD, 2020). Within vocational education and training (VET), integrating sustainable practices and fostering close cooperation with enterprises is essential for labor market alignment, especially through Work-Based Learning (WBL) models (ETF, 2021; ETF, 2022).

In Kosovo, Business Liaison Coordinators (BLCs) function as institutional intermediaries linking VET schools, businesses, and public authorities. Hence their roles include facilitating communication, raising awareness, monitoring WBL implementation and supporting

evidence-based governance for IVET and sustainable industrial practices. Despite recent reforms and donor support initiatives, challenges persist in formalizing BLC roles, securing business engagement and ensuring sustainability of VET-business collaboration (Likaj et al., 2025; Bajrami, 2024).

This paper presents findings from the internal evaluation of the regional project “Quality Assurance for the Work of Business Liaison Coordinators”, funded by OEAD and implemented between 2021–2024. The study assesses BLC effectiveness in enhancing institutional capacity, awareness and governance for IS and WBL, while providing policy-relevant recommendations for strengthening Kosovo’s VET system.

LITERATURE REVIEW

Industrial Symbiosis and Governance

Industrial Symbiosis refers to the systematic collaboration of diverse actors aimed at optimizing resource flows, reducing waste and achieving environmental and economic benefits. According to OECD (2020), effective IS requires coordinated governance, multi-stakeholder engagement and institutional mechanisms for monitor-

ing and learning. In this manner BLCs in Kosovo can be conceptualized as governance intermediaries that enable structured communication and policy coherence between VET institutions and businesses, facilitating IS adoption.

Work-Based Learning and Dual VET in Kosovo

WBL has emerged as a key approach for linking vocational education with labor market needs (ETF, 2021). Kosovo has made significant progress in WBL and dual education programs, guided by the National Development Plan 2030 and the Education Strategy 2022–

2026. Despite these improvements, some challenges remain in curriculum alignment, teacher capacity, contractual arrangements with businesses and systematic monitoring (Bajrami, 2024; Euler, 2024; MESTI, 2025).

Institutional roles and capacity development

BLCs function as institutional actors bridging schools, municipalities, ministries and businesses, thereby strengthening professional learning communities and WBL implementation. Previous studies indicate that formalized coordination structures, career centers and digital monitoring tools are critical to sustain-

able VET-business cooperation (Likaj, 2023; Likaj et al., 2025). On the other hand, development partners highlight the importance of standardizing instruments, improving teacher competencies and integrating sustainability and green skills into curricula (Themel, 2024; ETF, 2022).

Evidence-based policy and monitoring

Monitoring WBL practices requires outcome-oriented frameworks and systematic evaluation of stakeholder participation, coordination effectiveness and sustainability of collaboration models. According to the ETF (2021, 2022) evidence-based approaches, including surveys, interviews and case studies, play a vital role in

quality assurance and institutional learning in VET systems. The experience from Kosovo demonstrates the necessity of integrating legal frameworks, contractual clarity and financial support to sustain effective BLC coordination (Likaj et al., 2025).

METHODOLOGY

A mixed-methods approach was used to evaluate BLC impact on VET-business cooperation and WBL implementation:

1. Desk research, revision of a different projects activity reports, policy documents and partner reports (Likaj, 2023; Bajrami, 2024) was conducted to assess the progress in professional development, communication tools and quality assurance mechanisms.
 2. Semi-structured and quantitative electronic questionnaires (10 and 21 questions respectively) were distributed to 10 pilot VET schools. Accordingly, the target respondents were BLCs, school directors, teachers of professional practice, businesses and relevant authorities.
 3. Semi-structured interviews took place with businesses, policy makers, and project partners to capture qualitative insights.
 4. Case studies, with two pilot schools with distinct performance characteristics were analyzed to highlight best practices, obstacles, and lessons learned.
- Outcome measures included stakeholder comprehension, participation levels, coordination effectiveness and sustainability of collaboration models, in alignment with ETF and EU quality assurance approaches.

RESULTS

Key findings from desk research

- Progress in WBL implementation and documentation was observed, with schools having BLC roles and career centers showing better outcomes.
- Networking workshops and peer learning visits facilitated stakeholder collaboration and exchange of best practices.

Kosovo has made substantial progress in establishing WBL and Dual VET, guided by national policy frameworks such as the National Development Plan 2030 and the Education Strategy 2022–2026. Initially a government task force launched dual VET pilots in 2022/23 academic year, the efforts expanded in 2023/24 with the first graduates anticipated to be in 2025.

These reforms are supported by a legal framework adopted in 2020 which are being further strengthened through a new VET law led by the Ministry of Education, Science, Technology and Innovation (MESTI).

Moreover, the Kosovo Chamber of Commerce plays a key role in facilitating connections between businesses with VET providers. At the same time Kosovo continues to align its system with EU standards through benchmarking studies and preparation for joining the European Alliance for Apprenticeships (EAfA) (ETF, 2021;

Bajrami, 2024; Themel, 2024).

Strategic reforms prioritize close curriculum alignment with labour market needs, the expansion of dual VET profiles, increased employer involvement and strengthened institutional coordination at national and local levels (Euler, 2024). Within dual programs WBL has been expanded to account for up to 50% of learning time, supported by modular curricula, workplace instructor training and safety regulations. However, systemic challenges persist, including insufficient legal clarity for WBL contracts, limited financial incentives for companies, inconsistent quality assurance, and weak monitoring of graduate outcomes (ETF, 2021; Bajrami, 2024).

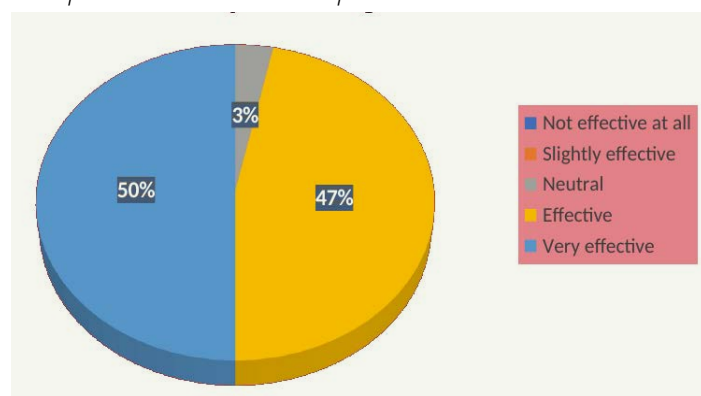
Policy recommendations emphasize strengthening legal frameworks, incentivizing business participation, enhancing the capacity of BLCs and teachers and improving career guidance, inclusion and student protection mechanisms. In addition, more coherent coordination is essential among ministries, municipalities and social partners, alongside stronger monitoring and evaluation systems, for ensuring the long-term sustainability and quality of WBL in Kosovo (OECD, 2020; Likaj, 2023; R. Likaj et al., 2025).

Survey and interview results

Regarding the effectivity of the intervention in strengthening cooperation between IVET and private sector, the findings as shown in Figure 1, suggest a high level of engagement among BLCs and vocational practice teachers while in comparison the participation from business representatives and school leadership was

lower. Results showed that 96.7% of respondents found learning communities useful whereas 96.4% rated VET-business cooperation as effective.

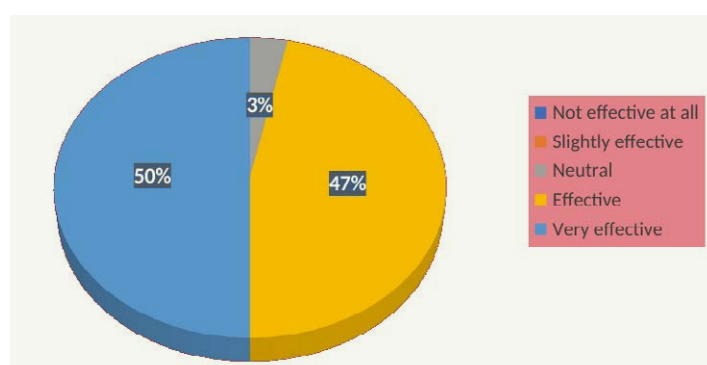
Figure 1: The effectivity of intervention in strengthening cooperation between IVET-private sector



WBL tools were largely accessible and user-friendly. However, persistent challenges were identified in legal recognition, business participation and monitoring mechanisms, while businesses stressed the need for more formal agreements, clearer financial support and improved risk/insurance management for students.

This part of the findings indicates that introduction of learning communities and improving communication and cooperation as shown in Figure 2, has been perceived as largely effective in strengthening cooperation between VET schools and businesses. Specifically, the results show that 50% of the respondents rated the initiative with “generally effective” while 46.7% replied with “very effective” and only a minor number of respondents seemed to be dissatisfied.

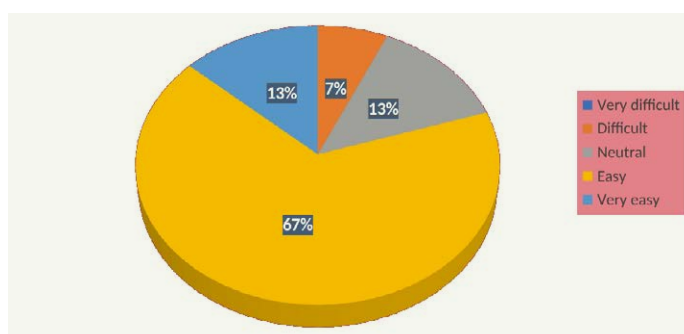
Figure 2: The effectivity of learning communities



When it came to professional learning communities, respondents see them as extremely beneficial, with 96.7% describing them as good or very useful for better communication. In terms of student opportunities, 66.7% believe the project has had a significant positive impact, while 33.3% see room for improvement. To improve outcomes, it is proposed to strengthen industry partnerships and ensure long-term student placement possibilities.

Regarding the efficiency of developed mechanisms for BLCs to use, survey responses shown in Figure 3, indicate that the developed WBL tools and documents are generally accessible, with 80% considering them easy or very easy to use, while 6.8% have difficulty. Likewise, project guidelines and resources are positively evaluated, with 93.3% rating them as clear or very clear and only 6.8% finding them unclear. Nevertheless, responses suggest that improving user support and improving materials based on feedback could further improve overall usability and clarity for all stakeholders.

Figure 3: Efficiency of developed mechanisms for BLCs



For the implementation of quality assurance measures in VET school-business cooperation the main challenges in professional school-business cooperation, survey findings show several challenges in implementing quality assurance criteria during WBL, indicating that there is still a great need for coaching and other capacity building:

- Lack of standardised WBL and dual approaches is a major concern, with 57.7% agree or fully agree.
- Monitoring and evaluation difficulties are even more critical, with 61.6% agreed.
- Limited business involvement in quality assurance of WBL processes remains another challenge, with 53.8% acknowledging the issue.
- Financial and technical constraints are another major barrier, with 78.6% citing it as a problem.
- Lack of training and coaching for BLC, especially for new teachers is also perceived as a significant issue, with 55.2% of respondents agreeing.

For the good practices have helped improve WBL quality assurance the survey results also point out several good practices that have significantly improved WBL quality assurance:

- The use of instruments and quality criteria for the work of BLC was the most impactful measure, with 75% agree or fully agree.

- Structured cooperation between VET schools and businesses also received strong support, with 80.7% agreed.
- Revised instruments for the evaluation of students performance during WBL were beneficial, with 74.1% acknowledging their benefit.
- Furthermore, coaching and training for BLC, teachers of professional practice and joint meetings with business representatives was considered effective by 69.3% of participants.
- Finally, the utilization of feedback from businesses and students was a key success factor, with 76.9% agreement rate among respondents.

As unaddressed needs to ensure the quality and sustainability of professional school - business cooperation, further insights from the survey point several critical unmet needs for improving quality and sustainability in professional school-business cooperation:

- The two most urgent priorities seem to be the increase of business involvement in quality assurance of WBL (92.3% agreement) and 84.6% of respondents deem greater financial aid for implementation of WBL.
- The development of a digital platform for sharing best practices and monitoring progress also ranks high in the list with 88.5% of respondents agreeing.
- Similarly, 88.5% of the interviewees emphasized the need for more effective monitoring and evaluation mechanisms.
- At last, training and certification programs for BLC and in quality assurance of WBL processes are perceived as necessary steps with 88.5% agreement ratio.

The main challenges in implementing these initiatives, the findings identify three challenges affecting effective project implementation:

Limited business involvement in WBL remains a continuous challenge with 73% of respondents acknowledging this issue. Accordingly, this calls for the need of stronger incentive mechanisms and more structured engagement strategies, to ensure a stable private sector participation.

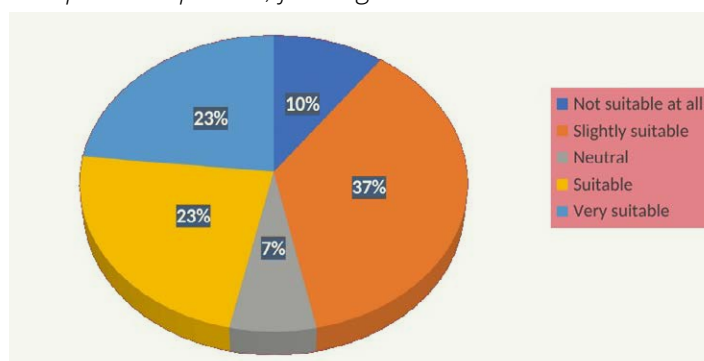
Insufficient capacities and resources for BLC were highlighted by 77% of the respondents, suggesting that training, funding and staffing improvements are critical for BLC effectiveness.

77% of interviewees point out the need for further improvement of WBL instruments and practices, showing the necessity of standardization of existing packages of instruments, contracts and guidebooks for WBL and Dual, for better implementation.

The survey findings shown in Figure 4, demonstrate a divided perception regarding the adequacy of supporting mechanisms for VET school-private sector coo-

peration. Hence results show that 48.2% of the respondents so nearly half of the group considers these mechanisms inadequate, including 10.3% who rated them as "not suitable at all" and the other 37.9% rated them as "slightly suitable".

Figure 4: Supporting mechanisms for IVET-private sector cooperation: policies, funding etc.



Respectively this indicates that present policies and funding do not adequately promote VET school-private sector cooperation.

However, 44.8% of respondents believe they are suitable or extremely suitable, showing that some processes are effective but may require additional adaptation. Whereas the 6.9% neutral response indicates that some respondents may lack the necessary knowledge or information to evaluate the effectiveness of these mechanisms.

The main needs that have not yet been addressed to improve cooperation between vocational schools and the private sector the results of the survey point out several critical gaps that need to be addressed to improve cooperation between vocational schools and the private sector.

The top unmet needs include:

- Insufficient financial support for joint projects and cooperation was cited by 53.85% of respondents. Like so, funding remains a major barrier limiting the sustainability and effectiveness of VET school-business partnerships.
- There is uncertainty surrounding the position of BLC which is highlighted by 50% of participants, pointing to the need for a clearer role definition and institutional formalization to improve cooperation efforts.
- A lack of qualified mentors or in-company instructors and experts from the business sector (46.15%), hinders the quality of work-based learning.
- Limited opportunities for WBL 46.2%, indicate a gap in business engagement and the structured expansion of dual programs.

- Coordination and communication issues reported by 53.85% of respondents, remain a significant challenge in aligning vocational education with business needs.

Interviews with businesses

Interviews with businesses participating in Work-Based Learning (WBL) initiatives in Kosovo show that structured WBL initiatives have significantly strengthened cooperation between VET schools and companies, improving students' practical skills and employability. Students benefit from hands-on workplace experience, with some already transitioning into employment.

The measures also supported schools and businesses in preparing training plans, communication channels and assessment tools, which are reported to be practical and easy to use.

However, system-level challenges remain as businesses report limited support and lack of incentives from central and local authorities, which constrains their capacity to host students and sustain cooperation. There is also a need to improve workplace safety awareness, ensure accidental insurance coverage for VET students during professional practice and strengthen institutional support for risk management in WBL placements. Good practices include strong collaboration with school-based learning coordinators (BLCs) and teachers, joint curriculum alignment with labour market needs, continuous communication and shared student assessment. Businesses also value ongoing dialogue to identify and solve cooperation challenges.

DISCUSSION

BLCs play a crucial role in governance, awareness-raising and institutional learning within the VET system. They facilitate structured communication, feedback mechanisms and enable evidence-based adjustments in WBL. However, some challenges remain, including inconsistent legal frameworks, limited resources and weak business participation, as shown in Figure 5. Strengthening professional development, career centers, monitoring mechanisms and formalizing BLC roles is essential.

The research also highlights the potential of VET schools to contribute to Industrial Symbiosis by fostering cross-sectoral collaboration, aligning curricula with labor market needs and integrating sustainability principles into practical training (ETF, 2022; OECD, 2020).

Although progress is evident key gaps remain unaddressed, particularly the need for:

- Financial support for students, teachers and BLCs during WBL,
- Government incentives (financial and non-financial) for companies,
- Stronger coordination mechanisms through institutions such as the Kosovo Chamber of Commerce and business associations,
- Sustainable, scalable WBL programmes aligned with labour market demand.

Case Studies

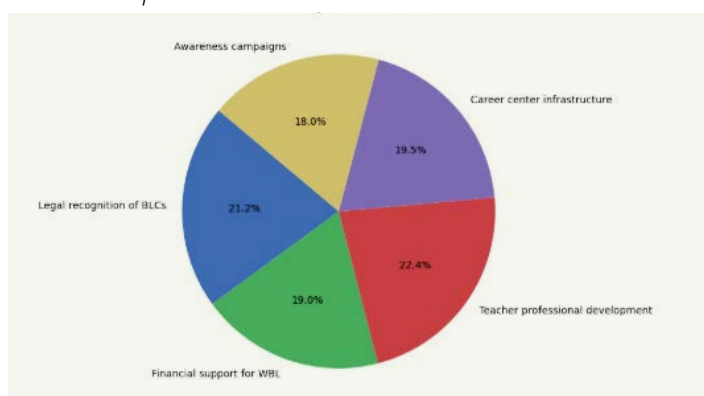
The two case studies from Isa Boletini and Lasgush Pogradeci VET schools clearly demonstrate that the OEAD-supported project strengthened VET-business cooperation WBL implementation.

In both schools, the introduction of the BLC role improved communication with businesses, increased the number of cooperation agreements and enhanced student access to professional practice. Students benefited through improved practical skills, work culture and direct employment opportunities after WBL.

At the same time both cases reveal common challenges such as the lack of legal recognition and sustainable financing of the BLC role, limited financial support for WBL (transport, insurance, student compensation) and the need for continuous teacher training alongside stronger institutional coordination.

Overall, the research proves strong potential for long-term sustainability, but its success depends on continued support from Ministry of Education, Science, Technology and Innovation and the ratification of school-business cooperation mechanisms.

Figure 5: Sustainability and future needs for IVET-private sector cooperation



CONCLUSIONS AND RECOMMENDATIONS

The project has contributed significantly to the development of WBL in Kosovo, particularly by strengthening structured collaboration between VET schools and employers and improving the overall quality of WBL provision. Through its interventions, a growing number of students have gained employment, demonstrating improved employability and closer alignment between VET outcomes and labour market demands.

Practical and user-friendly tools, guidelines and training plans were implemented aimed at supporting both schools and businesses in organizing WBL more effectively. Together with ongoing coaching for school-based learning coordinators (BLCs), teachers and key staff improved communication, cooperation and quality assurance processes across the system.

The initiative further reinforced multi-stakeholder cooperation, bringing together VET schools with municipal education directorates, ministries, donors and the business community. On top of it the Kosovo Chamber of Commerce is involved in planning and evaluating WBL. Moreover, it contributed to building sustainable cooperation structures, increasing the number of agreements between schools and businesses and raising awareness of the benefits of WBL across the VET ecosystem.

The introduction of national training programs for BLCs and teachers of professional practice, together with peer-learning exchanges between schools, helped move WBL implementation toward a more coordinated and consistent approach across Kosovo.

Worth mentioning is also the establishment of structured annual reporting on WBL which provided a clearer basis for monitoring progress and identifying areas for

future improvement. However, even with the above mentioned efforts some challenges persist to affect the process.

Despite recent progress the engagement of businesses remains at an unsatisfactory level. Companies lack proper incentives to make them participate actively in policy discussions and quality assurance efforts.

BLCs face unclear legal status and insufficient logistical and financial support. Systemic issues persist, including gaps in the legal framework, weak coordination among institutions and donor initiatives, and limited resources for training, monitoring, and curriculum alignment. Students continue to face constraints such as limited placement opportunities, insufficient workplace safety awareness, and lack of insurance and financial support.

For long-term sustainability the project showcases the need for stronger institutional support and policy coherence, including clearer legal frameworks, financial and non-financial incentives for businesses, ongoing capacity building for schools and companies and improved coordination among key actors such as MESTI, MEDs, business associations and international partners. Expanding career guidance services, strengthening entrepreneurship education, establishing career centres, improving digital platforms for WBL coordination and promoting public awareness of VET are also essential for scaling up results.

Overall, while the research shows encouraging progress of WBL development in Kosovo several factors will play a role in order to reach its full potential such as sustained investment, institutional alignment and deeper engagement from the private sector.

ACKNOWLEDGEMENTS

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Measuring the Progress: A Performance Ranking of European Union Countries in the Circular Economy Era

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ABSTRACT

The circular economy represents a paradigm shift from the traditional “take-make-dispose” linear model toward a restorative and regenerative system designed to keep resources at their highest utility and value at all times. By decoupling economic growth from resource consumption and environmental degradation, this model serves as a cornerstone of the European Union’s strategic priorities and green transition goals. Based on the significance of this theme, this study aims to evaluate and rank the circular economy performance of the 27 EU member states by utilizing a robust multi-criteria decision-making (MCDM) framework. To ensure data reliability, 20 comprehensive indicators were retrieved from the Eurostat database, reflecting the multidimensional nature of circularity.

The methodological approach consists of a two-stage analysis. In the first stage, the Skewness Impact Through Distributional Evaluation (SITDE) method was employed to determine the objective weights of the indicators. The analysis identified the top five most critical criteria as: “Trade in recyclable raw materials”,

“Generation of waste excluding major mineral wastes per GDP unit”, “Private investment and gross added value related to circular economy sectors”, “Persons employed in circular economy sectors”, and “Recycling rate of packaging waste by type of packaging”. These results highlight that economic integration and labour market participation are as vital as waste management metrics in defining CE success.

In the second stage, the TOTal DIFFerential of Alternative (TODIFFA) method was utilized to rank 27 EU countries. According to the findings, the top ten performing countries are Germany, France, the Netherlands, Cyprus, Italy, Bulgaria, Malta, Spain, Lithuania, and Romania. The results demonstrate a heterogeneous landscape where leading industrial powers and several Mediterranean and Eastern European nations exhibit competitive performances. This study provides a comprehensive roadmap for policymakers, emphasizing the need for targeted strategies to harmonize circularity across the Union.

KEYWORDS

Circular Economy • EU Countries • SITDE • TODIFFA

INTRODUCTION

The circular economy constitutes a transformative economic paradigm that fundamentally subverts the conventional linear “take-make-dispose” trajectory. Its primary objective lies in the perpetuation of resource utility through extended lifecycles, the systemic minimization of anthropogenic waste, and a comprehensive

structural reconfiguration of industrial logic. As articulated in the Ellen MacArthur Foundation’s seminal report, this model is defined as an “industrial system that is restorative or regenerative by intention and design” (Ellen MacArthur Foundation, 2013, p. 7). Operationalizing this framework necessitates a radical recalibration

of product architecture, material stewardship, corporate business models, and consumer behavioural patterns. By reconceptualizing “waste” not as an inevitable byproduct but as a systemic design flaw, the model ensures that materials remain value-generative in perpetuity across both biological and technical cycles. The significance of adopting this model is rooted in the necessity for environmental, economic, and social sustainability. The circular economy possesses the potential to enhance competitiveness by diminishing dependency on raw materials and mitigating supply risks, thereby fostering innovation and generating employment opportunities. Walter R. Stahel underscores the notion of the ‘performance economy,’ positing that durable products, repair processes, and service-oriented business models not only optimize resource efficiency but also engender new economic opportunities (Stahel, 2019, pp. 71–72). Moreover, the circular economy is regarded as a pivotal strategy in addressing climate change and conserving biodiversity, as it lessens raw material extraction and waste generation, thereby alleviating stress on natural ecosystems. The unsustainable escalation of global resource consumption and waste generation is precipitating sig-

nificant environmental challenges, including climate change, biodiversity loss, and water scarcity. In this context, the European Union seeks to expedite the transition to a circular economy model as part of the European Green Deal, with the objective of decoupling economic growth from resource utilization and achieving climate neutrality by 2050. Moreover, the circular economy model has the potential to create new economic opportunities, generate employment, and yield higher-quality, more durable products for businesses, small and medium-sized enterprises (SMEs), and individuals. The European Union aspires to assume a global leadership role in this transformative process. (European Commission, 2020). During the implementation phase, regulations such as the Ecodesign Directive for the Single Market establish criteria pertaining to durability, reusability, and recyclability of products. Furthermore, significant advancements are being achieved through sector-specific initiatives, including the Plastics Strategy and the Waste Framework Directive. The European Environment Agency is instrumental in overseeing this process and systematically assesses the European Union’s progress in ‘decoupling growth from resource use.’ (European Environment Agency, 2016)

METHODOLOGY

This research examines data from 27 EU member states in order to rank their performance in the circular economy. The data utilised in the research was obtained from the Eurostat database (Eurostat, 2026), the official statistics office of the European Union. The indicators supplied by this institution have been utilized

as evaluation criteria, with their corresponding weights determined through the application of the Skewness Impact Through Distributional Evaluation (SITDE) method. In the second stage, the performance ranking of the 27 EU countries was determined using the TOfal DIFFerential of Alternative (TOFIFFA) method.

SITDE Method

Introduced to the literature by Gopisetty and Sama in 2025, the SITDE method presents an objective framework for determining criterion weights within multi-criteria decision-making processes, leveraging the skewness and asymmetry characteristics of the data. The methodology operates through a series of systematic steps: initially, a decision matrix is constructed and normalized, followed by the calculation of standard deviation and skewness values for each criterion. These values are subsequently normalized on a logarithmic scale to derive the final criterion weights. In contrast to traditional methods that presuppose symmetrical data distribution, the SITDE method enhances the quality and balance of assessments by fully integrating asymmetric data sets and outliers into the analytical process. The principal advantages of this method include the mitigation of biases stemming from

subjective judgments of decision-makers, the provision of high reliability in complex decision-making contexts, and the generation of more transparent and robust outcomes, particularly in domains that inherently involve skewed data, such as financial risk assessment and environmental management.

The steps for implementing the method are as follows (Gopisetty & Sama, 2025):

Step 1. Construction of initial decision matrix by Equation

$$(1) \quad X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad (1)$$

Step 2. Normalization of initial decision matrix by Equation (2) or Equation (3)

$$r_{ij} = \frac{\min(x_j)}{x_{ij}} \quad ; \text{benefit criteria} \quad (2)$$

$$r_{ij} = \frac{x_{ij}}{\max(x_j)} \quad ; \text{cost criteria} \quad (3)$$

Step 3. Determination of skewness for each criterion by Equation (4)

$$S_j = \frac{m}{(m-1)(m-2)} \sum_{i=1}^m \left(\frac{r_{ij} - \bar{r}_j}{\sigma_j} \right)^3 \quad (4)$$

m ; number of alternatives

Step 4. Determination of normalized skewness for each criterion by Equation (5)

$$LS_j = \log \left| \left((S_j + 1) + (|\min(S_j)| + 1) \right) \right| \quad (5)$$

Step 5. Determination of final weights for each criterion by Equation (6)

$$\omega_j = \frac{LS_j}{\sum_{j=1}^n LS_j} \quad (6)$$

TODIFFA Method

Introduced to the literature by Gligoric et al. in 2024, the TODIFFA method is predicated on the principle of assessing the variation in a hypotenuse function, which encompasses both cost and benefit variables, in relation to an evaluated alternative and the optimal alternative. The methodology involves a systematic process, which includes the formulation of a decision matrix, the normalization of criteria, and the computation of the total differential value for each alternative with respect to the optimal point. The primary advantages of this method lie in its algorithmic structure, which is straightforward and comprehensible, thereby obviating the necessity for advanced mathematical expertise. Moreover, it provides a flexible decision-making framework, as the orientation of the criteria—whether aimed at maximizing or minimizing targets—does not adversely affect the outcomes.

The steps for implementing the method are as follows (Gligoric et al., 2024).

Step 1. Construction of initial decision matrix by Equation (1)

Step 2. Normalization of initial decision matrix by Equation (7)

$$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^m x_{ij}} \quad (7)$$

Step 3. Weighting the normalization of initial decision matrix by Equation (8)

$$V_{ij} = \omega_j * r_{ij} \quad (8)$$

Step 4. Defining the optimal alternative by Equation (9) or Equation (10)

$$f_j^{opt} = \max(V_{ij}) \quad ; \text{benefit criteria} \quad (9)$$

$$f_j^{opt} = \min(V_{ij}) \quad ; \text{cost criteria} \quad (10)$$

Step 5. Calculation of the magnitude of alternative components by Equations (11), (12), (13) and (14)

$$M_b^{opt} = \sum_{j=1}^n f_j^{opt} \quad ; n \in \text{benefit criteria} \quad (11)$$

$$M_c^{opt} = \sum_{j=1}^n f_j^{opt} \quad ; n \in \text{cost criteria} \quad (12)$$

$$M_b^i = \sum_{j=1}^n V_{ij} \quad ; n \in \text{benefit criteria} \quad (13)$$

$$M_c^i = \sum_{j=1}^n V_{ij} \quad ; n \in \text{cost criteria} \quad (14)$$

Step 6. Determination of total differential of the alternative functions by Equation (15)

$$dz_i = \frac{M_c^i(M_c^i - M_c^{opt}) + M_b^i(M_b^{opt} - M_b^i)}{\sqrt{M_b^{i^2} + M_c^{i^2}}} \quad (15)$$

RESULTS

The data required to examine the performance of 27 EU countries in terms of circular economy was obtained from the Eurostat database, and the relevant indicators are presented in detail in Table 1

Table 5 Circular Economy Indicators

I_1		Production and Consumption
I_{11}	(-)	Material footprint (tonnes per capita)
I_{12}	(+)	Resource productivity (Euro per kgs)
I_{13}	(-)	Waste generation per capita (kgs per capita)
I_{14}	(-)	Generation of waste excluding major mineral wastes per GDP unit (kgs per 1000*Euro)
I_{15}	(-)	Generation of municipal waste per capita (kgs per capita)
I_{16}	(-)	Food waste (kgs per capita)
I_{17}	(-)	Generation of packaging waste per capita (kgs per capita)
I_{18}	(-)	Generation of plastic packaging waste per capita (kgs per capita)
I_2		Waste Management
I_{21}	(+)	Recycling rate of municipal waste (%)
I_{22}	(+)	Recycling rate of all waste excluding major mineral waste (%)
I_{23}	(+)	Recycling rate of packaging waste by type of packaging (%)
I_{24}	(+)	Recycling rate of waste of electrical and electronic equipment separately collected (%)
I_3		Secondary Raw Materials
I_{31}	(+)	Circular material use rate (%)
I_{32}	(+)	Trade in recyclable raw materials (tonnes)
I_4		Competitiveness and Innovation
I_{41}	(+)	Private investment and gross added value related to circular economy sectors (M Euro)
I_{42}	(+)	Persons employed in circular economy sectors (Full-time equivalent (FTE))
I_{43}	(+)	Patents related to recycling and secondary raw materials (Number)
I_5		Global Sustainability and Resilience
I_{51}	(-)	Consumption footprint (Index, 2010=100)
I_{52}	(-)	Greenhouse gases emissions from production activities (kgs per capita)
I_{53}	(-)	Material import dependency (%)

The (+) sign in Table 1 indicates that the corresponding indicator is benefit-oriented, while the (-) sign indicates that the relevant indicator is cost-oriented. On the other hand, the coverage period for each indicator and the calculation method for the reference values are presented in Table 2.

Table 6 Circular Economy Indicators

I_{11}	The average of annual data covering the years 2000-2024
I_{12}	The average of annual data covering the years 2000-2024
I_{13}	The average of annual data covering the years 2004-2022
I_{14}	The average of annual data covering the years 2004-2022
I_{15}	The average of annual data covering the years 2000-2023
I_{16}	The average of annual data covering the years 2020-2023
I_{17}	The average of annual data covering the years 2000-2023
I_{18}	The average of annual data covering the years 2000-2023
I_{21}	The average of annual data covering the years 2000-2023
I_{22}	The average of biannual data covering the years 2010-2022
I_{23}	The average of annual data covering the years 2000-2023
I_{24}	The average of annual data covering the years 2014-2023
I_{31}	The average of annual data covering the years 2004-2024
I_{32}	The average of annual data covering the years 2015-2024
I_{41}	The average of annual data covering the years 2014-2023
I_{42}	The average of annual data covering the years 2014-2023
I_{43}	The average of annual data covering the years 2012-2021
I_{51}	The average of annual data covering the years 2014-2023
I_{52}	The average of annual data covering the years 2000-2024
I_{53}	The average of annual data covering the years 2000-2024

Since this research investigates the performance of 27 EU countries regarding the circular economy and is framed as a multi-criteria decision-making problem, the weights assigned to each indicator was determined by employing SITDE method, in the initial stage. The indicator values obtained for each EU countries are presented as the initial decision matrix in Appendix 1 using Equation (1).

By applying Equations (2) - (6) with consideration of the data in the initial decision matrix, the order of importance and weight values for each indicator were determined as presented in Figure 1.

On the other hand, utilizing the data presented in Appendix 1 alongside Equations (7) to (15) delineated in the TODIFFA method, the performance ranking of 27 EU countries concerning their circular economy has been established, with the findings detailed in Table 3.

Figure 1. The order of significance and weights of the 20 indicators

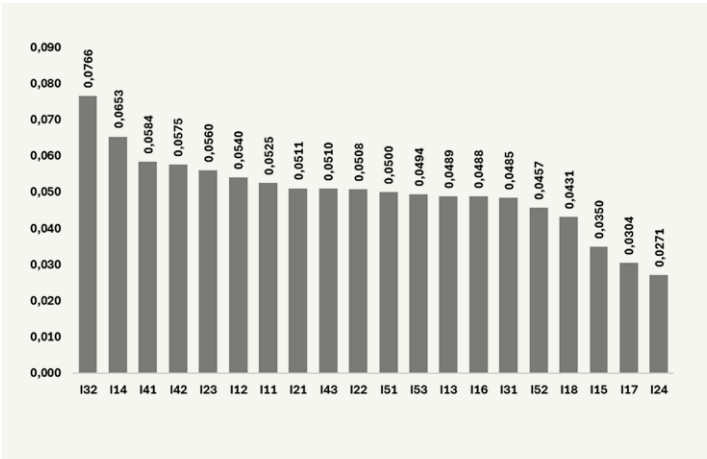


Table 7 Performance order of EU countries in terms of circular economy

Country	Rank	Country	Rank	Country	Rank
Germany	1	Romania	10	Croatia	19
France	2	Estonia	11	Belgium	20
Netherlands	3	Greece	12	Ireland	21
Cyprus	4	Slovakia	13	Luxembourg	22
Italy	5	Latvia	14	Czechia	23
Bulgaria	6	Hungary	15	Denmark	24
Malta	7	Poland	16	Slovenia	25
Spain	8	Finland	17	Austria	26
Lithuania	9	Portugal	18	Sweden	27

CONCLUSION

This study assessed the circular economy performance of the 27 Member States of the European Union by employing a structured multi-criteria decision-making framework grounded in Eurostat indicators. Utilizing twenty circular economy-related indicators sourced from the European Commission Eurostat database, the relative significance of each indicator was established through the SITDE method, while country rankings were produced via the TODIFFA approach. The integrated methodology facilitated both objective weighting and a comprehensive comparative evaluation of national performance levels, thereby enhancing the empirical literature on circular economy measurement at the macro level.

The results of the weighting analysis indicate that the dimensions of material trade and resource productivity are critical in influencing overall circular economy performance. Notably, "Trade in recyclable raw materials" emerged as the most significant indicator, followed by "Generation of waste excluding major mineral wastes per GDP unit," "Private investment and gross value added related to circular economy sectors," "Persons employed in circular economy sectors," and "Recycling rate of packaging waste by type of packaging." These findings imply that both market-based mechanisms, such as the trade in secondary raw materials and private investment, as well as efficiency-oriented indicators, such as waste intensity per GDP, are central determinants of the success of the circular transition within the European Union context.

According to the TODIFFA-based ranking results, the countries that exhibited superior performance were

Germany, France, and the Netherlands, followed by Cyprus, Italy, Bulgaria, Malta, Spain, Lithuania, and Romania. The prominence of leading industrial economies, such as Germany, France, and the Netherlands, suggests that robust institutional frameworks, advanced recycling infrastructures, and well-developed secondary materials markets significantly contribute to enhanced circular economy outcomes. Concurrently, the inclusion of smaller and cohesion countries within the top ten underscores the efficacy of targeted policy measures and EU-supported structural investments in promoting circular performance.

The findings emphasize the multidimensional character of circular economy development, indicating that the economic integration of secondary materials markets, investment intensity, and labor participation in circular sectors are essential determinants of national success. The proposed SITDE-TODIFFA framework offers policymakers a systematic evaluation tool for benchmarking performance, identifying structural strengths and weaknesses, and formulating evidence-based strategies in accordance with the European Union's circular economy agenda. Future research could enhance the analysis by integrating dynamic time-series data, conducting sensitivity analyses, and performing comparative assessments across various regional blocs to further substantiate the robustness and generalizability of the results.

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APPENDIX 1. INITIAL DECISION MATRIX

	<i>I</i> ₁₁	<i>I</i> ₁₂	<i>I</i> ₁₃	<i>I</i> ₁₄	<i>I</i> ₁₅	<i>I</i> ₁₆	<i>I</i> ₁₇	<i>I</i> ₁₈	<i>I</i> ₂₁	<i>I</i> ₂₂
Belgium	13,39	2,67	5.359,70	94,40	496,79	148,00	156,60	28,75	53,74	80,33
Bulgaria	16,96	0,32	20.954,80	453,80	517,13	106,00	57,36	15,61	23,87	21,60
Czechia	17,31	0,96	2.766,40	84,40	368,79	99,50	102,13	21,94	20,45	58,00
Denmark	23,21	1,99	3.224,60	37,30	772,17	241,50	166,59	34,15	44,59	59,67
Germany	14,98	2,41	4.638,60	51,30	612,67	130,75	206,55	33,52	63,46	54,00
Estonia	26,30	0,60	15.624,80	679,00	377,04	129,50	144,47	39,11	22,38	19,00
Ireland	18,21	2,09	4.081,20	35,10	658,58	150,00	213,85	53,86	31,85	40,00
Greece	14,44	1,27	4.959,00	98,50	477,83	195,25	85,90	22,06	15,51	27,00
Spain	11,25	2,08	2.873,70	64,40	526,46	67,00	164,76	33,57	32,71	46,17
France	14,22	2,68	5.013,80	46,60	533,46	134,50	193,15	32,39	35,33	51,17
Croatia	14,79	1,01	1.243,50	80,40	401,48	122,75	63,87	15,12	18,58	46,00
Italy	11,87	2,81	2.771,90	63,20	514,38	138,25	205,55	36,23	34,56	66,33
Cyprus	22,56	1,13	2.551,20	51,50	663,25	279,25	101,00	22,23	10,57	36,33
Latvia	14,67	0,93	997,10	81,10	368,57	131,50	123,82	20,06	17,44	60,00
Lithuania	18,30	0,79	2.103,10	133,90	426,13	138,33	112,55	23,76	23,15	59,60
Luxembourg	31,99	3,96	16.646,90	29,60	700,46	121,75	207,35	41,31	46,57	71,83
Hungary	12,45	0,88	1.950,00	118,70	419,92	89,50	116,27	29,28	21,50	42,83
Malta	11,84	2,04	5.248,40	56,50	626,75	151,50	133,83	27,43	10,33	29,00
Netherlands	9,11	3,95	7.116,50	64,50	553,04	138,50	176,10	29,73	50,70	71,00
Austria	23,84	2,12	6.789,50	60,00	619,83	132,75	148,23	30,98	60,03	63,17
Poland	15,96	0,65	4.312,80	177,60	314,33	123,00	126,72	22,86	19,13	56,83
Portugal	16,99	1,05	1.810,70	82,60	478,42	180,75	155,63	35,73	21,93	46,83
Romania	23,39	0,39	10.911,50	210,70	316,88	174,67	73,19	18,46	7,83	29,50
Slovenia	17,08	1,24	3.139,50	91,30	474,33	74,00	108,44	22,86	35,17	73,83

Slovakia	14,29	1,09	2.077,90	109,50	339,63	102,75	84,88	19,19	18,60	45,33
Finland	43,24	0,99	18.298,90	95,90	506,46	114,75	128,91	21,82	36,90	38,17
Sweden	24,75	1,97	13.439,00	55,22	449,33	121,75	132,81	23,16	44,48	50,80

	I_{23}	I_{24}	I_{31}	I_{32}	I_{41}	I_{42}	I_{43}	I_{51}	I_{52}	I_{53}
Belgium	78,54	74,67	18,85	1.575.196,90	6.676,30	63.275,30	15,13	108,20	8.267,82	71,31
Bulgaria	57,00	84,40	3,41	197.177,50	367,60	100.589,30	0,31	111,60	7.714,46	16,20
Czechia	68,05	89,31	9,15	64.825,10	1.543,70	136.306,60	6,06	104,20	9.626,06	28,80
Denmark	64,30	81,30	8,09	1.861.704,60	2.824,60	43.600,40	6,32	113,70	15.843,52	35,68
Germany	70,38	84,98	12,13	4.115.295,80	29.661,70	728.075,50	94,19	100,00	8.758,12	37,07
Estonia	57,36	83,69	15,50	32.103,30	203,10	28.761,70	0,53	109,40	12.666,84	22,33
Ireland	58,59	83,69	1,99	1.880.052,20	820,60	36.850,40	3,09	106,50	12.110,60	26,80
Greece	49,90	81,99	3,22	1.182.432,70	352,90	80.582,70	0,84	95,90	8.566,02	28,92
Spain	60,20	78,90	8,89	5.601.206,80	5.661,50	423.967,40	20,36	104,80	5.609,79	35,72
France	58,90	79,05	17,58	3.920.666,90	21.003,20	527.273,70	46,70	105,50	5.467,13	33,93
Croatia	54,73	93,04	4,75	522.807,30	311,00	65.886,40	0,23	110,40	4.985,00	29,63
Italy	61,86	85,08	17,26	3.725.014,20	8.863,10	522.178,50	33,87	100,80	5.822,51	42,57
Cyprus	49,92	85,92	3,50	155.434,00	75,60	11.899,60	0,23	107,50	8.257,97	28,82
Latvia	52,89	83,45	4,59	332.254,00	214,60	36.046,40	1,47	99,60	5.245,07	29,31
Lithuania	55,29	81,46	3,99	319.571,20	367,80	58.337,90	0,47	104,70	6.816,56	38,13
Luxembourg	64,35	87,77	12,37	22.815,30	773,10	10.268,90	3,46	122,70	14.243,39	88,92
Hungary	48,61	82,66	5,88	231.657,50	944,90	114.245,10	1,91	105,60	5.675,19	26,36
Malta	32,43	77,01	10,37	2.690,70	66,00	8.058,40	0,24	131,70	6.638,55	60,96
Netherlands	69,86	77,04	27,87	6.703.566,20	9.128,30	108.471,30	23,72	108,60	10.712,60	75,71
Austria	66,23	81,53	10,88	340.302,90	5.454,30	65.538,30	14,43	104,30	6.795,05	40,55
Poland	47,58	82,28	9,73	3.513.370,80	3.482,60	409.638,30	34,55	114,60	9.172,07	16,94
Portugal	53,73	78,01	2,42	893.365,10	1.719,40	119.649,50	2,29	109,70	5.938,15	27,44
Romania	44,93	78,79	1,91	712.647,90	1.072,10	205.530,40	7,65	106,50	5.261,89	10,37
Slovenia	60,03	83,94	9,01	1.211.094,40	130,20	24.759,00	0,78	99,80	6.433,47	40,49
Slovakia	58,79	90,39	7,07	60.335,50	508,80	65.396,40	1,46	108,80	6.744,28	42,15
Finland	56,05	89,28	6,09	302.918,60	876,40	42.600,60	21,69	99,90	9.837,45	23,30
Sweden	63,62	81,86	7,93	1.263.378,80	2.204,80	80.142,10	9,48	100,40	4.787,58	26,38

Mapping Industrial Symbiosis for Circular Economy Transition: Comparative Insights Across Countries

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ABSTRACT

Industrial symbiosis, which allows industries to exchange materials, energy and by-products for mutual benefit, is a powerful driver of circular practices. Based on the principles of ecological mutualism and the circulation of nutrients within ecosystems, industrial symbiosis involves intensive cooperation between interested actors within a relatively limited geographical area. This study aims to map the development of Industrial Symbiosis across 23 countries, including 10 EU member states, 5 Western Balkan countries, 4 from Eastern Europe and the Caucasus region, 2 from the Levant, and 1 from North America, and to examine how cross-sectoral cooperation contributes to sustainable growth, resource efficiency and eco-innovation. For the purposes of the research, a multi-criteria analysis was applied to rank countries according to the degree of development of their industrial symbiosis practices using indicators such as recycling rates of municipal waste, recycling rates of all waste excluding major mineral wastes, circular material use rate, contribution of recycled materials to raw material demand (EOL-RIR), trade in recyclable raw materials, resource producti-

vity, and packaging and plastic waste generation per capita.

The ranking identified leading countries and critical factors enabling successful cross-industry cooperation, including high recycling rates, efficient material loops, integration of recycled materials into raw material supply, and reduction of packaging and plastic waste. The analysis reveals significant differences in adoption levels and highlights the elements that drive resource efficiency, waste reduction and the creation of new value chains. These findings provide practical insights for policymakers, business managers and decision-makers who want to strengthen cross-sectoral cooperation, promote eco-innovation and accelerate the transition to circular economy models. Integrating multi-criteria assessment with industrial symbiosis mapping, this research offers a comprehensive understanding of the operational and strategic factors that drive sustainability and competitiveness across countries, providing a basis for tailored policies and cooperation strategies to advance the green transition

KEYWORDS

Industrial Symbiosis • Circular Economy • Cross-Sectoral Cooperation • Resource Efficiency • Multi-Criteria Analysis

INTRODUCTION

Industrialization is a key driver of long-term economic growth (Haraguchi et al., 2019), but it is essential to identify approaches that allow for the mitigation of its negative effects on the environment without threatening economic growth. Industrial Symbiosis is recognized as a key mechanism for reducing emissions and more efficient use of resources, while maintaining economic growth (Fan et al., 2017). This importance has also been recognized by the European Commission, which has highlighted the role of Industrial Symbiosis in several directives and official documents (European Commission, 2018).

The concept of Industrial Symbiosis, borrowed from biology, refers to cooperation between different industries through the exchange of materials, energy, and resources for mutual benefit (Schwarz & Steininger, 1997). Today, it is also recognized as a business opportunity and an instrument of eco-innovation (Neves et al., 2020). The goal of Industrial Symbiosis is to increase production without additional consumption of resources, by using waste or by-products of other companies, thus closing the material cycle and striving for zero waste (Mantese & Amaral, 2017). Therefore, Industrial Symbiosis is the cooperation of multiple industries for the purpose of resource exchange, whereby waste or unused materials from one company are used as a resource in another, thereby achieving their reuse and waste reduction (Holck, 2018; Mantese & Amaral, 2017).

Although a large number of studies have been published in the literature on the tools and technical

aspects of Industrial Symbiosis, most of the research has focused on methodological approaches without including comparisons between countries. What is missing is a quantitative assessment of the degree of development of Industrial Symbiosis across countries, as well as an analysis of indicators that reflect the real application of this concept within the framework of a circular economy. Accordingly, this paper seeks to contribute to the existing literature by analyzing relevant research questions in the field of Industrial Symbiosis:

RQ1: Which countries show the highest level of development of Industrial Symbiosis based on the analyzed indicators?

RQ2: How do quantitative circular economy indicators explain variations in Industrial Symbiosis development across countries?

Hence, this paper aims to rank 23 European countries according to the level of development of Industrial Symbiosis as one of the key operational aspects of the circular economy, using the PROMETHEE method, based on quantitative indicators related to material flows, recycling, and the use of secondary raw materials.

The remainder of the paper is organized as follows: Section 2 provides a review of the relevant literature. Section 3 describes the data collected and the methodology applied. Section 4 encompasses the discussion of key findings along with the concluding remarks.

THEORETICAL BACKGROUND

Industrial Symbiosis is an effective approach to sustainable development that enables resource conservation, economic gain and compliance with environmental standards by reducing greenhouse gas emissions, exploiting limited natural resources and reducing waste. Its application has spread worldwide, bringing significant economic, environmental and social benefits (Neves et al., 2020).

Although Industrial Symbiosis has long been studied within industrial ecology, it has recently received increasing attention as a means of advancing the circular economy through more efficient resource use (Lazarević & Valve, 2017). It is based on the collaboration of multiple firms that, rather than acting in isolation, exchange resources and knowledge to achieve mutual benefits, with geographical proximity and innovation playing an important role (Martin & Harris, 2018).

Industrial Symbiosis is increasingly being implemented around the world, both in developed countries such as the United Kingdom, the United States and Japan, and in developing countries such as Thailand, Morocco and Algeria, encompassing different sizes and types of collaboration from simple local partnerships, such as those in Sweden, to complex industrial networks as is the case in China (Neves et al., 2020). In practice, Industrial Symbiosis networks in Sweden have led to the creation of new jobs and the reduction of CO₂ emissions (Martin & Harris, 2018), in Denmark the replacement of groundwater with surface water has resulted in large savings in the use of natural resources (Jacobsen, 2006), while in China, urban Industrial Symbiosis has enabled the reduction of the urban carbon footprint by over a million tons of CO₂ per year (Fang et al., 2017).

These examples confirm that Industrial Symbiosis can be applied in different contexts and brings measurable benefits, highlighting the need for its broader adoption as a model for regional sustainable development. In order to systematically monitor and compare these benefits, it is necessary to rely on validated indicators that allow for a quantitative assessment of progress towards a circular economy.

The promotion and acceptance of Industrial Symbiosis as an approach to regional sustainable development requires awareness among companies and governments of the potential benefits that this model brings. In order to reliably monitor progress towards a circular economy, it is necessary to rely on a set of validated indicators that measure different aspects of resource and waste management efficiency. One of the most commonly used indicators is the recycling rate of municipal waste, which is a basic indicator for assessing the engagement of local communities in the implementation of circular practices (Kirchherr et al., 2017). In this regard, Germany stands out as one of the leading countries, with a developed waste management infrastructure and systematic monitoring of recycling rates within the framework of a national resource efficiency program (Koller et al., 2022). Additional insight is provided by the recycling rate of all waste types except large mineral waste, which allows for a more precise analysis of industrial and municipal waste, excluding construction and demolition waste, which often dominates the total mass (Ghisellini et al., 2016). This indicator is increasingly used in Sweden, especially in the analysis of plastic waste generation per capita and as part of the Plastic Waste Strategy, which monitors and reduces packaging waste (European Environment Agency, 2023).

For a systemic insight into the degree of circularity, the circular material use rate (CMU) is used, which measures the share of recycled materials in total raw material consumption and provides a broader framework for assessing the efficiency of the system (Lazarevic & Valve, 2017). This indicator is used intensively in the Netherlands, where the CMU has reached around 30%, which

is well above the European Union average, indicating a high degree of integration of circular practices into the economic system (Rybárová, 2024).

Similarly, the contribution of recycled materials to meeting the demand for raw materials reflects efforts to reduce dependence on primary sources and supports sustainable supply chains (Haas et al., 2015). This indicator is of particular importance in Germany, where it is used to plan the transition to green industry and digital supply chains within the framework of a circular economy.

Trade in secondary raw materials is becoming important in the analysis of international waste and material flows, but at the same time it raises dilemmas regarding quality control and regulation (Velenturf & Purnell, 2021). In this context, Romania and Bulgaria mainly rely on indicators provided by the European Union monitoring mechanisms, as domestic statistical and institutional capacities are not yet fully developed to apply these indicators in national policies.

At the macroeconomic level, resource productivity is one of the central indicators of sustainable production, as it shows how much economic value is generated per unit of resource consumed (European Commission, 2015). Germany and the Netherlands are leading the way in this area thanks to strong energy efficiency policies and the linking of industry and innovation.

From a waste infrastructure perspective, indicators such as the generation of packaging waste per capita and the amount of plastic packaging waste point to challenges in terms of waste prevention and low efficiency of waste management systems, especially in the context of plastics, which represent one of the biggest environmental problems (European Environment Agency, 2023; Stuchtey et al., 2016). Sweden is actively using these indicators to monitor the results of its ambitious packaging and plastics management strategy, while Bulgaria and Romania are in the process of gradually integrating these indicators into their national waste management strategies.

METHODOLOGY

In this research, a multi-criteria analysis was applied using the PROMETHEE method to rank countries according to the degree of development of Industrial Symbiosis as a narrow area of the circular economy. Eight quantitative criteria related to material flows and recycling, which represent key indicators of Industrial Symbiosis operability, were selected for evaluation purposes. The analysis covered 23 countries, including

10 EU Member States, 5 Western Balkan countries, 4 from Eastern Europe and the Caucasus region, 2 from the Levant, and 1 from North America. The data were obtained through a questionnaire developed on the basis of important indicators from relevant European databases (Eurostat, 2024).

The research was conducted during the year 2023, as part of a broader analysis of the efficiency of circular

economy implementation, with a focus on operational indicators of Industrial symbiosis. The questionnaire was created to include quantitative data on key aspects of material flows, recycling and use of secondary raw materials, as well as other indicators that are recognized as important for assessing the degree of development of industrial symbiosis. After validation, the questionnaire was distributed electronically, using a network of researchers and collaborators involved in COST actions dealing with circular economy topics. In total, 81 validly completed questionnaires from 23 different participating countries were collected, thus

PROMETHEE - GAIA method

The PROMETHEE method was initially developed by Brans and later expanded and refined by Brans and Vincke (1985). This method falls into the category of “outranking” methods, which allow comparing multiple alternatives based on given criteria in order to determine which one has an advantage or superiority. PROMETHEE is closely related to the GAIA method, which is a graphical representation of multi-criteria problems and helps in their better understanding and making optimal decisions. In order to perform the ranking of alternatives according to the selected criteria, it is necessary to set specific parameters. As Brans and Vincke (1985) point out, these parameters include direction of preference, weighting coefficients, preferen-

Data processing and interpretation of results

To implement a multi-criteria analysis, it is necessary to set the appropriate parameters for each indicator in

providing a representative basis for conducting multi-criteria analysis. The collected data were then prepared, standardized and analyzed using the PROMETHEE method, with the aim of ranking countries according to the degree of development of industrial symbiosis. The PROMETHEE method enabled the formation of a ranking list based on the preferential structure of criteria and evaluation of each country in relation to the defined indicators.

ce threshold, indifference threshold, and preference function. The PROMETHEE method is implemented in several phases, as described by Brans and Mareschal (2005):

Phase 1: Formation of a decision matrix, in which alternatives are compared according to defined criteria.

Phase 2: Selection and assignment of an appropriate preference function for each criterion individually.

Phase 3: Calculation of the preference index $\pi(a, b)$, taking into account the relative importance of the criteria (weights).

Phase 4: Determination of positive and negative preference flows for all alternatives, which allows their ranking according to overall dominance.

the Visual PROMETHEE software. The values and settings of these parameters are shown in detail in Table

Table 1. Indicators for ranking countries according to the degree of development of Industrial Symbiosis

Indicator	Max/min	Weight	Preference function	Limitation
Recycling rate of municipal waste (cei_wm011)	Max	1.00	Usual	Percentage
Recycling rate of all waste excluding major mineral wastes (cei_wm010)	Max	1.00	Usual	Percentage
Circular material use rate (cei_srm030)	Max	1.00	Usual	Percentage
Contribution of recycled materials to raw material demand (EOL-RIR) (cei_srm010)	Max	1.00	Usual	Percentage
Trade in recyclable raw materials (cei_srm020)	Max	1.00	Usual	Percentage
Resource productivity (cei_pc030)	Max	1.00	Usual	Percentage
Packaging waste generation per capita (cei_pc040)	Min	1.00	Usual	Percentage
Plastic packaging waste generation per capita (cei_pc050)	Min	1.00	Usual	Percentage

Table 2 shows the indicators used as criteria for ranking countries according to the degree of development of Industrial Symbiosis. The selected indicators reflect

different aspects of the circular economy and resource management. All indicators are expressed in percentage values. The values of most indicators are maximized

(higher values indicate a higher level of development of Industrial Symbiosis), while the last two indicators, such as the generation of packaging and plastic packaging waste, are minimized, which means that lower values are considered more favorable. All indicators had equal weight, which indicates that they equally influenced the countries' final scores. As a preference function, a regular function (usual) was used without defined thresholds, which means that differences in indicator values directly influenced the evaluation without additional interpretation of the intensity of the

difference. This table provides a starting point for a multi-criteria analysis to determine the relative position of countries in the domain of industrial symbiosis, taking into account a comprehensive set of key indicators of the circular economy.

After determining the parameters of the multi-criteria analysis, the countries were ranked according to the degree of development of industrial symbiosis. Table 2 gives the values of the net flow of preferences (Φ), as well as the positive (Φ^+) and negative flow of preferences (Φ^-), and Figure 1 illustrates them.

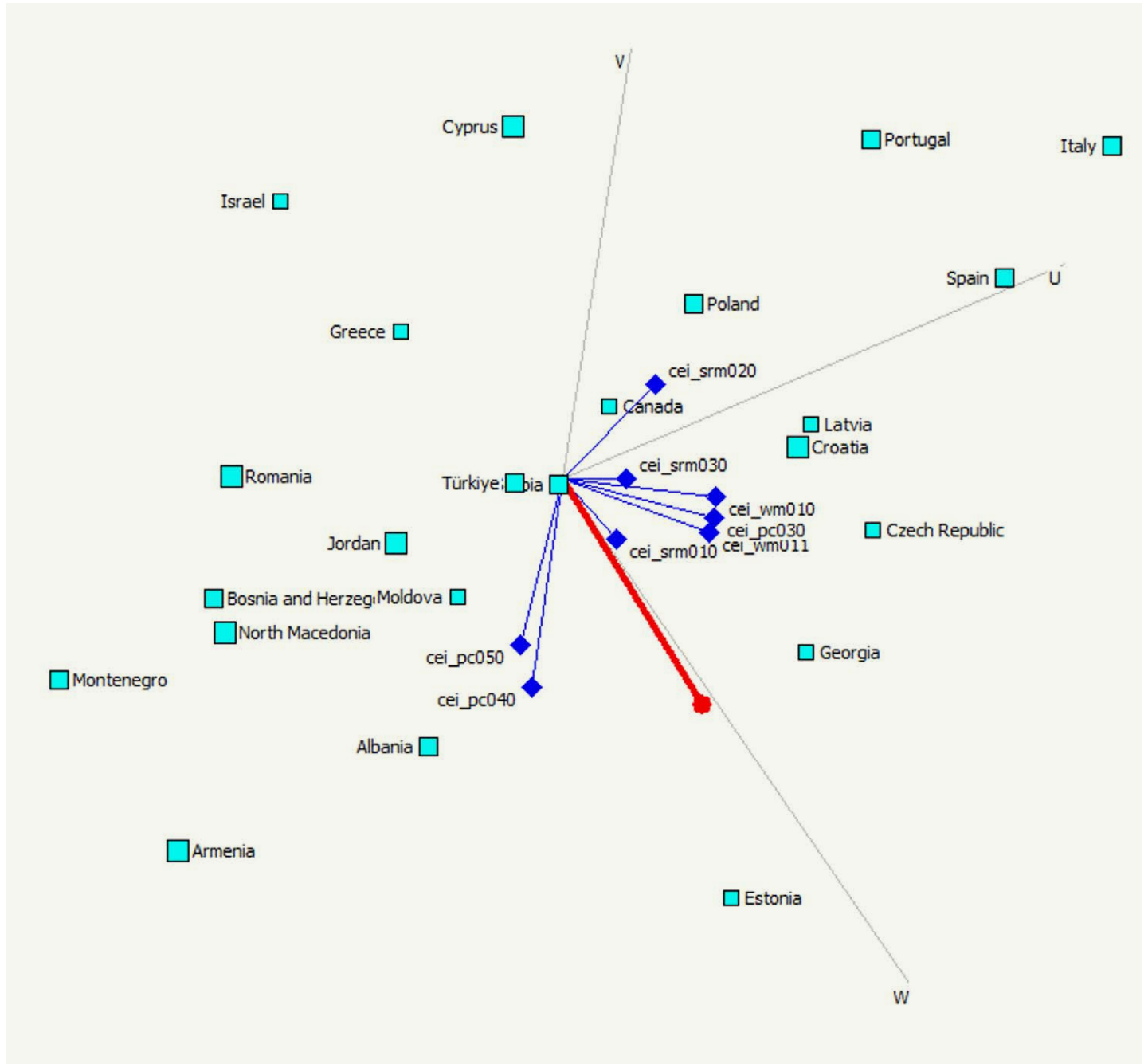
Table 2. Results of the ranking of the countries according to the degree of development of Industrial Symbiosis

Rank	Alternative	Phi	Phi ⁺	Phi ⁻
1	Estonia	0.4659	0.6193	0.1534
2	Georgia	0.3068	0.5398	0.2330
3	Czech Republic	0.2955	0.6080	0.3125
4	Spain	0.2784	0.5625	0.2841
5	Italy	0.2102	0.5227	0.3125
6	Latvia	0.1648	0.5170	0.3523
7	Albania	0.1477	0.5739	0.4261
8	Croatia	0.1193	0.4375	0.3182
9	Poland	0.0966	0.4890	0.3923
10	Serbia	0.0625	0.5170	0.4545
11	Portugal	-0.0057	0.4489	0.4546
12	Canada	-0.0057	0.3636	0.3693
13	Türkiye	-0.0114	0.4943	0.5057
14	Jordan	-0.0284	0.3409	0.3693
15	Moldova	-0.0398	0.4205	0.4602
16	Armenia	-0.1023	0.3068	0.4091
17	Romania	-0.1193	0.3011	0.4205
18	Cyprus	-0.1989	0.2784	0.4773
19	North Macedonia	-0.2330	0.2102	0.4432
20	Bosnia and Herzegovina	-0.2614	0.2102	0.4716
21	Montenegro	-0.3125	0.1932	0.5057
22	Greece	-0.3636	0.1932	0.5568
23	Israel	-0.4773	0.1080	0.5852

The results of the ranking of countries according to the degree of development of Industrial Symbiosis show that Estonia took first place, thanks to the highest value of net preferences. In contrast, Israel is in last place and

represents the worst-rated country in this context. Figure 1 provides a graphical representation of the obtained results in the form of a GAIA plane.

Figure 2 Figure 1. GAIA analysis



The positions of the criteria in the GAIA plane, represented in the form of diamonds, provide insight into the degree of harmony or opposition between them. Based on the orientation of the criteria vectors shown in Figure 1, it can be concluded that there were no significant conflicts, since most of the criteria move in similar or complementary directions.

The criteria with the most similar assessments were the Recycling rate of all waste excluding major mineral wastes (cei_wm010) and the Circular material use rate (cei_srm030) because in almost all countries, they have very close values of preferential flows, which indicates

a high degree of agreement in their evaluation when ranking countries by the development of industrial symbiosis.

The positions of the alternatives, shown in a plane by a square, determine the strength or weakness of the alternative concerning the criteria. According to the criteria cei_wmd30, cei_ure30, and cei_pdt30, Estonia is the best-ranked country, so the decision stick is in the direction of this alternative's position. On the other hand, Israel, Greece, and Montenegro are ranked as the worst, indicating their poor compliance with the dominant criteria.

CONCLUSIONS

This study seeks to rank 23 European nations based on the extent of industrial symbiosis development, which is a crucial operational factor in the circular economy. Using the PROMETHEE method and relying on quantitative indicators, a thorough understanding of the present condition and relative standing of the examined countries was achieved. This approach allowed for the transparent and objective identification of countries that are at the forefront in the application of the principles of industrial symbiosis, as well as those that are lagging behind in the development of circular practices. The results obtained provide the basis for a critical discussion on the differences in the level of development and potential directions for improving resource management policies in the European context.

The use of a comprehensive set of percentage-based indicators, equally weighted and selected to reflect the different dimensions of the circular economy and waste management, ensured a balanced and holistic assessment. These results underscore notable disparities among nations in their advancement towards industrial symbiosis. Although countries like Estonia, Georgia, and the Czech Republic have demonstrated impressive outcomes, others like Israel, Greece, and Montenegro exhibit considerably lower results, highli-

ghting the necessity for additional measures to enhance resource management and decrease waste.

The theoretical contribution of this study is evident in the enhancement of the current scientific body focused on circular economy evaluation by incorporating multi-criteria approaches into the examination of industrial symbiosis globally. The results expand the understanding of the factors influencing the successful implementation of circular practices and enable comparative analysis based on objective criteria.

The practical contribution is that the results obtained can serve as a useful starting point for policymakers, decision-makers and business entities. By identifying weak points and areas for improvement in individual countries, the research provides guidelines for creating targeted strategies for improving resource management and developing the circular economy.

Future research will aim to deepen the analysis of the causal factors behind the observed differences in the development of industrial symbiosis and develop tailored policies that could encourage progress in countries with lower results. Such research can significantly contribute to a more efficient transition to a circular economy in the European and wider context.

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Bridging the Education Gap in Industrial Symbiosis for North Macedonia's Alignment With the EU Green Agenda

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ABSTRACT

Accession to the European Union is a core strategic objective for North Macedonia. This commitment requires the country to align its industrial policies with the EU Green Agenda. Industrial symbiosis (IS) offers a practical pathway to achieve these goals while simultaneously fostering long-term sustainable development. However, while national strategies emphasize the importance of circularity and IS, a significant “education gap” persists between high-level policy goals and operational implementation within the industrial sector. This paper examines the extent to which concepts related to circular economy (CE) and IS are reflected in the formal education system in North Macedonia, with a focus on primary, secondary, and tertiary education. Using qualitative document analysis, the study reviews official curricula and study programmes in order to identify the availability, accessibility, and relevance of CE- and IS-related content. The findings show that CE is already present across all educational

levels, although unevenly and with varying depth, most commonly through themes such as environmental protection, natural resources, energy efficiency, recycling, waste management, and sustainable development. By contrast, IS remains weakly represented and is mostly addressed only indirectly. The strongest entry points for CE were identified in vocational and higher education, particularly in chemistry and technology, agriculture, and economics-related programs. The paper concludes that North Macedonia already has a meaningful educational basis for expanding CE, but that a significant educational gap persists in relation to IS. To address this gap, the study recommends more explicit curricular integration of IS, stronger alignment with sectoral and industrial realities, and the development of accessible educational tools, including Macedonian-language training resources and digital learning formats.

KEYWORDS

Industrial Symbiosis • Knowledge Transfer • Education Gap • Circular Economy • North Macedonia

INTRODUCTION

Industrial symbiosis (IS) describes a collaborative arrangement in which traditionally separate industries exchange materials, energy, water, and by-products in ways that generate competitive advantage and reduce environmental impact (Chertow, 2000). More recent systematic reviews have confirmed that IS operates effectively across micro, meso, and macro levels simultaneously,

implicating consumers, enterprises, supply chains, and governments in shared systems of environmental and economic responsibility (Palagonia et al., 2025). The European Union (EU) has positioned the circular economy at the heart of its industrial and climate strategy, most notably through the European Green Deal and the Circular Economy Action Plan (CEAP),

which together set out a comprehensive roadmap for decoupling economic growth from resource consumption (European Commission, 2020). The CEAP explicitly identifies education and training systems as key instruments for accelerating this transition, recognizing that workforce transformation is as important as regulatory reform in enabling circular industrial models. IS serves as a critical mechanism for resource efficiency and waste valorization, yet its implementation remains uneven across emerging economies, where constraints in governance, infrastructure, and institutional capacity significantly limit systemic IS adoption (Boom-Cárcamo & Peñabaena-Niebles, 2022; Munonye et al., 2025).

For EU candidate countries, alignment with these frameworks carries additional political weight. The EU's Growth Plan for the Western Balkans (European Commission, 2023) links accession progress directly to implementation of the green and digital agendas, creating a dual pressure on candidate countries to transpose EU environmental legislation rapidly while simultaneously building the human and institutional capacities. This disparity is particularly pronounced in North Macedonia. The European Commission's 2024 Progress Report on North Macedonia confirms that

while the country has engaged actively with its Reform Agenda, progress on the green transition remains at an early stage, with significant capacity gaps in both the public administration and the private sector (European Commission, 2024). In 2024, the OECD published a dedicated Circular Economy Roadmap for North Macedonia, which proposes over 40 policy recommendations across five priority sectors, including construction, textiles, and mining/metallurgy. The Roadmap identifies low business awareness, weak academia-industry collaboration, and limited investment in research and development (at just 0.4% of GDP) as critical structural barriers to circular transition (OECD, 2024).

To achieve smooth transition towards circularity, a strong educational and training background is a prerequisite. The main objective of the study is to identify the educational offerings for IS and circular economy (CE) in the educational system in North Macedonia at primary, secondary and tertiary level. This study contributes to the existing literature by providing the first ever empirically grounded analysis of IS and CE education gaps in the country.

LITERATURE REVIEW

The relationship between education and CE transition has attracted growing scholarly attention. Yuana et al. (2024) argue that mainstreaming CE education through schools requires active institutional agency, including curriculum revision, investment in teacher preparation, pedagogical tools, and school-industry linkages. Kosta et al. (2025) find that primary teachers frequently lack a sufficiently robust knowledge base to convey the complexity of circular economy concepts, which can hinder the development of positive environmental attitudes among students. Marcon et al. (2025) confirm the results across multiple countries, noting that teachers face the challenging task of supporting students in problem-solving, fostering critical thinking, and promoting sustainable lifestyles.

IS and CE are particularly relevant for the Vocational Education and Training (VET) system. It is crucial to include the circular economy in VET curricula, lifelong learning systems, and workplace training (Circularity Gap Report 2024). However, one recent study finds that existing VET programs predominantly address technical competencies, such as product design, circular manufacturing processes and neglect the soft skills and digital capabilities essential for managing IS networks (Trevisan et al., 2025).

At the tertiary level, research on CE education has demonstrated steady growth in the past years. Serrano-Bedia and Pérez-Pérez (2022) identify universities/faculties as pivotal enablers of circular transformation. Akyazi et al. (2023) find that workforce upskilling and reskilling in IS and energy efficiency remains the central human capital challenge, and proposing the ESCO classification as a common skills reference framework to reduce complexity and align training programs across institutions and sectors. Kruja et al. (2025), studying CE education in Albanian higher education institutions find uneven incorporation of CE concepts across disciplines and limited institutional support, but also identify emerging innovations in interdisciplinary approaches and student-led sustainability projects.

Informal and non-formal learning remains one of the most overlooked aspects of IS education. In many SMEs, sustainability knowledge and circular practices develop organically through peer exchange, supply-chain interactions, and community networks rather than through formal training programs. Munonye et al. (2025) argue that IS adoption in SMEs is hindered by information gaps and coordination difficulties, and that community-level awareness and peer learning mechanisms often build the trust and social infrastructure needed for IS more effectively than top-down training.

In addition, digital platforms are becoming increasingly recognized as a powerful infrastructure for informal IS learning. Fric and Rončević (2018) demonstrate through the Slovenian e-Simbioza platform that online tools and short educational modules can substantially

accelerate IS awareness and network formation. The Circularity Gap Report (2024) similarly advocates for digital tools that facilitate knowledge transfer and skills development outside formal institutional settings.

METHODOLOGY

We apply qualitative document analysis to assess the extent to which the educational institutions at primary, secondary and tertiary level incorporate themes related to the CE and IS in their study programs. The analysis covered all official course syllabi for primary and secondary education. For tertiary education, we could not retrieve all course syllabi, so the analysis is conducted on the level of a study program and existence of possible IS/CE courses within the study programs. Where course syllabi were available, we followed the following three-stage analytical procedure. First, all curricula were screened for explicit references to the terms CE and IS. No direct mention of either concept was identified in the reviewed programs. Given this absence, the analysis proceeded to a second stage focused on conceptually related content. In the second stage, the curricula were examined for topics, learning outcomes, thematic units, and competencies that could be associated with the underlying logic of CE and IS. For CE, the analytical focus included themes such as recycling, reuse, waste separation, repair, responsible consumption, efficient use of natural

resources, renewable energy, environmental protection, and sustainable development. For IS, attention was given to content related to production systems, industrial activity, resource efficiency, technological innovation, interdependence between economic activities, and the circulation or exchange of materials and energy within broader systems of production and use. In the third stage, each curriculum was assigned a level of relevance according to the strength and directness of its connection to CE and IS based on interpretive classification based on the substantive presence of related concepts. A curriculum was classified as having high relevance when it contained themes closely aligned with core CE principles. Medium relevance was assigned where the curriculum addressed broader issues of environmental sustainability, energy use, or ecological responsibility that provide a conceptual foundation for CE or IS, but without directly addressing circular practices or industrial interconnections. Low relevance was assigned where the link was only indirect.

RESULTS

Primary education

Primary education in North Macedonia is compulsory and lasts nine years. The curriculum analysis indicates that CE is most strongly represented in History and Society (Grade IV) and Environmental Education (Grades VII–IX), where students are introduced to concepts such as natural resources, pollution, recycling, reuse, waste processing, sustainability, and responses to environmental problems. High relevance was also identified in Natural Sciences (Grade IV) and Biology (Grade VII) through topics such as renewable energy, protection of

natural resources, circulation of matter and energy, and sustainable development.

Several other subjects show moderate relevance to CE, including Natural Sciences (Grade VI), Life Skills (Grades VII–IX), and Physics (Grade IX). These curricula cover themes such as sustainable consumption, repair, reduction of unnecessary use of goods, renewable energy, and environmental costs. By contrast, IS is only marginally present in primary education, as none of the analyzed programs explicitly addresses resource exchange, use of waste and by-products, or cooperation between firms.

Secondary education

Secondary education includes general secondary education (gymnasium) and vocational education and training (VET), both of which are compulsory. The results show a clear difference between the two tracks: while gymnasium curricula provide a general conceptual basis for CE, VET programs are more directly connect-

ed to resource-intensive sectors and therefore offer stronger entry points for both CE and, indirectly, IS. In gymnasium education, CE is most clearly reflected in Geography (Grades I and II), Physics (Grade IV elective), Chemistry (Grade I), and Biology (Grades I and IV). Subjects such as Physics (Grade I), Chemistry (Grades

II and III), Biology (Grades II and III), and Sociology (Grade IV elective) show moderate relevance, mainly by providing broader conceptual foundations. IS, however, remains weak and indirect, appearing primarily through references to industry, trade, raw materials, and economic organization rather than through explicit treatment of industrial resource exchange.

In VET education, the strongest findings relate to the analyzed four-year profiles in geology, mining and metallurgy; Civil engineering and geodesy; Economics, law and trade; Agriculture, fisheries and veterinary medicine; and Chemistry and Technology. In Geology, mining and metallurgy, CE is most clearly represented in Protection of the Living and Working Environment and Business and Entrepreneurship, while Management in Geology, Mining and Metallurgy and Modern Technologies of the Economic Sectors in the Labour Market provide additional indirect links, especially to IS through resource management, sectoral linkages, and cross-sector coordination.

In Civil engineering and geodesy, the strongest CE-related subjects are Energy Efficiency and Fire Protection and Management, Standardisation and Planning in Architecture, with additional indirect relevance found in Urbanism and Business and Entrepreneurship. Here, CE is mainly linked to energy efficiency, climate change, construction planning, optimisation of processes, and sustainable spatial development, while IS is inferred through industrial buildings, infrastructure, and construction-chain coordination.

In the Economics, law and trade profile, the most relevant subjects are Economic Geography and Entrepreneurship and Business, both of which provide strong and explicit foundations for CE through natural resources, environment and sustainable development, green business models, green financing, innovation, and efficient resource use. Internal Trade and Foreign Trade also show moderate relevance. IS is again present only indirectly, mainly through trade relations, partnerships, and business coordination.

In the Agriculture, fisheries and veterinary medicine educational profile, CE is most clearly reflected in Environmental Protection and Technologies in Plant Production. Additional support is provided by Agrometeorology with Climatology, Economics in Agriculture, and Agromanagement. IS is less visible and appears mainly through sectoral interconnectedness, coordination, and the broader economic organisation of agricultural production.

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The Chemistry and Technology profile proved to be the most highly relevant of all analysed VET fields. The strongest CE-related subjects include Raw Materials, Products and Packaging, Protection of the Working and Living Environment, Pollution and Protection of Water, Soil and Air, Sustainable Development, Renewable Energy Sources, Alternative Energy Sources, Waste Management, and Ecology and Environmental Protection. These subjects directly address packaging, material flows, resource conservation, pollution prevention, energy transition, and waste, making them especially relevant to CE. Although IS is still not explicitly covered, this profile offers the strongest indirect basis for it, particularly through waste management, raw materials, environmental protection, and industrial process-related topics.

Tertiary education

At the tertiary level, the analysis covered four universities: Ss. Cyril and Methodius University in Skopje, St. Kliment Ohridski University – Bitola, Goce Delčev University – Štip, and the University American College Skopje. Among them, Ss. Cyril and Methodius University in Skopje stands out as the leading institution, with CE- and IS-related curricula identified across eight faculties and several programmes explicitly focused on energy, ecology, environmental protection, agroecology, and ecoengineering. The university and its faculties have also participated in 15 relevant projects, including 3 as coordinator and 12 as partner.

At St. Kliment Ohridski University – Bitola, three faculties were identified as covering CE- and/or IS-related topics. At Goce Delčev University – Štip, the programme in Environmental Engineering covers a broad range of environmental fields, including waste management, recycling technologies, energy efficiency, environmental legislation, and pollution control. At the University American College Skopje, the programme in Business Administration, Management and Innovation includes the courses Green Society and Sustainability and Circular Economy, which are directly relevant to the focus of this study.

CONCLUSIONS AND RECOMMENDATIONS

The findings show that the educational system in North Macedonia already contains a meaningful basis for the integration of CE concepts, while IS remains considerably less visible and insufficiently developed. Across all analysed levels of education, CE is more strongly represented than IS. CE-related content appears through themes such as environmental protection, natural resources, energy efficiency, renewable energy, waste management, recycling, and sustainable development, whereas IS is usually present only indirectly, mainly through references to industry, production, trade, logistics, resource management, and sectoral linkages. This distinction is important because it suggests that the transition towards circularity in education has already begun, but it is uneven and still incomplete. The results indicate that CE is not absent from the curricula; rather, it is already incorporated in a fragmented but identifiable way. This is a positive finding, since it means that future reform does not need to start from zero. Existing curricular content in primary, secondary, vocational, and higher education can serve as a foundation for a more systematic and coherent integration of CE principles.

At the same time, the results clearly show that IS remains underrepresented. While some curricula, especially in VET, include themes that may serve as indirect entry points, these do not amount to a clear or explicit treatment of IS. Key IS dimensions, including by-product exchange, industrial networks, inter-firm cooperation, and waste-to-resource linkages, are largely absent. This suggests that learners may acquire partial knowledge of production and environmental management without being introduced to the systemic logic of industrial collaboration that is central to IS.

The gap is particularly relevant in vocational and higher education, where the connection between education and the labour market is strongest. Strengthening such content would make the education system more responsive to the practical demands of green and circular transition.

Limitations of the study

This study has several limitations. First, it analyzed only a subset of VET profiles, rather than the full range of vocational education and training programs available in the country. In addition, the analysis was limited to four-year VET programs, while two-year and three-year VET curricula were not included. Second, the study did not cover all higher education institutions in North Macedonia. Third, at the tertiary level, detailed syllabi and course-level teaching materials were not consistently available. This made it impossible to apply the same methodological approach used for primary and secondary education curricula in a fully consistent manner at the university level.

Recommendations for future research

Future research should broaden the scope of analysis in several directions. First, it would be useful to assess the presence of CE and IS concepts in non-formal and informal education, including training programs, short courses, awareness-raising initiatives, and other educational materials beyond the formal system. Second, further studies should include the remaining VET providers and higher education institutions in North Macedonia in order to provide a more comprehensive national picture.

Policy recommendations

Existing curricula should be reviewed and revised in order to strengthen the presence of CE-related content and to introduce IS more explicitly into teaching plans and subject programmes. Particular attention should be given to subjects and profiles already linked to production, industry, logistics, resource management, agriculture, and environmental protection, as these provide the most suitable entry points for further development. In parallel, greater effort is needed to raise public awareness of both CE and IS, so that educational reform is accompanied by broader societal understanding of their importance for sustainable development and economic transition.

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Policy-Driven Technological Innovation in Industrial Symbiosis: A Patent-Based Global Analysis (1971–2024)

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ABSTRACT

Industrial symbiosis (IS) plays a crucial role in accelerating circular economy transitions through the cross-sectoral valorization of waste. While a growing literature exists on how regional, national, and international policy and regulatory initiatives affect IS implementations, a significant gap remains in understanding how political and regulatory frameworks drive IS innovation. The main objective of this study is to assess how circular economy and waste-management policies across diverse regulatory environments have influenced technological progress relevant to industrial symbiosis. To this end, this study utilizes a dataset of 1,553 global patent publications filed between 1971 and 2024 under the Y02P80/30 subgroup of Cooperative Patent Classification (CPC) of EPO, entitled “Reducing waste in manufacturing processes”. Preliminary analysis suggests that the global technology landscape related to waste valorization has experienced three structural breaks in 2002, 2015, and 2018, resulting in four distinct periods, namely 1971-2001, 2002-2015;

2016-2018, and 2019-2024. These structural breaks coincide with the global initiatives on combating climate change, fostering sustainable development and waste-reduction such as the UN’s World Summit on Sustainable Development in 2002; Paris Agreement and UN’s Sustainable Development Goals in 2015, and the EU’s revised Waste Framework Directive in 2018 and the launch of European Green Deal in 2019. The analysis employed in this study further integrates major policy milestones from multiple countries and regions, including EU countries, the USA, China, Japan and South Korea. By comparing patenting trends before and after these regulatory shifts, the study evaluates how policy pressure and institutional awareness stimulate IS-enabling technological innovation. The study contributes to the literature by demonstrating how governance frameworks influence technological readiness for IS, and to WG3 objectives by providing empirical foundations for developing policy-responsive indicators of IS-related technological innovation.

KEYWORDS

Industrial symbiosis • policy-driven technological progress • patent landscape analysis • innovation dynamics

INTRODUCTION

Industrial symbiosis (IS) is considered to be one of the most innovative circular economy (CE) strategies by facilitating intra- or cross-sectoral exchanges of waste, energy, and materials (Chertow, 2000; Lombardi & Laybourn, 2012). While IS implementation has traditionally been examined through case studies involving eco-industrial parks, symbiotic networks, and firm-level collaborations (Erceg et al., 2024), far less attention has been devoted to the technological evolution and innovation dynamics underpinning IS (Burmaoğlu et al., 2026). Technological innovation is central to IS for several reasons. First, waste valorization technologies enable converting by-products and wastes into valuable resources, making IS and CE implementations economically feasible (Ambaye et al., 2023). Second, innovations in process engineering reduce the cost of capturing, separating, and processing waste streams (Sahajwalla, 2018). Third, digitalization increasingly supports IS by enabling real-time resource tracking, by-product matchmaking, and optimization of symbiotic networks (Ceccarelli, 2023; Palagonia et al., 2023). Thus, understanding the evolution of IS-enabling technologies is critical for assessing IS readiness and scalability.

The literature has a particular gap in analyzing how innovation in IS and in general CE technologies, responds to regulatory and political developments. Addressing this gap is critical as the diffusion of enabling technologies for waste reduction, resource valorization and process integration for IS implementation depends on the availability of enabling regulatory environment. As suggested by Krzeminski et al. (2025), regulatory related barriers, namely “Lack of/Inadequate regulatory framework to support industrial symbiosis implementation” ranks as one of the most important non-technical barriers towards implementation of IS. This result has also been confirmed by many studies in the literature (Islam et al., 2016; Technopolis Group, 2016; Wuni, 2022; Vimal et al., 2021; Yang et al., 2022). Environmental policies influence innovation through mechanisms such as regulatory pressure, market creation, subsidy incentives, and informational signaling (Popp, 2019). A stream of literature following the Porter Hypothesis (Porter and Linde, 1995) showed that political commitment towards environmental stringency via establishing regulatory framework can shift firms’ expectations and investment priorities by establishing long-term targets. Moreover, prior studies also show that environmental policies can significantly boost technological innovation in clean technologies,

such as renewable energy, pollution control, and materials efficiency, through accelerating patenting activity (Aghion et al., 2016). However, evidence specific to IS remains rather limited, and most IS research does not empirically examine how global and national policies and regulatory framework shape innovation trajectories.

This paper contributes to the literature by analyzing patent data collected via Lens.org data repository. A total of 1,553 patent filing documents between 1971-2024 classified under European Patent Office’s Cooperative Patent Classification (CPC) subgroup of Y02P80/30, entitled “Climate change mitigation technologies for sector-wide applications; Reducing waste in manufacturing processes; Calculations of released waste quantities”. This sub-classification is chosen since it is relevant to the IS implementation as it captures technologies associated with waste minimization, process efficiency, and by-product utilization, which are considered as the key enablers of industrial symbiosis (Maille and Frayret, 2016). The main objective of this paper is to assess how global patenting trends in Y02P80/30 classification have been affected by global political and regulatory framework related to IS and CE during the period between 1971 and 2024.

Although the Earth Summit held in 1972 in Stockholm, generally is recorded as the first international initiatives towards combatting climate change and fostering sustainability, the past two decades have witnessed substantial political and regulatory activity in both global and regional levels surrounding climate change mitigation and also circular economy. At the global level initiatives such as the 2002 World Summit on Sustainable Development (WSSD), the 2015 Paris Agreement, and the 2015 UN Sustainable Development Goals (SDGs), created a mutual understanding for the importance of circular economy. For instance, 2002 WSSD introduced a global emphasis on 3Rs (Reduce, Reuse, Recycle) and integrated waste management, while one of the SDGs is devoted to responsible production and consumption, emphasizing material efficiency, waste reduction, and sustainable production as means of climate change mitigation. At the regional level, moreover, regulations such as European Union’s First Circular Economy Action Plan (2015) European Union’s amended Waste Framework Directive (2018) and European Green Deal (2019) represented major shifts in environmental governance. All these EU level initiatives highlighted the importance of improving waste management and of facilitating the transition to a circular economy.

In line with these global and regional initiatives, numerous countries, including EU members, the USA, China, Japan, South Korea, and Türkiye, have also introduced CE-oriented policies serving as facilitators for CE- and IS-enabling technological development, such as 2000 Basic Act for Establishing a Sound Material-Cycle Society of 2000 (South Korea), 2008 Circular Economy Promotion Law (China), 2009 Executive Order 13514 (the USA), 2019 Zero Waste Act (Türkiye).

Utilizing structural break analysis, this paper assesses whether the patent trends are systematically and signifi-

cantly affected by these shifts in global, regional and national political and regulatory framework. The paper also aligns with the objectives of LIAISE COST Action WG3, particularly its emphasis on governance, policy awareness, and the development of Key Performance Indicators (KPIs) for monitoring IS implementation. By providing empirical evidence linking policy frameworks to technological innovation, this research provides a basis for constructing innovation-oriented IS KPIs.

METHODOLOGY

This study uses a global patent dataset of 1,553 patent publications spanning the period from 1971 to 2024. These patents are all classified under the Y02P80/30 subgroup of the Cooperative Patent Classification (CPC) system, covering innovations aimed at “reducing waste in manufacturing processes” sits within the broader Y02P class dedicated to climate change mitigation technologies in production and processing. The data is obtained from Lens.org, a comprehensive open-access database that pulls together records from patent offices around the world. Before analysis, the dataset underwent a cleaning process to weed out duplicates, misclassified entries, and records with missing information. Patent counts were then aggregated by year, allowing us to trace a time series of global technological activity in the areas of waste valorization and process efficiency. Patent data are commonly used in innovation research as a window into technological progress; they reflect where R&D investment is flowing, what knowledge is being created, and in which direction technology is heading (OECD, 2009).

In this study, three different structural break tests, namely Zivot-Andrews (ZA) Test, Lee-Strazicich (LS) test and Bai-Perron (BP) test, have been used to allow for comparability. The ZA test identifies a single endogenous structural break in the time series while simultaneously testing for stationarity. Unlike conventional unit root tests, the ZA approach allows the break date to be determined within the model rather than imposed exogenously (Zivot and Andrews, 2002). This provides insight into whether a major regime shift occurs in the innovation trajectory and when it takes place. The LS test extends this framework by allowing two

endogenous structural breaks, based on a Lagrange Multiplier (LM) unit root approach (Lee and Strazicich, 2003). This method is particularly useful for identifying multiple regime shifts while avoiding spurious detection of breaks due to non-stationarity.

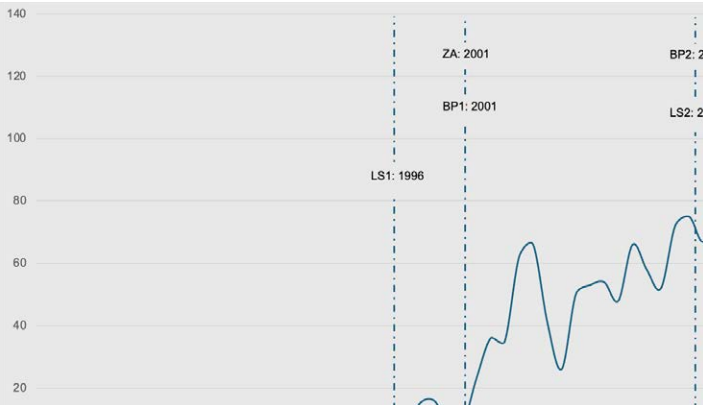
The BP test, moreover, enables the detection of multiple structural breaks in time series with deterministic components such as trends (Bai and Perron, 1998). The method identifies breakpoints by minimizing the residual sum of squares (RSS) and determines the optimal number of breaks using information criteria such as the Bayesian Information Criterion (BIC). A key parameter in the BP testing framework is the minimum segment length (h), which defines the minimum number of observations required within each regime. Following the literature, the ratio of segment length to total sample size (h/T) is typically set between 10% and 20% to ensure reliable estimation and avoid issues such as heteroskedasticity or serial correlation. In this study, the 10% threshold (for 54 data; $h=6$ is used) is selected as it provides greater flexibility in detecting shorter innovation regimes, which is particularly relevant for rapidly evolving technological fields such as circular economy and industrial symbiosis.

Following the identification of structural breaks, the resulting breakpoints are then compared with major global, regional, and national policy milestones related to circular economy, industrial symbiosis and waste management, such as WSSD in 2002, Paris Agreement and UN SDGs in 2015, EU’s First CEAP in 2015, EU Amended Waste Framework Directive in 2018, EU Green Deal in 2019.

RESULTS

Figure 1 provides the time series data of patent filings globally and of the leading five innovator countries: (1) the USA, (2) South Korea, (3) Japan, (4) Germany and (5) China, respectively. Two important findings can be deduced from Figure 1. Firstly, global patenting activity has increased significantly after 2000s, such that while annual average of patent filings pre-2000 was only 5.1, it has increased exponentially to 56.3. Secondly, while during the period between 1970 and 2000, leading innovators have similar patenting dynamics, during post-2000 period the USA has clearly become dominant in the Y02P80/30 technology field.

Figure 1. Y02P80/30 Class Patenting Activity, 1971-2024



Structural break tests applied to the global patent series (1971–2024) reveal a consistent pattern of regime shifts in IS-related technological innovation. The ZA test identifies 2001 as the main structural break year, while the LS test detects two endogenous breakpoints in 1996 and 2017. Similarly, the BP test identifies two statistically significant breaks in 2001 and 2017 (Figure 2). Furthermore, as shown in Table 1, all identified breakpoints are statistically significant at high confidence levels according to the Chow test.

Figure 2. Structural Breaks in Y02P80/30 Class Global Patenting Activity, 1971-2024

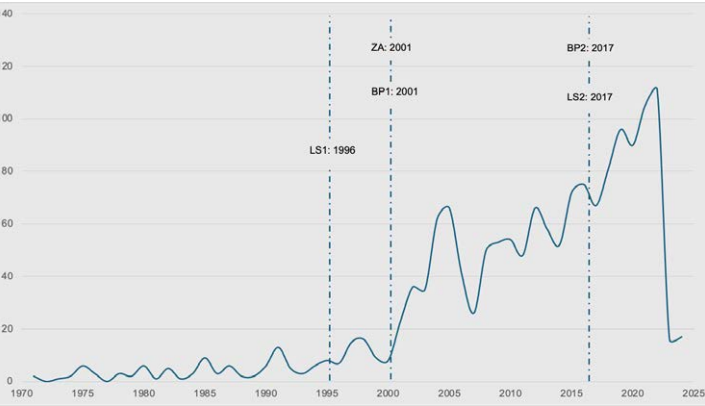


Table 1. Statistical significance of the identified structural breaks according to the Chow test

Break Year	Corresponding Test	F-statistics
1996	LS	13.175***
2001	ZA, BP	16.001***
2017	LS, BP	6.049***

According to the results depicted in Figure 1, the main structural break identified by both ZA and BP tests is 2001, which divides the whole period into two regimes. The first regime, spanning the period between 1971 to 2000, is characterized by low, relatively stable patenting activity. During this period, we do not observe stringent environmental regulations towards waste management. Most of the global initiatives during this period concentrates on greenhouse gas emissions. On the other hand, in the second regime, during the period from 2002 to 2024, we observe increasing patenting activity, particularly intensifying after 2010. As afore-mentioned this period corresponds directly to the growing global efforts on sustainable development and waste management policies, starting with the 2002 World Summit on Sustainable Development. Moreover,

2017 emerges as the other structural break identified by both LS and BP tests. As discussed above the period after this structural break, namely post-2018, marks intensified circular economy and waste-management policies particularly led by European Union. Following the Circular Economy Action Plan in 2015, EU has increased its sustainable circular economy targets towards more ambitious levels first with revised Waste Framework Directive in 2018 followed by European Green Deal in 2019 and Fit-for-55 package in 2021. Although LS test reveals 1996 as a structural break, it is not supported by other tests and no significant regulatory developments are recorded. In addition, Paris Agreement and the United Nations Sustainable Development Goals (SDGs) in 2015 do not correspond one-to-one to a distinct structural break,

they represent an important global coordination phase that likely contributed to the acceleration of innovation observed in the late 2010s. In this sense, 2015 can

be interpreted as a policy-induced transition period, bridging the early 2000s expansion and the late-2010s high-growth regime.

CONCLUSIONS

Using a global dataset of 1,553 patents in the Y02P80/30 classification over the period 1971–2024, this study aims to provide how policy and regulatory developments affect technological landscape related to industrial symbiosis (IS). Structural break analyses identified two major structural breaks identified by different tests, namely 2001 by ZA and BP tests and 2017 by BP and LS tests. These major structural breaks correspond to main global and regional initiatives towards sustainable waste management and circular economy. The increase in the patenting activity in the Y02P80/30 classification during the post 2010 period signals that key global and regional political and regulatory developments have affected innovation landscape related to the industrial symbiosis. Overall, the findings indicate that IS-related technological innovation has evolved through a process characterized by policy-induced regime shifts, where major global and regional regulatory initiatives play a crucial role in shaping long-term innovation trajectories.

From a policy perspective, the results highlight the critical role of coherent, long-term regulatory frameworks in fostering innovation in waste valorization and circular economy technologies. The evidence supports the

view that policy signals, through regulations, ambitious targets, and strategic roadmaps, shape expectations and investment decisions, thereby influencing the direction and intensity of technological change. In line with the objectives of the LIAISE COST Action WG3, this study contributes to the development of policy-responsive indicators by demonstrating how patent-based metrics can capture shifts in IS-related innovation dynamics. These insights can inform the design of Key Performance Indicators (KPIs) that link governance frameworks with technological readiness and implementation capacity.

Without a doubt, this study serves as a preliminary analysis due to two reasons. Firstly, it concentrates on global patent application data without investigating data on different countries and even different sectors. Secondly, structural break analysis does not directly show whether the corresponding global initiatives significantly affected the trend breaks. Future research may extend this analysis by incorporating country-level heterogeneity, sectoral disaggregation, and input-output linkages to better understand how policy-driven innovation translates into measurable industrial symbiosis outcomes.

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Educational Leadership and Institutional Learning in Advancing Industrial Symbiosis Awareness in Higher Education

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ABSTRACT

Industrial Symbiosis (IS) is widely recognised as a key strategy for advancing environmental sustainability and resource efficiency; however, its implementation remains uneven across regions and sectors. While technical and infrastructural dimensions of IS have been extensively examined, comparatively less attention has been paid to the role of education, leadership, and institutional learning in fostering awareness and enabling sustained cross-sectoral engagement at higher education institutions. This study addresses this gap by exploring how educational leadership and institutional learning processes contribute to the development of IS awareness among key stakeholders. Grounded in perspectives from educational leadership and organisational learning, the study conceptualises IS awareness not merely as knowledge acquisition but as a dynamic learning process embedded within institutional cultures, governance structures, and leadership practices. This study adopts a qualitative, exploratory research design with a policy-oriented perspective. Data were collected through two primary

sources: (a) document analysis of European Union policy documents related to industrial symbiosis, sustainability, and higher education, and (b) semi-structured interviews with eight stakeholders, including five representatives from higher education institutions and three from the public sector. Data were analysed using thematic analysis. Interview transcripts and policy documents were coded inductively and iteratively, following the stages of familiarisation, initial coding, theme development, and refinement. The findings indicate that industrial symbiosis awareness in higher education remains limited and fragmented, primarily due to weak educational leadership and insufficient institutional learning mechanisms. By conceptualising educational leadership and institutional learning as key mechanisms in advancing IS awareness at higher education, this study contributes a practice-oriented framework that offers policy-relevant insights for universities, public institutions, and policymakers seeking to strengthen institutional readiness and support the transition from awareness to action.

KEYWORDS

Industrial Symbiosis • Educational Leadership • Institutional Learning • Awareness
Knowledge Transfer • Higher Education

INTRODUCTION

Industrial Symbiosis (IS) has emerged as a central strategy within the broader framework of the circular economy, aiming to optimise resource use, reduce waste, and foster sustainable industrial systems (Chertow, 2000; Lombardi & Laybourn, 2012). Despite its growing prominence in policy and practice, the implementation of IS remains uneven across regions and sectors. Existing literature has predominantly focused on technical, economic, and infrastructural aspects of IS, often overlooking the social, educational, and institutional dimensions that underpin its effective adoption (Boons et al., 2011; Domenech et al., 2019).

In recent years, scholars have emphasised that awareness, knowledge transfer, and stakeholder engagement are critical for scaling IS practices (Golev et al., 2015). However, the role of higher education institutions (HEIs) in fostering such awareness through leadership and institutional learning processes remains

underexplored. Universities are not only knowledge producers but also key actors in shaping sustainability-oriented competencies, behaviours, and governance structures (Lozano et al., 2013). Within this context, educational leadership plays a crucial role in embedding sustainability principles into institutional practices and facilitating organisational change (Leithwood et al., 2020).

This study addresses this gap by examining how educational leadership and institutional learning contribute to the development of IS awareness in higher education. Specifically, it explores how leadership practices and learning processes shape the translation of IS concepts into educational and governance practices. By adopting a policy-oriented and qualitative approach, the study aims to provide both conceptual and practical insights aligned with the objectives of advancing awareness and cross-sectoral engagement.

THEORETICAL BACKGROUND

Educational Leadership

Educational leadership has been widely recognised as a key driver of organisational change and improvement in educational settings (Hallinger, 2011; Leithwood et al., 2020). Contemporary approaches emphasise distributed and transformational leadership models, which promote collaboration, shared vision, and capacity building (Spillane, 2006). In the context of sustainability, educational leaders are increasingly expected to act as change agents who foster innovation and guide institutions towards environmentally responsible practices (Sterling, 2011).

Importantly, educational leaders can function as knowledge brokers, facilitating the translation of complex sustainability concepts, such as industrial symbiosis, into accessible and actionable knowledge within institutional settings (Meyer, 2010). This brokerage role is critical in bridging the gap between policy frameworks and educational practices.

Institutional Learning

Institutional learning, grounded in the work of Argyris and Schön (1978), refers to the processes through which organisations acquire, interpret, and respond

to knowledge. Senge's (1990) concept of the "learning organisation" further highlights the importance of continuous learning, systems thinking, and shared vision in fostering organisational adaptability.

In sustainability contexts, institutional learning is essential for integrating new practices and norms into organisational routines (Lozano, 2014). IS awareness, therefore, should not be viewed merely as individual knowledge acquisition but as a collective learning process embedded within institutional structures and cultures.

Awareness as a Learning Process

IS awareness is conceptualised as a transition from knowledge to action. This aligns with socio-constructivist approaches, where learning is seen as a socially embedded process shaped by interaction, dialogue, and institutional context (Wenger, 1998). Thus, advancing IS awareness requires not only information dissemination but also the development of institutional capacities and learning environments that support behavioural and organisational change.

METHODOLOGY

This study adopts a qualitative, exploratory research design with a policy-oriented perspective to examine the role of educational leadership and institutional learning in fostering IS awareness.

Document Analysis

Document analysis was conducted on key European Union policy documents related to industrial symbiosis, sustainability, and higher education. These included policy frameworks, strategic reports, and institutional guidelines. The analysis aimed to identify how IS awareness, education, and stakeholder engagement are framed within policy discourse.

A qualitative content analysis approach was employed, focusing on recurring themes related to awareness, education, leadership, and governance (Bowen, 2009).

Stakeholder Perspectives

To complement the document analysis, semi-structured interviews were conducted with eight stakeholders, in-

cluding five representatives from higher education institutions and three from the public sector. Participants were selected using purposive sampling to ensure their involvement in sustainability-related educational or governance processes. The interviews were based on five open-ended questions and lasted between 45 and 60 minutes. The questions explored participants' perceptions of IS awareness, the role of leadership, and institutional learning processes. Particular attention was given to the role of educational leaders as knowledge brokers.

Data were analysed using thematic analysis following Braun and Clarke's (2006) framework, including familiarisation, coding, theme development, and refinement. To enhance credibility, data triangulation was applied by comparing interview data with policy documents, and peer debriefing was used during the coding process.

FINDINGS

Findings from Document Analysis

The document analysis reveals that industrial symbiosis (IS) is strongly embedded in European sustainability and circular economy policies, yet its integration into higher education remains limited and largely indirect. The reviewed documents, such as the European Commission's Circular Economy Action Plan (European Commission, 2020), the Industrial Symbiosis Programme (European Commission, 2023), the European Green Deal (European Commission, 2019), and the UNESCO Roadmap for Implementing ESD (2021), consistently underline the importance of awareness, education and capacity building as enabling conditions for IS. However, the policy emphasis is predominantly placed on industry-industry collaboration, economic incentives and technological infrastructure, while education is positioned as a supportive rather than a central lever for change.

A recurring theme across the documents is the call for "strengthening competences and skills for the green transition" (EC, 2020, p. 7) and for "mainstreaming sustainability in education and training" (UNESCO, 2020, p. 12). However, the documents provide limited guidance on how IS awareness should be operationalised in higher education curricula, professional development or institutional governance. In particular, the explicit role of educational leadership and institutional learning is rarely addressed. This finding is consistent with previous studies highlighting a policy-practice gap in sustainability transitions, where high-level policy ambitions are not reflected in concrete educational or organisational

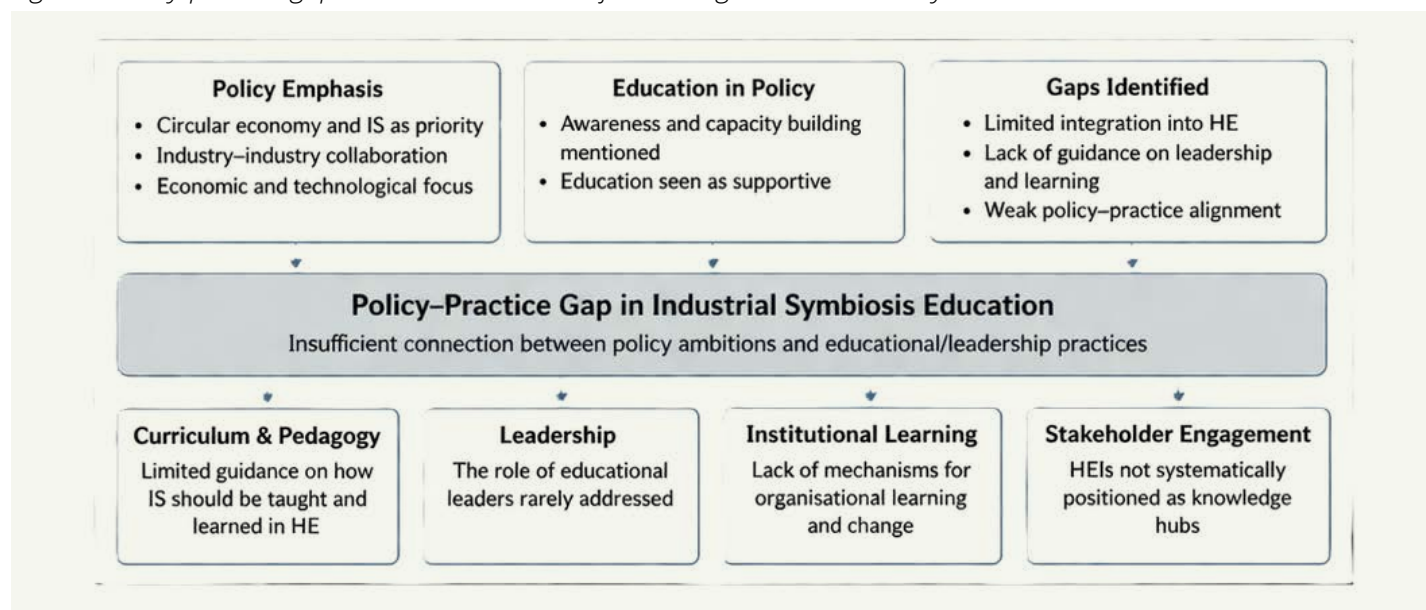
practices (Barth et al., 2007; Lozano et al., 2013).

The analysis also indicates that IS is often framed as a technical and economic concept. While the Industrial Symbiosis Programme (European Commission, 2023) and the Green Deal (European Commission, 2019) emphasise stakeholder engagement, collaborative governance and knowledge exchange, higher education is not systematically positioned as a knowledge hub or as a key actor for diffusion. The lack of explicit references to leadership, institutional learning and pedagogical approaches suggests an underdeveloped policy discourse on how universities can meaningfully contribute to raising IS awareness and enabling cross-sectoral action. Figure 1 synthesises the main gaps identified in the policy documents.

This finding reflects a broader policy-practice gap, where ambitious sustainability goals are not adequately translated into institutional practices (Lozano et al., 2013). Moreover, education is frequently positioned as a supportive rather than a central mechanism for advancing IS, indicating a need for stronger alignment between policy and educational frameworks.

Overall, the document analysis reveals that while policies create a favourable context for IS, the mechanisms for translating these ambitions into higher education practices, especially through leadership and institutional learning, remain weak. This highlights the need for more coherent strategies that explicitly link education, governance and stakeholder engagement.

Figure 3 Policy-practice gaps in IS education identified through document analysis.



Findings from the Stakeholders

In this section, the findings from stakeholder interviews are presented to complement the policy analysis and provide insights into how leadership and learning processes operate in practice within higher education and public institutions.

This section presents the findings derived from semi-structured interviews with eight stakeholders, including five higher education representatives (P1–P5)

and three public sector representatives (P6–P8). Participants were directly involved in sustainability-related education, policy, or governance processes. The analysis generated three overarching themes: (1) Awareness and Conceptualisation of IS, (2) Educational Leadership and Institutional Role, and (3) Institutional Learning and Collaboration Capacity.

Awareness and Conceptualisation of Industrial Symbiosis

The first theme highlights stakeholders' perceptions and understanding of IS. Findings indicate that IS awareness is limited and unevenly distributed, with only 2 out of 8 participants demonstrating a clear and comprehensive understanding of the concept. The remaining participants associated IS with broader sustainability or circular economy concepts without specific conceptual clarity.

A frequently recurring code under this theme is "IS as a technical concept" (f=5), reflecting the perception that IS is primarily relevant to industry rather than education.

"We are familiar with sustainability and circular economy ideas, but industrial symbiosis is not something we explicitly address in our educational programmes." (P2, Higher Education)

"Industrial symbiosis sounds more like an engineering or industrial issue. It is not something that is currently integrated into teaching practices." (P6, Public Sector)

Another important code is "implicit awareness through sustainability discourse" (f=6), suggesting that while IS is not explicitly recognised, related ideas are indirectly present.

Educational Leadership and Institutional Role

The second theme focuses on the role of educational leadership in promoting IS awareness. Findings reveal that leadership practices are largely fragmented and non-strategic, with only 3 participants reporting institutional initiatives linked to sustainability leadership.

The most prominent code in this theme is "lack of strategic leadership" (f=5), indicating that leadership

does not systematically prioritise IS or related awareness-building processes.

"There is no clear leadership vision specifically addressing industrial symbiosis. Sustainability is mentioned, but it remains quite general." (P4, Higher Education)

In contrast, a smaller group of participants (f=3) highlighted "emerging leadership initiatives", particularly in

institutions where leaders actively support interdisciplinary collaboration.

"When leadership encourages collaboration across departments, we start to see more awareness and engagement with sustainability topics, including industrial symbiosis."
(P1, Higher Education)

Institutional Learning and Collaboration Capacity

The third theme addresses institutional learning mechanisms and collaboration practices. Findings indicate a significant lack of structured organisational learning processes, with 7 out of 8 participants emphasising the absence of systematic knowledge-sharing mechanisms. The most dominant code is "lack of institutional learning structures" (f=7).

"There is no formal system for sharing knowledge or learning from sustainability-related projects within the institution." (P5, Higher Education)

Another key code is "individualised learning processes" (f=6), suggesting that learning remains dependent on personal initiative rather than institutional design.

"It depends mostly on individual efforts. If someone is interested, they learn and apply it, but it is not embedded in the system." (P7, Public Sector)

DISCUSSION

This study reveals a clear policy–practice gap in advancing Industrial Symbiosis (IS) awareness within higher education. While European policy frameworks strongly emphasise awareness, education, and capacity building (European Commission, 2019, 2020, 2023; UNESCO, 2020), IS is predominantly framed within technical and industrial domains. As a result, education is positioned as a supportive rather than a transformative mechanism, confirming earlier findings on the limited operationalisation of sustainability policies in educational contexts (Barth et al., 2007; Domenech et al., 2019; Lozano et al., 2013).

Stakeholder findings reinforce this gap, indicating that IS awareness remains limited, implicit, and fragmented, often embedded within broader sustainability discourse rather than recognised as a distinct concept. This aligns with previous research showing that sustainability-related knowledge is insufficiently integrated into higher education systems (Lozano, 2014; Sterling, 2011; Wiek et al., 2011). The perception of IS as a primarily technical concept further constrains its adoption within educational settings (Boons et al., 2011; Chertow, 2000).

A central contribution of this study is the identification of educational leadership as a critical but underdeve-

loped mechanism linking policy and practice. Although policy documents emphasise stakeholder engagement and knowledge exchange, they rarely articulate the role of leadership in enabling these processes. The findings suggest that leadership remains fragmented and reactive, limiting its capacity to foster awareness and institutional change. This is consistent with research highlighting the role of transformational and distributed leadership in promoting organisational learning and innovation (Hallinger, 2011; Leithwood et al., 2020; Spillane, 2006).

Additionally, "leaders as knowledge brokers" (f=2) emerged as a less frequent but critical code, suggesting that the brokerage role of leaders remains underdeveloped. In terms of collaboration, participants frequently referred to "ad hoc stakeholder engagement" (f=5), indicating that partnerships between universities, industry, and public institutions are irregular and unsystematic. *"We collaborate with external partners occasionally, but these collaborations are not sustained or strategically planned."* (P3, Higher Education)

Synthesis of Findings

Across all themes, the findings reveal a consistent pattern: IS awareness is constrained not only by limited knowledge but also by weak leadership structures and insufficient institutional learning capacity. While policy frameworks emphasise awareness and collaboration, these priorities are not systematically translated into institutional practices.

In parallel, the study underscores the importance of institutional learning as a prerequisite for embedding IS awareness. The lack of structured learning mechanisms and knowledge-sharing processes indicates that learning remains individualised rather than institutionalised. This finding reflects core arguments in organisational learning theory, which emphasise that sustainable change requires systemic learning supported by organisational routines and shared practices (Argyris & Schön, 1978; Crossan et al., 1999; Senge, 1990).

Furthermore, despite strong policy emphasis on collaboration, stakeholder accounts reveal that cross-sectoral engagement remains weak and ad hoc, limiting

the role of universities as knowledge brokers in IS ecosystems. This is consistent with existing literature identifying coordination and stakeholder alignment as key challenges in industrial symbiosis implementation (Golev et al., 2015; Lombardi & Laybourn, 2012).

Overall, the findings suggest that advancing IS awareness requires a shift from policy discourse to institutionally embedded practices, where educational leadership and institutional learning function as key leverage points. Strengthening these dimensions can enhance the capacity of higher education institutions to support the transition from awareness to action in industrial symbiosis.

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Key social and cultural factors influencing Industrial Symbiosis (IS) implementation

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ABSTRACT

Social and cultural dimensions are fundamental to the effective deployment of Industrial Symbiosis (IS), as they shape levels of societal awareness, stakeholder interaction, mutual trust, and the broader acceptance of circular economy practices. These dimensions affect not only the mechanisms through which industries share resources, but also the ways in which communities, institutions, and decision-makers participate in and support IS-related initiatives. This research explores these interdependencies using empirical evidence gathered from 85 participants representing 29 countries, including both EU and non-EU regions, and encompassing a wide range of professional profiles. Data were collected through a structured questionnaire addressing indicators related to awareness, stakeholder roles, perceived barriers, and societal involvement. The analytical approach applies multivariate elastic net regression techniques, in which individual survey responses are treated as standardized indicator variables. Variable normalization, aggregation, and scaling enabled the detection of statistically meaningful

associations among social, cultural, and institutional drivers influencing IS implementation. The findings indicate that IS adoption at the national level remains generally constrained, with most countries positioned at early or emerging stages of development. Key enabling factors include industrial demand, regulatory frameworks, and international sustainability objectives, while significant obstacles are associated with low awareness, limited cross-sectoral collaboration, and insufficient policy backing. Influence among stakeholders is most pronounced within academia, industry, and public authorities; however, coordination between these actors remains weak. Public understanding and local participation are notably limited, reflecting minimal integration within educational systems and a lack of leadership at the local scale. Cultural characteristics present both enabling and constraining effects, with cooperative norms facilitating progress in some contexts, while entrenched practices within traditional industries act as a barrier to transformation.

KEYWORDS

Industrial Symbiosis • Social and Cultural Drivers • Stakeholder Engagement • Public Awareness and Participation

INTRODUCTION

Industrial Symbiosis (IS) has emerged as a central strategy within the broader transition toward a circular economy, offering a practical framework through which industries can enhance resource efficiency, reduce waste, and generate mutual economic and environmental benefits. By facilitating the exchange of materials, energy, water, and by-products among traditionally separate industries, IS transforms linear production systems into more integrated and regenerative networks. While technical feasibility and economic viability have long been

recognized as key prerequisites for IS development, there is growing consensus that these factors alone are insufficient to ensure successful implementation. Increasingly, attention has shifted toward the social and cultural dimensions that underpin, enable, or constrain the formation and sustainability of industrial symbiotic relationships (Oughton et al., 2022; Rentería Núñez & Perez-Castillo, 2023; Palagonia et al., 2025).

Social and cultural factors are fundamental because IS is inherently a collaborative and relational process. It depends not only on infrastructure and technology, but also on the willingness of organizations and individuals to cooperate, share information, build trust, and engage in long-term partnerships. Unlike conventional industrial operations that often prioritize competition and confidentiality, IS requires a paradigm shift toward openness, interdependence, and collective value creation. This shift is deeply embedded in social norms, cultural values, institutional practices, and behavioral patterns that vary significantly across regions and contexts (Katana et al., 2024; Mirata et al., 2024).

One of the most critical social dimensions influencing IS implementation is societal awareness and understanding of circular economy principles. Awareness shapes how industries, policymakers, and the general public perceive the value and feasibility of resource-sharing practices. In contexts where circular economy concepts are well integrated into public discourse, educational systems, and policy frameworks, there is a higher likelihood of acceptance and proactive engagement with IS initiatives. Conversely, low levels of awareness often lead to skepticism, resistance to change, and a lack of motivation among stakeholders. Awareness is not merely about knowledge dissemination; it also involves shaping attitudes, perceptions, and expectations regarding sustainability and industrial collaboration (Chrysikopoulos et al., 2024; Sellitto et al., 2025; Palagonia et al., 2025).

Closely related to awareness is the role of education and knowledge systems. Educational institutions, including universities, technical schools, and training centers, play a pivotal role in embedding IS-related concepts into curricula and professional development programs. When future engineers, managers, and policymakers are trained with an understanding of circular systems and industrial collaboration, they are more likely to support and implement IS practices in their professional roles. Furthermore, knowledge transfer mechanisms such as workshops, networks, and knowledge-sharing platforms facilitate the diffusion of best practices and innovation. The absence of such systems often results in fragmented understanding and limited capacity to design and manage symbiotic exchanges (Rentería Núñez & Perez-Castillo, 2023; Katana et al., 2024).

Another key social factor is stakeholder interaction and network dynamics. IS relies on the creation of interconnected networks involving industries, government agencies, research institutions, and local communities.

The structure, density, and quality of these networks significantly influence the success of symbiotic initiatives. Strong networks enable efficient communication, resource matching, and coordination of activities. They also foster a sense of shared purpose and collective responsibility. However, weak or fragmented networks can hinder collaboration, limit information flow, and increase transaction costs. The effectiveness of these networks is often shaped by existing social relationships, institutional arrangements, and communication practices. At the core of stakeholder interaction lies the issue of trust, which is widely recognized as a critical enabler of IS. Trust reduces uncertainty, facilitates information sharing, and lowers the perceived risks associated with collaboration. In industrial contexts, where companies may be reluctant to disclose sensitive information or depend on external partners, trust becomes a decisive factor. It is built over time through repeated interactions, transparency, and the demonstration of mutual benefits. Cultural norms play a significant role in shaping trust dynamics. In some cultures, trust is more easily extended based on shared identity or long-term relationships, while in others, it is contingent upon formal agreements and institutional guarantees (Vahidzadeh et al., 2021).

Institutional support and governance structures also represent important social dimensions influencing IS implementation. Governments and public authorities can create enabling environments through policies, regulations, incentives, and facilitation mechanisms. For instance, regulatory frameworks that encourage waste valorization, provide tax incentives for resource efficiency, or mandate environmental reporting can stimulate IS development. Equally important is the role of intermediary organizations, such as industrial associations, clusters, and innovation hubs, which act as facilitators by connecting stakeholders, providing technical assistance, and coordinating initiatives. The absence of coherent and supportive institutional frameworks often results in fragmented efforts and limited scalability of IS projects. In addition to formal institutions, informal social norms and cultural values exert a profound influence on IS practices. Cultural attitudes toward collaboration, competition, risk, and innovation shape how stakeholders approach symbiotic opportunities. In societies where cooperation and collective action are highly valued, there is typically greater openness to industrial partnerships and resource sharing. Conversely, in contexts characterized by strong individualism or competitive norms, companies may be more hesitant to engage in collaborative

arrangements. Cultural perceptions of waste also play a role; in some settings, waste is viewed as a liability to be disposed of, while in others, it is recognized as a potential resource (Uusikartano et al., 2022; Katana et al., 2024; Palagonia et al., 2025).

Leadership and agency constitute another critical dimension. The presence of visionary leaders whether in industry, government, or academia can significantly accelerate the development of IS by championing initiatives, mobilizing resources, and fostering collaboration. Leadership is particularly important in overcoming initial barriers, such as lack of awareness, resistance to change, or coordination challenges. Local leadership, in particular, has been identified as a key driver of successful IS cases, as it enables context-specific solutions and sustained engagement at the community level. The absence of leadership often results in stagnation, even when technical and economic conditions are favorable (Chrysikopoulos et al., 2024).

The role of public participation and community engagement is increasingly recognized as essential for the long-term sustainability of IS initiatives. Communities are not merely passive beneficiaries of industrial activities; they are active stakeholders whose perceptions, acceptance, and involvement can influence project outcomes. Public opposition, often driven by concerns about environmental impacts or lack of transparency, can hinder the implementation of IS projects. Conversely, community support can enhance legitimacy, facilitate knowledge exchange, and contribute to the co-creation of solutions. Effective communication and participatory processes are therefore crucial in aligning industrial activities with societal expectations (Sellitto et al., 2025).

Cross-sectoral collaboration represents another important social factor. IS requires the integration of diverse sectors, including manufacturing, energy, agriculture,

and services. This integration often involves bridging differences in organizational cultures, operational practices, and regulatory frameworks. Successful collaboration depends on the ability to align interests, negotiate agreements, and manage interdependencies. Social capital defined as the networks, norms, and trust that facilitate coordination and cooperation plays a central role in enabling such collaboration. High levels of social capital are associated with more resilient and adaptive IS networks (Katana et al., 2024; Fric et al., 2025).

Cultural factors also influence the pace and direction of innovation within IS systems. Societies that value experimentation, learning, and adaptability are more likely to embrace innovative approaches to resource management. In contrast, cultures characterized by risk aversion or adherence to traditional practices may resist change and limit the adoption of new technologies or business models. This is particularly relevant in traditional industries, where established routines and legacy systems can act as barriers to transformation. Understanding these cultural dynamics is essential for designing interventions that are both effective and context-sensitive (Palagonia et al., 2025).

In this context, the present study aims to explore the social and cultural factors influencing IS implementation through a cross-country empirical analysis. By examining data from a diverse set of participants and regions, the research seeks to identify patterns, relationships, and key drivers that shape the development of IS systems. The use of advanced analytical techniques allows for a nuanced understanding of how different factors interact and contribute to outcomes. Ultimately, the findings are intended to inform policymakers, practitioners, and researchers in designing strategies that leverage social and cultural dimensions to enhance the effectiveness and scalability of Industrial Symbiosis.

METHODOLOGY

This study seeks to identify the main challenges and barriers affecting the adoption of industrial symbiosis, with a particular focus on the European context, while also providing practical insights to improve its effectiveness. The methodological approach integrates both quantitative and qualitative methods, addressing indicators related to awareness, stakeholder roles, perceived barriers, and societal involvement, that influence the implementation of industrial symbiosis.

The research examines the interconnections among these factors based on empirical data collected from 85 participants representing 29 countries, including

both EU and non-EU regions. The sample covers a diverse range of professional backgrounds, such as scientific researchers, field experts, and evaluators specialized in industrial symbiosis. Participants were selected based on their expertise and direct involvement in projects or evaluations related to this field. The questionnaire consisted of two main types of questions: (1) Likert-scale items (ranging from 1 = strongly disagree to 5 = strongly agree), used to assess the perceived intensity, relevance, or effectiveness of various influencing factors; and (2) multiple-choice questions designed to capture common practices, key stakehol-

ders, and contextual conditions associated with the adoption of industrial symbiosis.

The research develops an ordered logit model to investigate the link between the dependent variable (resource synergies) and the set of independent indices. This method enables the estimation of elasticity coefficients and facilitates the analysis of proportional shifts in resource synergies in response to changes in the underlying determinants. The Ordered Logit model is based on an unobserved latent variable Y^* :

$$Y^* = X\beta + \varepsilon$$

where:

Y^* is the latent (unobserved) variable;

X is the vector of explanatory variables;

β represents the parameters to be estimated;

ε is the error term, assumed to follow a logistic distribution.

The observed ordinal variable Y is defined as:

$$Y = \begin{cases} 1 & \text{if } Y^* \leq \mu_1 \\ 2 & \text{if } \mu_1 < Y^* \leq \mu_2 \\ 3 & \text{if } \mu_2 < Y^* \leq \mu_3 \\ 4 & \text{if } \mu_3 < Y^* \leq \mu_4 \\ 5 & \text{if } Y^* > \mu_4 \end{cases}$$

Where μ_1, μ_2, μ_3 , and μ_4 are the threshold parameters separating the categories. The model parameters are

estimated using “maximum likelihood estimation”, where the probability of observing outcomes j is given by:

$$P(Y = j) = \varphi(\mu_j - X\beta) - \varphi(\mu_{j-1} - X\beta)$$

Where φ denotes the cumulative logistic distribution function. Dependent variable (latent variable) “IS – IS implementation level”, measured by current level of IS implementation in each country.

Independent variables:

- “PA – public awareness”, measured by the question: What is the level of public awareness regarding IS practices in your country?
- “SC – stakeholder collaboration”, measured by the question: What level of collaboration exists among key stakeholders for IS in your country?
- “CV – cultural value”, measured by the question: To what extent do the following cultural factors promote or hinder IS adoption? [Public trust in institutions promoting IS].
- “EL – Education level”, measured by the question: What are the barriers to effective IS education and training? [Cultural resistance to new practices].
- “PPP – Public-Private Partnerships usage”, measured by the question: How often do public-private partnerships result in successful IS projects?

To estimate the parameters β_i , the Ordered Choice method will be applied (Verbeek, 2017).

RESULTS

The Spearman correlation matrix (Table 1) shows several statistically significant relationships ($p < 0.01$). IS is moderately and positively correlated with SC (0.51), PPP (0.39), and PA (0.37), indicating that higher collaboration, partnerships, and awareness are associated with higher IS implementation. EL is negatively correlated with IS (-0.29), suggesting that educational or cultural barriers reduce IS

levels. SC is also positively related to PA and PPP, highlighting interconnected institutional factors. CV shows weak and insignificant correlations with all variables. Median values suggest moderate levels overall, with IS highest (4 – developing option), while most independent variables cluster around medium levels (2–3).

Table 1. Correlation matrix (Spearman rank order) and descriptive statistics

	IS	SC	PA	CV	PPP	EL	Median
IS	1.00						4
SC	0.51*	1.00					2
PA	0.37*	0.44*	1.00				2
CV	0.12	0.14	0.05	1.00			3
PPP	0.39*	0.31*	0.49*	0.05	1.00		3
EL	-0.29*	-0.28*	-0.03	-0.01	-0.08	1.00	3

Source: Author’s calculation in the Eviews. Note: “*” denote the statistical significance $p < 0.01$.

Using above methodology and proceeding data in Eviews program, it is realized the final model estimation with dependent variable IS – “IS implementation level” and independent variable as shown in Table 2.

SC – Stakeholder Collaboration: Stakeholder collaboration is positive and statistically significant ($p = 0.0044$). A one-unit increase raises the odds of being in a higher IS implementation category by about 2.75 times (about 175% increase). This fact suggests that stronger coordination among institutions and actors substantially improves IS outcomes, likely because collaboration enhances resour-

ce sharing, alignment of strategies, and effective execution of IS initiatives.

PPP – Public-Private Partnerships: Public-private partnerships have a positive and statistically significant effect ($p = 0.0176$). A one-unit increase increases the odds of higher IS implementation by about 2.03 times (about 103% increase). This indicates that frequent successful PPPs play a major role in advancing IS, as they combine public oversight with private sector efficiency, innovation, and financial capacity.

Table 2. Econometric estimation model approach. Source: Author's calculation in the Eviews.

Variable	Coefficient	Odd Ratio	z-Statistic	Prob.
SC	1.0115	2.7496	2.8501	0.0044
PA	0.3701	1.4479	1.0198	0.3078
CV	0.1179	1.1251	0.5734	0.5664
PPP	0.7079	2.0297	2.3733	0.0176
EL	-0.3890	0.6778	-1.8885	0.0590

EL – Education Level (Cultural Resistance): Education-related cultural resistance has a negative and marginally significant effect ($p = 0.0590$). A one-unit increase reduces the odds of higher IS implementation by about 32%. This implies that stronger cultural resistance to new practices hinders IS adoption, as it limits knowledge transfer, reduces acceptance of innovation, and slows down the development of necessary skills.

PA – Public Awareness: Public awareness shows a positive but statistically insignificant effect ($p = 0.3078$). A one-unit increase raises the odds of higher IS implementation by about 45%, but this effect is not reliable.

Although awareness may encourage IS adoption, the lack of significance suggests that awareness alone is insufficient without supporting institutional or structural mechanisms.

CV – Cultural Value (Public Trust): Cultural value, measured through public trust, has a positive but statistically insignificant effect ($p = 0.5664$). A one-unit increase raises the odds of higher IS implementation by about 12%. However, the effect is weak and not significant, indicating that trust alone does not strongly drive IS implementation without concrete actions or institutional support.

CONCLUSIONS

The social and cultural factors play a critical role in shaping the IS implementation, complementing the theoretical expectations outlined in the introduction. While IS is often discussed in technical and economic terms, the findings demonstrate that relational and institutional dimensions are decisive in determining real-world outcomes. The results indicate that IS implementation across countries remains at a moderate, developing stage, reflecting structural and social constraints. Among the examined variables, stakeholder collaboration emerges as the most influential and statistically significant driver, highlighting the importance of coordinated networks among industry, government, and academia. Similarly, public-private partnerships show a strong positive and significant effect, emphasizing the

role of integrated governance and shared investment in advancing IS practices. Conversely, cultural resistance related to education represents a negative and marginally significant barrier, suggesting that insufficient skills, knowledge diffusion, and openness to innovation hinder progress. Correlation results further support these findings, showing positive associations between IS and collaboration, partnerships, and awareness, while educational barriers are negatively related to IS levels. In contrast, public awareness and cultural trust, although theoretically important, do not show statistically significant effects in the statistical model. This implies that awareness and trust alone are insufficient to drive IS unless supported by concrete institutional mechanisms and active collaboration structures.

Successful IS implementation depends less on isolated social factors and more on the interaction between collaboration, institutional support, and practical engagement mechanisms. Strengthening stakeholder

networks and fostering effective partnerships appear to be the most critical pathways for accelerating IS development across different national contexts.

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Legal and Political Barriers to Industrial Symbiosis Development

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ABSTRACT

Industrial Symbiosis has evolved from a distant and often undesirable concept into a preferred approach within the European Union, gaining increasing attention in the context of sustainability transitions and the circular economy.

Despite its growing relevance, however, the practical implementation of Industrial Symbiosis remains uneven across EU Member States.

This paper examines how legal and political factors influence the development of Industrial Symbiosis, arguing that regulatory fragmentation and political

dynamics play a decisive role in shaping its adoption. Using a comparative qualitative case study of Denmark, Italy, the Netherlands, and Lithuania, the study reviews selected national experiences.

The findings show that legal clarity, political support, and institutional coordination are crucial enabling factors, while regulatory uncertainty and fragmented governance structures hinder progress. The paper highlights the need for greater policy coherence and stronger political commitment.

KEYWORDS

Industrial Symbiosis • EU Regulations • Legal Barriers • Political Barriers • Challenges • Fragmentation

INTRODUCTION

Industrial Symbiosis is increasingly recognised within the European Union as a key approach to advancing the circular economy and supporting sustainability transitions. It cannot be considered a purely technical solution. On the contrary, it represents a sustainable shift from traditional industry towards industrial interaction, with a specific focus on the exchange of resources, energy, and by-products. A few decades ago, Marian R. Chertow (2000) described industrial symbiosis as part of industrial ecology, which “engages traditionally separate entities in a collective approach to competitive advantage involving the physical exchange of materials, energy, water, and by-products” (p. 314). She identified collaboration and the synergistic opportunities arising from geographic proximity as key elements of industrial symbiosis. Such collaboration among industries generates positive environmen-

tal and economic benefits.

This importance is also reflected in European Union policy. The European Commission (2020) identifies industrial symbiosis as a key element of the circular economy transition, highlighting the need to facilitate its implementation through measures such as industry-led reporting and certification systems.

Despite its recognised benefits and increasing policy attention, the practical implementation of Industrial Symbiosis remains uneven across EU Member States. While some countries and regions have successfully developed integrated symbiotic networks, others continue to face significant challenges in adopting such practices. In many cases, these challenges are not primarily technological, but are instead rooted in legal and governance frameworks. Legal and political barriers can prevent promising initiatives. At both the European Union and national levels, the regulatory

framework relevant to Industrial Symbiosis remains fragmented, often lacking clarity and consistency. For instance, legal uncertainties related to waste classification, by-product status, and liability regimes continue to create obstacles for the exchange of resources between industries. These legal challenges are further compounded by institutional fragmentation and limited coordination among public authorities.

Legal frameworks are inherently shaped by political decision-making processes, institutional priorities, and lobbying activities. These factors may either facilitate or hinder the development of Industrial Symbiosis. This leads to the conclusion that the success of Industrial Symbiosis initiatives depends not only on technical or economic feasibility, but also on political willingness, policy coherence, and institutional awareness.

METHODOLOGY

This paper applies a qualitative comparative case study approach to examine how legal and political factors influence the development of Industrial Symbiosis in the European Union.

The analysis focuses on four cases representing different levels of development and governance approaches: Kalundborg Symbiosis in Denmark, regional industrial symbiosis programmes in Emilia-Romagna, circular economy cluster initiatives in the Netherlands, and emerging policy frameworks in Lithuania. These cases were selected based on their relevance, diversity of institutional contexts, and varying degrees of Industrial Symbiosis maturity.

RESULTS

The results are presented through a comparative analysis of selected cases of Industrial Symbiosis development in the European Union. The analysis focuses on four cases representing different levels of maturity and governance approaches: Kalundborg Symbiosis in Denmark, regional industrial symbiosis programmes in Emilia-Romagna, circular economy cluster initiatives in

This paper analyses how legal and political factors influence the development of Industrial Symbiosis in selected EU Member States. It focuses on four cases: Kalundborg Symbiosis in Denmark, regional industrial symbiosis programmes in Emilia-Romagna, circular economy cluster initiatives in the Netherlands, and emerging policy frameworks in Lithuania. By comparing these cases, the paper identifies key factors that enable or hinder Industrial Symbiosis and contributes to broader discussions on sustainability governance, policy integration, and institutional capacity within the European Union.

The study is based on document analysis, including European Union legislation, national and regional policy documents, and academic literature. Particular attention is given to relevant regulatory provisions.

To ensure a structured comparison, the cases are analysed based on legal clarity and regulatory conditions, political support and policy prioritisation, and institutional coordination.

The paper seeks to identify key factors that shape the development of Industrial Symbiosis across different contexts.

the Netherlands, and emerging policy frameworks in Lithuania.

Each case is examined in light of legal clarity, political support, and institutional coordination, allowing for the identification of both enabling conditions and key barriers. The following subsections present the findings for each case, followed by a comparative analysis.

Denmark: Case Study

Kalundborg Symbiosis is widely regarded as the most well-known and cited example of successful industrial symbiosis, spanning several decades (Kalundborg Symbiosis, n.d.). In 2022, it marked 50 years of circular production practices. This period demonstrates the maturity of cooperation, which cannot be explained solely by the willingness to collaborate or by the obvious economic and environmental benefits. It also reflects the presence of enabling legal and political conditions, with

relatively limited regulatory and institutional barriers. Mantese et al. (2018) note, in line with existing literature, that the case of Kalundborg in Denmark is widely regarded as the seminal example of industrial symbiosis. The development of Kalundborg Symbiosis was not bound by strict regulatory mandates; on the contrary, it emerged as a gradual, bottom-up initiative supporting cooperation between public and private actors (Chertow, 2007). It can be described as a collaborative

governance model, involving multiple private actors and local authorities, which allows for flexible decision-making and takes into account the local context. Such preconditions are crucial for ensuring the long-term stability of resource exchange systems.

As noted by Paché (2024), the successful implementation of industrial symbiosis requires long-term plan-

ning and a deep understanding of local dynamics, including the assessment of available resources, identification of potential partners, and the promotion of stakeholder awareness, cooperation, and mutual trust.

Italy: Case Study

An interesting case is provided in Italy, particularly in the region of Emilia-Romagna, where Industrial Symbiosis has been actively promoted through regional policy initiatives (ENEA, n.d.). While the Danish case represents a successful bottom-up initiative, the Italian case reflects a more structured and policy-driven approach. In this context, public authorities play a central role. A key facilitating factor is the political will and commitment to achieve concrete results. The results of the

project reveal not only a significant number of identified synergies but also a strong interest in industrial symbiosis as a tool for enhancing the circular economy, saving resources, and supporting local opportunities through the involvement of companies and local authorities (Cutaia et al., 2015).

The Netherlands: Case Study

In the case of the Netherlands, there are no clearly defined flagship cases; however, an advanced, cluster-based approach to Industrial Symbiosis can be observed. In this context, policymakers create conditions that encourage businesses to engage in attractive forms of cooperation. Industrial hubs, such as the Rotterdam Industrial Cluster, benefit from these conditions, as companies cooperate in the exchange of energy, materials, and by-products.

National strategic documents strongly support such cooperation, particularly when it contributes to effi-

cient resource distribution. The ambition of the Dutch government to achieve full circularity by 2050 has played an important role in mobilising stakeholders and placing the circular economy on the policy agenda (PBL, 2023).

However, the regulatory framework can be restrictive, as strict interpretations of waste and secondary materials create additional barriers for companies seeking to enter or expand within the market.

Lithuania: Case Study

Despite promising preconditions, Lithuania remains at an early stage of Industrial Symbiosis development. A document submitted to the European Commission (2025) states that “there is a need to promote the use of reusable, environmentally friendly materials in production. This includes adopting ‘safe by design’ technological solutions, implementing eco-design principles, developing innovative circular business models, and promoting industrial symbiosis.”

From a strategic policy perspective, Lithuania demonstrates strong ambitions to address this gap. However, limited institutional coordination and the absence of dedicated platforms for industrial cooperation continue to constrain the practical implementation of Industrial Symbiosis. This reflects broader challenges related to the limited development of coordinated industrial networks and supporting infrastructure.

Comparative Analysis

The comparative analysis of the selected cases demonstrates that the development of Industrial Symbiosis in different countries is strongly influenced by the interaction between legal frameworks, political support, and institutional coordination.

The case of Kalundborg in Denmark illustrates a bottom-up model that attracts entities to cooperate due

to flexible governance and relatively limited regulatory constraints. In contrast, the Emilia-Romagna region in Italy represents a policy-driven approach, where public authorities actively facilitate cooperation through structured programmes and institutional support mechanisms.

In the case of the Netherlands, an advanced cluster-based model can be observed, supported by strong policy ambitions. However, the regulatory framework is not always supportive. Lithuania reflects an emerging stage of development, where favourable policy directions exist but institutional fragmentation and limited

practical implementation constrain progress.

While technical constraints are important, legislative and political frameworks are equally influential in determining success. Successful Industrial Symbiosis requires not only regulatory clarity but also sustained political commitment and effective institutional coordination.

CONCLUSIONS

The analysis of four cases demonstrates varying levels of Industrial Symbiosis maturity. Even where favourable legal and political conditions exist, successful implementation is not guaranteed. As noted by Paché (2024), a key challenge lies in the limited replicability of industrial symbiosis across different regional contexts. The analysis demonstrates that Industrial Symbiosis develops at different speeds across EU Member States.

While some cases show mature and well-established systems, others – such as Lithuania – illustrate an emerging stage characterised by growing policy attention and significant future potential.

These findings highlight the need for greater regulatory coherence and stronger coordination between policy levels to support the wider development of Industrial Symbiosis across the European Union.

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Navigating the Symbiotic Transition: A Cross-Sectional Analysis of ESRS E5 Adoption in the European Automotive Industry

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ABSTRACT

The implementation of the Corporate Sustainability Reporting Directive (CSRD) and the accompanying ESRS E5 standard fundamentally restructures environmental disclosure requirements for the European automotive sector. This paper investigates the initial compliance strategies of seven major automotive manufacturers (OEMs) during the 2023-2024 reporting cycle, focusing on the operational transition from linear resource management to circular economy principles. Employing a cross-sectional mixed-methods approach, qualitative content analysis was utilized to map corporate reporting against the specific structural requirements of ESRS E5, specifically concerning resource inflows, outflows, and double materiality. Concurrently, a Fisher’s exact test evaluated the presence of institutional isomorphism regarding the explicit adoption of regulatory nomenclature between EU and non-EU entities. Qualitative results indicate a structural transition among EU-headquartered groups from traditional eco-efficiency models toward formalized industrial symbiosis, characterized by documented cross-sectoral material exchanges. Statistically, although complete observational separation occurred between EU and non-EU groups concerning nomenclature adoption, the limited sample size yielded a non-significant p-value. Ultimately, the findings suggest that early ESRS E5 adherence actively drives the standardization of sustainability terminology and facilitates the operationalization of closed-loop material networks within the applicable regulatory jurisdiction.

KEYWORDS

Key Performance Indicators • Circular Economy • Industrial Symbiosis • Automotive Industry • ESG Reporting

INTRODUCTION

The European automotive industry occupies a pivotal position in the transition to a low-carbon economy. As one of the most emissions-intensive industrial ecosystems, it is increasingly subject to regulatory pressure not only to reduce operational emissions, but also to account for the much larger downstream impacts associated with the use of sold products. In the EU, the transport sector is the single largest source of greenhouse gas emissions, comprising nearly 30% of the bloc’s total (Panjaitan et al., 2025). Emissions from transport have shown only marginal declines in recent years (Beba and Öztürk, 2026). Road vehicles alone accounted for roughly 73% of all transport emissions in 2023. This makes decarbonizing the automotive industry an urgent priority (Dhawan et al., 2026).

To address this challenge, the European Green Deal has introduced new regulatory requirements. Among the most consequential is the Corporate Sustainability Reporting Directive (CSRD), under which the European Commission formally adopted the European Sustainability Reporting Standards (ESRS) on 31 July 2023. These binding rules oblige large companies, including the automotive OEMs examined in this study, to disclose their sustainability impacts in a standardized manner (Valcu and Spataru-Negura, 2025).

This mandatory framework improves the comparability and transparency of disclosed information (Christensen et al., 2021; Grewal et al., 2019) and reduces information asymmetry between companies and investors (Grewal et al., 2019). ESG can influence a firm's valuation and cost of capital (Dhaliwal et al., 2011; Christensen et al., 2021). However, empirical research does not yield consistent actual effects. Some studies document substantial improvements, while others point to token compliance (Christensen et al., 2021). Another issue is the strategic adaptation of reporting practices without corresponding operational changes (Grewal et al., 2019), primarily due to the methodological flexibility

that persists within ESG reporting frameworks (Christensen et al., 2021).

From a broader industrial perspective, true circularity in the European automotive sector would imply the development of industrial symbiosis, understood as an eco-industrial network in which one firm's output or waste becomes another's input (Eccles, 2025; Oyewo et al., 2024). The significance of the ESRS shock therefore extends beyond reporting architecture alone. It also concerns whether the new regime can encourage substantive transformation in production systems, resource use, and downstream carbon performance, or whether firms may continue to preserve only symbolic "green hopes" through favourable assumptions and analytical boundary adjustments.

The remainder of the paper proceeds as follows. The next section reviews the literature on ESG reporting, double materiality, and circularity in the automotive sector. The methodology section then outlines the panel construction and empirical design. The subsequent sections present the results of the qualitative research and discuss the implications for stakeholders.

LITERATURE REVIEW

Recent literature emphasizes that ESG disclosure has evolved beyond a purely reporting function and increasingly serves as a strategic signal shaping investor perception, firm valuation, and access to capital. While improved transparency reduces information asymmetry, empirical evidence remains mixed, with several studies pointing to the persistence of symbolic compliance rather than substantive operational change. Earlier non-financial reporting frameworks were characterized by a high degree of flexibility and lack of standardization, allowing firms to selectively disclose information and strategically shape their sustainability narratives. The transition toward the CSRD therefore represents an attempt to enhance comparability, enforcement, and the overall credibility of ESG disclosures.

However, because the ESRS allows companies flexibility in defining actuarial boundaries for downstream emissions, there is an unstudied risk that companies might achieve compliance through mathematical optimization rather than physical decarbonization. ESG metrics and ratings themselves may not reliably reflect underlying sustainability performance. Methodological inconsistencies and differences in measurement approaches can lead to situations where improved disclosure substitutes for real environmental progress,

reinforcing the gap between reported and actual outcomes (Arslan et al., 2025).

In the automotive sector specifically, Beba and Öztürk (2025) find that circular economy disclosures by EU OEMs remain largely symbolic as firms emphasize the compliance ideas such as general waste management targets while stepping away from detailing concrete circular practices such as reuse or remanufacturing. Their analysis of 53 auto sustainability reports reveals a strong dominance of symbolic communication over substantive disclosures when firms discuss circular economy.

This distinction reflects a broader theoretical divide between symbolic and substantive corporate action. While firms may engage in sustainability communication to enhance legitimacy, stakeholders increasingly differentiate between superficial disclosures and tangible value creation, rewarding firms that demonstrate measurable environmental impact over those relying on public relations strategies (Zhu et al., 2016).

By contrast, genuine circularity is incorporated by industrial symbiosis. Munonye et al. (2025) has documented the industrial symbiosis case in the auto domain scrap sheet steel from vehicle production is upcycled into architectural panels, yielding substantial energy and cost savings. However, Ali et al. (2019) warns that

industrial symbiosis can suffer from pseudo-circularity and emphasizes the need for robust, transparent metrics to ensure industrial symbiosis initiatives deliver real environmental gains, otherwise reported circular efforts may be largely symbolic. The literature underscores the risk that, in the absence of strict boundaries and KPIs, OEMs could meet ESRS reporting requirements through optimistic assumptions alone rather than by forging true circular value-chain linkages (Ali et al., 2019; Munonye et al., 2025).

In this context, the risk of greenwashing becomes particularly salient, as firms may exploit disclosure frameworks to create a perception of sustainability without corresponding structural change. This undermines stakeholder trust and highlights the importance of aligning internal practices with externally communicated ESG commitments (Li et al., 2024; Asif and Searcy, 2014).

METHODOLOGY

Sample Selection and Data Collection

The transition to the CSRD represents a critical regulatory shock. Consequently, the longitudinal panel data requisite for advanced causal inference models, such as Difference-in-Differences estimators, is not yet available. Such approaches require extensive pre-treatment and post-treatment time-series data across both an affected treatment group and an unaffected control group to establish parallel trends. Because the analysed reports represent a single cross-sectional snapshot of 2023 to 2024 reporting cycle, establishing a pre-intervention baseline is methodologically unviable at this stage. Therefore, this paper employs a rigorous

cross-sectional and mixed-methods approach. The purposive sample comprises seven globally significant automotive groups representing a dichotomy of immediate regulatory exposure. The group subject to immediate European Union regulatory pressures includes BMW Group, Mercedes-Benz Group, Renault Group, Stellantis, Volvo Group, and Volkswagen Group. Jaguar Land Rover, headquartered in the United Kingdom, serves as the non-European Union comparative entity. A directed qualitative content analysis was conducted on the latest available reports, mapping data against the six ESRS E5 Disclosure Requirements.

Operationalisation

To ensure analytical comparability across manufacturers of vastly different production scales, raw data parameters extracted from the ESG reports were conceptualised into normalised KPIs. The extraction focused specifically on Disclosure Requirement E5-4, pertaining to resource inflows, and Disclosure Requirement E5-5, pertaining to resource outflows and waste. The first primary construct, the circularity rate, measures the proportion of secondary, recycled, or reused materials entering the manufacturing process relative to the total material consumption. This metric directly operationalises the EU’s mandate to decouple production from the extraction of virgin, non-renewable resources. The construct is calculated using the following formula:

The second primary construct, the waste intensity, normalises the aggregate volume of waste generated by the operational scale of the manufacturer. By dividing the total waste tonnage by the total vehicle production volume, this metric provides a standardized measure of resource outflow inefficiency that is resilient to fluctuations in overall market demand or corporate size. The construct is calculated using the following formula:

$$\text{waste intensity} = \frac{\text{total waste generated}}{\text{total vehicle production volume}}$$

$$\text{circularity rate} = \frac{\text{total secondary material inflows}}{\text{total material inflows}}$$

Hypothesis

To test the presence of coercive isomorphism driven by the new regulatory environment, formal statistical hypotheses were developed regarding the explicit adoption of ESRS E5 structural nomenclature. Institutional theory suggests that companies within the jurisdiction of the CSRD will rapidly align their reporting lexicon with the mandated taxonomy to maintain institutional legitimacy. The explicit use of terms such as “resource inflows”, “resource outflows”, and “double materiality” serves as the primary indicator of this alignment.

H0: The probability of an automotive manufacturer explicitly adopting ESRS E5 structural nomenclature in its corporate reporting is independent of its jurisdictional headquarters.

H1: Automotive manufacturers headquartered within the EU are significantly more likely to explicitly adopt

ESRS E5 structural nomenclature than their non-European counterparts.

A binary scoring system was applied to the sample to quantify the qualitative content analysis. A value of one was assigned for the explicit, structural adoption of the ESRS E5 nomenclature as primary reporting categories, and a value of zero was assigned for non-adoption or reliance on legacy frameworks. Given the categorical nature of the dependent and independent variables, alongside the heavily constrained sample size of seven distinct observations, traditional parametric tests and standard chi-square approximations are statistically invalid. Consequently, a Fisher’s exact test was selected as the most robust and mathematically appropriate nonparametric procedure to calculate the exact probability of the observed frequency distribution.

RESULTS

Qualitative ESRS E5 Alignment and Evidence of IS

The directed content analysis reveals varying degrees of alignment with the ESRS E5 paradigm across the sampled organizations. Among the OEMs headquartered within the EU, the reporting structure demonstrates a profound shift from internal eco-efficiency toward complex models of industrial symbiosis. Industrial symbiosis involves the synergistic exchange of materials, energy, water, and by-products among traditionally separate industries. The ESRS E5 framework, specifically through its demands on tracing resource inflows and outflows across the broader value chain, appears to be catalysing the public articulation of these symbiotic networks.

The qualitative data indicates the EU OEMs are no longer merely reporting on internal waste reduction, but are actively detailing cross-sectoral material exchanges. Renault Group provides explicit empirical evidence through dedicated circular economy hubs where end-of-life vehicle dismantling is integrated with third-party recycling and energy storage companies. Similarly, the sustainability narratives of Volkswagen Group and Stellantis emphasize closed-loop metallurgical networks, specifically battery mineral recovery where by-products are redirected as critical secondary inflows for adjacent industries.

Conversely, the qualitative analysis of the comparative non-European group, Jaguar Land Rover, reveals a reporting narrative still predominantly rooted in traditional environmental management, focusing on waste

diversion within the immediate manufacturing footprint rather than cross-industry resource exchanges. Beyond the statistical divergence in structural nomenclature, the most critical finding of the qualitative analysis is the role of the ESRS E5 standard in formalising industrial symbiosis within corporate strategy. Historically, automotive environmental reporting has been dominated by the paradigm of eco-efficiency, which focuses on minimising the negative environmental impacts of a linear production model. However, the explicit requirements of ESRS E5 to map specific secondary material inflows and categorised waste outflows across the value chain fundamentally alter the strategic utility of sustainability data.

The analysis reveals that the rigorous data collection required for ESRS compliance acts as a crucial enabler for industrial symbiosis. By forcing OEMs to accurately quantify and publicly disclose their waste streams, the directive inadvertently transforms these ESG reports into catalogues of available secondary resources for other industrial sectors. OEMs that successfully articulated these complex material flows, particularly in the context of battery supply chains and rare earth element recovery, demonstrated a superior strategic capacity to frame circular economy initiatives. The integration of double materiality assessments further compounds this effect. Rather than presenting waste generation merely as a compliance cost, companies deeply aligned with the ESRS E5 framework utilised

industrial symbiosis to reposition waste streams as revenue-generating by-products. By establishing symbiotic partnerships for the off-take of manufacturing scrap and the intake of recycled polymers and metals, these OEMs are actively hedging against raw material scarcity, geopolitical supply chain disruptions, and the volatility of virgin commodity markets. Consequently, the ESRS E5 standards appears to not only harmonise

non-financial reporting but also structurally accelerate the automotive industry's integration into broader, cross-sectoral circular economies.

In summary, the rigorous data collection required for ESRS E5 compliance transforms ESG reports from passive disclosures into active catalogues of available secondary resources for other industrial sectors.

Hypotheses

The application of the binary scoring system yielded a complete observational divergence regarding the explicit structural adoption of ESRS E5 nomenclature. All six EU-headquartered OEMs received a positive adoption score, reflecting their explicit integration of the mandated reporting structures. Conversely, the comparative non-EU group received a non-adoption score, as its reporting remained structured around legacy frameworks.

The Fisher's exact test yielded a calculated p-value of 0.1428. Because this exceeds the 0.05 threshold, the null hypothesis cannot be formally rejected. While the small sample size limits statistical power, the absolute separation observed—100% adoption in the EU vs. 0%

outside—provides compelling preliminary evidence of the directive's coercive power in standardizing sustainability terminology.

The observation that entirely one hundred percent of the EU OEMs adopted the rigid nomenclature, compared to zero percent of the comparative non-EU OEM(s), suggests that the regulatory environment is precipitating a rapid standardisation of corporate sustainability terminology. The reliance of non-EU OEMs on legacy frameworks highlights an emerging divergence in global reporting standards, which poses immediate comparability challenges for international analysts attempting to evaluate the maturity of firm's circular economy transition.

CONCLUSIONS

This study examined whether the introduction of the CSRD and ESRS E5 operates as a mechanism for substantive transition in the European automotive industry. Using a panel of seven major automotive OEMs, the analysis indicates a dual-track response to the regulatory shock.

On one hand, the evidence suggests a "regulatory nomenclature effect." Highly exposed European manufacturers have rapidly aligned their reporting architecture with the ESRS E5 requirements, facilitating the operationalization of industrial symbiosis. This alignment allows firms to reposition waste streams as revenue-generating by-products and hedge against raw material scarcity.

On the other hand, the results indicate that the reported trajectory of circularity remains sensitive to firm-level boundaries. While the CSRD framework is strong enough to formalize material tracking and governance priorities, it is not yet sufficiently standardized to eliminate asymmetries in how firms define secondary material inflows.

For policymakers, the findings suggest that while mandatory disclosure acts as a necessary first step in

transparency, more prescriptive and sector-specific guidance may be required to prevent "materiality arbitrage" in resource outflow reporting. Without stricter boundaries for modelling assumptions and KPIs, firms may continue to meet reporting requirements through optimistic adjustments rather than physical operational changes. For managers, the transition demonstrates that integrating reporting obligations directly with product strategy and capital allocation allows firms to translate regulatory pressure into credible circular capacity rather than mere disclosure optics. By establishing symbiotic partnerships for manufacturing scrap and recycled materials, these managers can actively hedge against raw material scarcity and supply chain disruptions.

Future research should extend the empirical window as more reporting cycles under CSRD become available and examine whether this nomenclature adoption leads to a measurable increase in the "circularity rate" over time.

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Cross-Sectoral Fermentation Pathways for Sustainable Production

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ABSTRACT

Fermentation-based processes are increasingly recognised as critical enablers of sustainable production within circular bioeconomy frameworks. However, their large-scale implementation remains constrained by sectoral fragmentation, economic barriers, and governance challenges. This presentation examines cross-sectoral fermentation pathways as integrative production models that connect agri-food systems, industrial biotechnology, waste management, and policy domains to enhance sustainability outcomes.

Drawing on recent biorefinery and systems-level studies, the analysis highlights how geographically and operationally integrated value chains can improve resource efficiency and economic viability. For instance, citrus-sugarcane biorefineries in Brazil demonstrate how agricultural residues can be valorised through microbial fermentation to produce polyhydroxyalkanoates (PHA), reducing feedstock costs while leveraging existing industrial infrastructure (Kanbe et al., 2024). Such cross-sectoral models illustrate the potential of fermentation to link primary production, waste valorisation, and biopolymer manufacturing.

The presentation further situates fermentation within broader systemic and technological contexts. Multi-sectoral metabolism analyses of water–ener–

gy–nutrient nexuses show that combining anaerobic fermentation with complementary processes such as composting or fungal cultivation can optimise resource flows at regional scales (Wen et al., 2021). In parallel, advances associated with Industry 5.0, including AI-enabled process monitoring, smart waste management, and digital traceability are shown to enhance the efficiency and circularity of fermentation-based systems in sustainable food production (Gaikwad and Anerao, 2025).

Despite these opportunities, significant barriers remain. Technical scale-up challenges, high capital costs, regulatory uncertainty, and socio-political acceptance continue to hinder commercial deployment of integrated biorefineries (Makepa and Chihobo, 2024). Cross-sectoral collaboration, supportive policy frameworks, and international knowledge exchange are therefore identified as key enablers for overcoming these constraints. Taken together, this presentation proposes a cross-sectoral analytical perspective on fermentation pathways, demonstrating how integrated biorefinery models and systemic coordination can position fermentation as a central driver of sustainable and low-carbon production systems.

KEYWORDS

Cross-sectoral fermentation • Sustainable production • Integrated biorefineries
Circular bioeconomy • Waste valorisation

INTRODUCTION

The conventional linear model of industrial production, characterized by the extraction–use–disposal paradigm, has led to significant environmental degradation, resource depletion, and excessive waste generation. In response, the concept of sustainable production systems has emerged as a strategic framework to enhance resource efficiency, minimize environmental impacts, and support long-term economic resilience (Hegab et al., 2023). Within this transition, the circular economy paradigm has gained increasing attention, promoting the reuse, recycling, and valorisation of waste streams into value-added products.

Among the available technological pathways, fermentation has re-emerged as a cornerstone of sustainable biotechnology. Historically used in food preservation and processing, fermentation is now recognized as a versatile platform capable of converting a wide range of renewable and waste-derived substrates into high-value products, including organic acids, biofuels, enzymes, bioactive compounds, and biopolymers (Gabriele et al., 2026). This transformation aligns closely with circular bioeconomy principles, where biological processes are leveraged to close material loops, reduce greenhouse gas emissions, and enhance overall system sustainability.

The growing importance of fermentation extends beyond environmental sustainability to encompass food security and human health. Fermented products and postbiotics have been shown to contribute to gut microbiome modulation, immune system enhancement, and the prevention of metabolic and inflammatory disorders (Gabriele et al., 2026). In parallel, advances in precision fermentation and synthetic biology enable the design of tailored microorganisms for the production of specific food ingredients and chemicals, reducing reliance on traditional agricultural systems and enabling more controlled and resource-efficient production processes.

From an industrial perspective, fermentation also plays a critical role in the transition toward bio-based chemical production. Biomass-derived feedstocks, which are inherently rich in oxygenated functional groups, are particularly suitable for microbial conversion processes. Consequently, fermentation technologies are increasingly considered key enablers for replac-

ing fossil-based production routes with renewable alternatives (Ewing et al., 2022). Several fermentation processes have already reached pilot or industrial scale, demonstrating their feasibility for producing bulk chemicals within a circular economy framework. In addition to standalone applications, fermentation is increasingly integrated into biorefinery systems, where multiple conversion processes are combined to maximise resource utilisation. For instance, brewery wastewater has been explored as a low-cost substrate for lactic acid production through microbial fermentation, illustrating how industrial effluents can be transformed into valuable biochemical products while simultaneously reducing environmental burdens (Zacharof, 2021). Such approaches exemplify industrial symbiosis, where waste streams from one sector become inputs for another, enhancing both economic and environmental performance.

Despite these promising developments, the large-scale implementation of fermentation-based sustainable production systems remains constrained by several challenges. These include technical limitations related to process scale-up and feedstock variability, economic barriers such as high capital investment and uncertain market competitiveness, and regulatory complexities that hinder innovation and deployment (Hegab et al., 2023). Furthermore, the lack of cross-sectoral integration often results in fragmented systems that fail to fully exploit the potential of fermentation technologies. In this context, there is a growing need for integrative approaches that connect fermentation processes across multiple sectors, including agriculture, food processing, industrial biotechnology, and waste management. Cross-sectoral fermentation pathways offer a promising solution by enabling the design of interconnected value chains that enhance resource efficiency, support waste valorisation, and contribute to sustainable production systems. Therefore, this study aims to explore fermentation as a cross-sectoral platform for sustainable production by synthesizing current technological advances, identifying key implementation challenges, and highlighting strategic pathways for integration within circular bioeconomy systems.

METHODOLOGY

Cross-sectoral fermentation can be conceptualized as an integrative, systems-based biomanufacturing approach that connects agricultural production, food

processing, waste management, and industrial biotechnology through biologically mediated conversion processes. Unlike conventional linear or sector-specific

production models, this framework is grounded in the principle of interconnected resource flows, where heterogeneous biomass streams are continuously revalorised across sectors. In this context, fermentation functions not merely as a unit operation but as a central technological platform that enables the transformation of low-value or residual biomass into a diverse portfolio of high-value products, including bioactive compounds, microbial biomass, enzymes, and bio-based chemicals. This systemic perspective aligns closely with the principles of the circular and regenerative bioeconomy, in which waste is redefined as a resource and production systems are designed to maintain material value over extended cycles (Singh et al., 2021; Girotto and Beggio, 2025).

Recent advances in biomanufacturing highlight that fermentation-driven systems can substantially contribute to sustainability objectives by reducing greenhouse gas emissions, lowering land and water use, and minimizing waste generation compared to conventional agricultural and industrial practices (Bandari et al., 2026). However, these benefits are not uniformly realized across contexts, as the implementation of such systems introduces complex trade-offs spanning environmental, economic, social, and governance dimensions. Therefore, cross-sectoral fermentation must be understood within a multi-dimensional sustainability framework, where environmental gains are evaluated alongside economic feasibility, societal acceptance, and institutional readiness. This holistic perspective is essential, as technological efficiency alone does not guarantee successful adoption or long-term sustainability (Bandari et al., 2026).

A defining characteristic of cross-sectoral fermentation systems is their reliance on diverse and often underutilised biomass resources. Agro-industrial by-products originating from sectors such as fruit and vegetable processing, dairy production, fisheries, and meat industries represent nutrient-rich substrates with significant biochemical potential. Through microbial biotransformation, these substrates can be converted into functional metabolites, antimicrobial compounds, and nutritionally enhanced products, while also improving their stability and bioavailability (Gonçalves et al., 2026; Olagoke-Komolafe, Oyeboade, 2025). Importantly, the integration of multiple substrate streams within a single system enhances process efficiency and supports cascading utilisation strategies, where biomass is sequentially converted into multiple products of increasing value. Such approaches not only reduce waste but also maximise the economic return from

available resources (Gonçalves et al., 2026).

Within this framework, fermentation is increasingly embedded in broader circular and regenerative bioeconomy systems that extend beyond waste minimisation toward active value creation. The concept of upcycling, defined as the transformation of organic residues into products with higher functional or economic value, is central to this transition. In parallel, digital and technological innovations are emerging as critical enablers of cross-sectoral integration. Data-driven tools, including artificial intelligence, machine learning, and digital twins, facilitate real-time monitoring of fermentation processes, optimisation of operational parameters, and dynamic allocation of biomass resources across interconnected value chains (Girotto and Beggio, 2025).

Despite these technological advancements, the realization of cross-sectoral fermentation systems is strongly influenced by institutional and governance factors. Empirical evidence suggests that integrative solutions are often constrained by fragmented decision-making structures, misaligned stakeholder interests, and unequal distribution of costs and benefits. In particular, differences in perceived objectives among stakeholders, limited inclusion of relevant actors in governance processes, and the absence of clear coordination mechanisms can significantly hinder the operationalization of cross-sectoral systems (Bakhanova et al., 2025). These findings underscore the importance of establishing coherent governance frameworks that facilitate collaboration, ensure transparency, and promote equitable value-sharing among participating actors.

Furthermore, the broader implementation of cross-sectoral fermentation is challenged by persistent structural barriers, including knowledge fragmentation across sectors, lack of standardized methodologies for evaluating circular economy performance, and insufficient integration of system-level assessment tools such as life cycle assessment and material flow analysis (Singh et al., 2021). In many cases, research and industrial applications remain confined to isolated case studies, limiting the transferability and scalability of successful models. This highlights the need for integrative analytical frameworks that can capture the complexity of cross-sectoral systems while providing actionable insights for stakeholders. Taken together, the conceptualization of cross-sectoral fermentation as a multi-layered and interdisciplinary system provides a foundation for advancing sustainable production models. By linking biomass resources, microbial conversion processes,

digital technologies, and governance structures within a unified framework, this approach enables the design

of production systems that are not only efficient and low-carbon but also resilient and socially inclusive.

CROSS-SECTORAL BIOREFINERY MODELS

Cross-sectoral biorefinery models represent advanced configurations of sustainable production systems in which multiple sectors, resource streams, and technologies are integrated to maximize biomass valorisation within circular production frameworks. In these systems, fermentation plays a central role as a flexible bioconversion platform capable of transforming heterogeneous feedstocks into high-value bio-based products.

A representative example is the citrus–sugarcane biorefinery model in Brazil, where citrus residues are utilized as carbon sources for polyhydroxyalkanoates (PHA) production while leveraging existing industrial infrastructure (Kanbe et al., 2024).

Recent European circular bioeconomy initiatives further highlight the diversity and applicability of cross-sectoral biorefinery approaches (<https://circulareconomy.europa.eu/>).

These projects demonstrate how heterogeneous waste streams including agricultural residues, industrial wastewater, and food waste can be converted into value-added products through fermentation and integrated processing pathways. Notably, initiatives such as Water2REturn, PROMOFER, and ELLIPSE exemplify the recovery of nutrients, biopolymers, and bio-based compounds from complex waste streams, while industrial implementations such as Corbion and NP-bioTech demonstrate scalable fermentation-based production systems. Additional projects, including BioSupPack, Vanheede, and Hydal biotechnology, further illustrate the expansion of cross-sectoral integration into packaging, energy, and material applications. For clarity, the main characteristics of these initiatives are summarized in Table 1.

Table 1. European Cross-Sectoral Biorefinery and Circular Bioeconomy Initiatives

Project / Company	Feedstock	Sector Integration	Technology	Main Output	Key Contribution
Water2Return (Spain)	Slaughterhouse wastewater	Agriculture, Food, Forestry	Nutrient recovery, fermentation	Fertilisers	Nutrient recycling from wastewater
PROMOFER (EU)	Straw, wastewater, starch	Multi-sector	Fermentation, downstream processing	Bio-based compounds	Valorisation of low-value feedstock
ELLIPSE (Spain)	Slaughterhouse waste, pulp, glycerol from biodiesel industry, sludge from dairy industry	Multi-sector (food, biofuel, waste)	Fermentation	PHA biopolymers	Multi-stream integration
Corbion (Netherlands)	Sugars and Algae	Agriculture, Food, Biotech	Microalgae fermentation	Omega-3 (DHA)	Circular nutrient production
NP-bioTech (Italy)	Citrus pulp, sewage sludge	Biobased industries	Accelerated fermentation	Biofertiliser	Fast biomass stabilization
BioSupPack (Aimplas, Spain)	Organic waste streams	Packaging	Fermentation	Sustainable packaging	Circular packaging solutions
Vanheede Biomass Solutions (Belgium)	Packed food waste	Energy	Anaerobic fermentation	Biogas	Waste-to-energy integration
NAFIGATE Corporation (Czechia)	Waste cooking oil	Plastic and Polymer	Fermentation	PHA bioplastics (Hyal)	Industrial-scale biopolymer
Envien Group (Slovakia)	Crops, used oils	Agriculture, Energy and Refineries	Biorefinery, biofuel production	Biofuels, feed	Integrated fuel systems

CONCLUSION

This study has demonstrated that cross-sectoral fermentation pathways and integrated biorefinery models represent a transformative approach for advancing sustainable production systems within the circular bioeconomy. By linking diverse sectors including agriculture, food processing, industrial biotechnology, and waste management fermentation-based systems enable the efficient valorisation of heterogeneous biomass streams into a wide range of bio-based products. Such integration not only enhances resource efficiency and reduces environmental impacts but also supports the development of resilient and diversified value chains.

The analysis highlights that the effectiveness of cross-sectoral biorefinery models is strongly dependent on system-level integration, where technological, economic, and institutional dimensions are addressed simultaneously. Case studies and large-scale assessments demonstrate that fermentation-driven processes, particularly those integrated into existing industrial infrastructures, offer significant advantages in terms of feasibility and scalability. Moreover, the incorporation of digital technologies and optimization tools further strengthens the capacity of these systems to adapt to dynamic resource availability and market conditions. However, despite their considerable potential, the widespread implementation of cross-sectoral fermentation systems remains constrained by multiple challenges.

Technical barriers related to feedstock variability and process scale-up, economic limitations associated with high investment costs, and regulatory complexities continue to hinder industrial adoption. In addition, fragmented governance structures and insufficient cross-sectoral collaboration limit the realization of fully integrated bioeconomy systems. To address these challenges, future efforts should focus on developing flexible and modular biorefinery designs capable of processing multiple feedstocks, supported by robust techno-economic and life cycle assessment frameworks. Strengthening cross-sectoral collaboration platforms, enhancing policy coherence, and promoting data-driven decision-support tools will be critical for scaling these systems. Furthermore, the integration of digitalization, artificial intelligence, and system-level optimization approaches can enable more efficient and adaptive biomanufacturing processes.

In conclusion, cross-sectoral fermentation and biorefinery integration offer a powerful pathway toward sustainable, low-carbon, and circular production systems. Realizing this potential will require coordinated efforts across technological innovation, policy development, and stakeholder engagement, ultimately contributing to the transition toward a more sustainable and resilient bio-based economy.

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Industrial symbiosis and entrepreneurship Croatian case studies

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ABSTRACT

Industrial symbiosis (IS) represents one of the key mechanisms for implementing a circular economy, enabling resource optimization through cooperation between companies from different industrial sectors. In the context of the Croatian economy, which faces challenges of low productivity, limited innovation capacity, and slow transformation towards sustainable business models, IS opens new opportunities for the development of sustainability- and innovation-based entrepreneurship. In this framework, green entrepreneurship occupies a special place, connecting economic growth with environmental protection and the efficient use of resources through innovative business models.

This paper explores the link between IS and green entrepreneurship (GE) by presenting a Croatian example of an IS-based entrepreneurial venture. Research applied quantitative analysis of secondary data on waste management in the member states of the European Union; a structural review of the academic literature on

green entrepreneurship and IS; and a case study methodology to exemplify the implementation of green entrepreneurship grounded in IS. Given the empirical focus on Croatia, the study provides country-specific insights while recognizing that some conclusions may have limited generalizability across the broader European Union.

The results show how IS can stimulate the development of innovative business models, especially in the waste, energy, and agriculture sectors, where there is significant potential to optimize resource flows. The analysis also highlights the need for institutional support, resource exchange platforms and education of entrepreneurs to encourage the broader application of IS solutions in Croatia. This paper contributes to understanding the role of entrepreneurship in implementing IS and offers practical guidelines for fostering entrepreneurial ecosystems geared toward sustainable economic growth.

KEYWORDS

Industrial symbiosis • waste management • entrepreneurship • innovation

INTRODUCTION

In recent years, waste management has become a central component of the European Union's transition from a linear to a circular economy. The traditional "take-produce-discard" model has led to resource depletion, environmental degradation, and economic losses (European Parliament, 2017). In the broader economic context, waste is increasingly viewed not as

a final by-product but as a secondary raw material that can be reintegrated into production processes, contributing to economic growth, employment, and the development of innovative business models such as industrial symbiosis (IS). IS, defined by Chertow (2007), refers to cooperation between firms through the exchange of

materials, by-products, energy, or waste to improve resource efficiency and reduce environmental impacts. Within the broader framework of industrial ecology, IS relies not only on spatial proximity but primarily on functional relationships that allow the waste streams of one organization to serve as input resources for another (Chertow, 2007). In the field of waste management, IS is particularly significant because it shifts the perception of waste from a final-stage by-product to a resource with untapped potential. Chertow (2007) emphasizes that such an approach shifts the focus from traditional waste-disposal methods or incineration to the optimization of material and energy flows within industrial networks. Instead of the linear logic of “production-consumption-disposal”, a network model is introduced in which by-products, waste heat or secondary materials circulate between companies. Consequently, the amount of waste sent for final disposal decreases while overall resource efficiency increases. Analyzing empirical examples, Chertow (2007) concludes that forms of IS that emerge gradually, through the spontaneous connections of existing industrial actors, show greater long-term stability than models introduced

in a planned, top-down manner, such as formally established eco-industrial parks. This approach highlights IS as an important instrument of sustainable industrial development. In this context, the paper analyses the macroeconomic trends, challenges, and development potential of waste management in the European Union, with a particular focus on Croatia. The analysis, based on secondary sources including Eurostat and the European Environment Agency (EEA), shows how improved waste management strategies can stimulate the development of green entrepreneurship. This is particularly important for countries like Croatia, which continue to face below-average levels of resource circularity and productivity (World Bank, 2022).

The main aim of the paper is to explore the potential of IS to promote green entrepreneurship within the Croatian context. In the first two sections, waste management is explored as an opportunity for green entrepreneurship. In the following sections, case studies of two Croatian companies are examined to demonstrate how green entrepreneurship and IS can be combined. In the last part, the conclusion and the proposals for further research are given.

WASTE MANAGEMENT AS AN OPPORTUNITY – MACROECONOMIC VIEW

Macroeconomic Context of Waste Generation in the EU and Croatia

Eurostat (2024a) defines waste as material that the holder discards or intends to discard, covering flows from households, industry and the construction sector. In 2022, around 5.0 tons of waste per inhabitant were generated in the European Union, and more than 60% of the total waste treated was recovered through processes such as recycling, reuse, and energy recovery. In 2023, the average EU resident produced 511 kg of municipal waste, while the quantities of packaging waste (177.8 kg per inhabitant) and food waste, which amount to around 130 kg per person per year, continue to pose a significant challenge, due to the high share of waste originating from households (Eurostat, 2024a).

Data on municipal waste provide insight into consumption patterns and the efficiency of waste management in EU Member States. Municipal waste accounts for around 10% of total waste in the EU, of which almost 48% was recycled or composted in 2023, while about a quarter was incinerated with energy recovery (Eurostat, 2024b). Although landfill rates have declined over time, significant differences between Member States remain, indicating that further improvements in waste management policies are necessary to achieve the 2030 circular economy targets. Eurostat data indicate gradual

progress in waste recovery, but also a persistent link between consumption levels and waste generation. Sverko Grdić et al. (2020) show that more economically developed EU Member States tend to produce more municipal waste per capita due to higher consumption and industrial activity. However, these countries also achieve higher recycling and recovery rates, suggesting that effective waste management systems can partially decouple economic growth from environmental pressure. In this sense, the results of Sverko Grdić et al. (2020) complement Eurostat’s indicators by confirming that more developed countries have a greater capacity to implement circular models, but at the same time bear greater responsibility for further reducing waste per capita.

In Croatia, waste generation patterns largely coincide with those in the rest of the European Union. However, they are strongly influenced by the level of economic development and the relatively modest industrial structure. According to the European Environment Agency, in 2022, Croatia generated around 7.1 million tons of waste, with a continuous increase over the last ten years (EEA, 2025a). On a per capita basis, total waste amounts to around 1.3 tons per year, which is significantly below the EU-27 average of around

5 tons. Despite this, municipal waste volumes have been increasing significantly over the last decade (EEA, 2025b). Municipal waste growth in Croatia is driven by demographic changes, tourism-related consumption, and underdeveloped waste prevention systems (World Bank, 2022). Compared to leading countries such as Germany and Denmark, which generate around 700 kg of municipal waste per capita while maintaining highly developed recycling systems, Croatia still has significant potential to improve resource efficiency (Sverko Grdić et al., 2020). At the European Union level, the average municipal waste generation is around 511 kg per capita, while in Croatia it is estimated at 400-450 kg per capita. This difference can partly be explained by inconsistencies in reporting systems and informal disposal practices that are not fully captured by official statistics (EEA, 2025a). From an economic perspective,

waste volumes reflect the level of economic activity but also generate high financial and environmental costs when not managed effectively; at the EU level, billions of euros are spent annually on waste disposal and incineration, while environmental externalities are estimated at €50–100 per ton of waste (European Parliament, 2017). In Croatia, the problem is further exacerbated by the fact that more than 60% of municipal waste is still landfilled, well above the EU target of reducing landfill use to no more than 10% by 2035 (World Bank, 2022). This approach burdens public finances and represents a loss of potential revenue. Valuable materials that could be returned to production flows through recycling end up in landfills, thereby missing opportunities to develop the secondary raw materials market, reduce import dependence, and strengthen domestic economic resilience (Stojanović et al., 2025).

Recycling and recovery rates: shortcomings, potential and progress

Recycling and material recovery measures are key indicators of the level of development of the circular economy, as they enable the transformation of waste into economically usable resources. At the European Union level, almost half (48%) of municipal waste was recycled or composted in 2023, while the recycling rate for packaging waste was significantly higher, at around 65% (Eurostat, 2024b). Countries with developed waste management systems, such as Austria, where more than 60% is recycled, and Germany, with shares above 65%, show the effects of targeted policies, in particular extended producer responsibility (EPR) systems, which encourage higher material recovery rates (Sverko Grdić et al., 2020). In this context, information and technical coordination within eco-industrial clusters play an important role; for example, waste from the food industry can be used to produce biogas, which in more efficient systems reduces the total amount of waste by 20 to 30% (Neves et al., 2020). Despite these good practices, Croatia still lags behind the European average. The recycling rate for municipal waste in 2022 was between 25 and 30 %, well below the EU average and the 50 % target set for 2020 (EEA, 2025b; World Bank, 2022). This situation is the result of structural problems, including insufficiently connected waste collection systems, limited citizen involvement and infrastructure deficiencies, especially in less urbanized areas (Erceg et al., 2024). At the same time, the packaging waste segment shows more favorable trends, with approximately 55% of volumes recycled, mainly due to binding European regulations and private-sector engagement (Eurostat, 2024b). The economic potential of increasing recycling

rates in Croatia is significant. It is estimated that more efficient material recovery could generate additional revenues of 200 to 500 million euros per year through the value of secondary raw materials, based on average EU indicators (European Parliament, 2017).

Comparative research at the international level confirms that higher recycling rates are associated with greater economic development. According to the findings of Sverko Grdić et al. (2020), a 1% increase in GDP is associated with a 0.16% increase in the municipal waste recycling rate, suggesting that more developed economies invest more in waste management systems. In transition economies such as Croatia, which is often classified in the literature as a so-called frontier economy due to its emerging-market characteristics (Costa et al., 2010), obstacles include technical limitations and stakeholder mistrust. Despite existing limitations, opportunities to improve waste management systems are emerging through the financial instruments of the European Union, among which the NextGenerationEU program stands out for its aim to encourage sustainable structural transformations (Erceg et al., 2025). The area of biowaste, which is currently recycled in relatively modest quantities in Croatia, estimated at around 50 kg per capita, stands out. Increasing its recycling rates could enable more efficient use of digital and analytical tools in agriculture, thereby allowing organic matter to be reused as fertilizer while reducing greenhouse gas emissions (Sund et al., 2025).

Waste management as a driver of economic opportunities and IS

The macroeconomic perspective of waste management highlights its potential as a driver of economic development, primarily through the application of circular economy principles and information systems. According to the EU Circular Economy Action Plan, approximately 700,000 new jobs are expected to be created by 2030, a significant proportion of which are linked to waste management sectors. This effect is primarily achieved by closing material flows, thereby reducing dependence on imported resources and strengthening the economy's competitiveness (European Parliament, 2017). Information systems support these processes by enabling collaboration between companies, while European experience shows that policies encouraging material substitution can reduce costs by 10–20% while simultaneously lowering emissions (Costa et al., 2010). In developing countries, the integration of information systems can facilitate the inclusion of informal economic activities and local resources, potentially increasing the contribution of the waste management sector to gross domestic product from less than 1% to around 2–3% (Cárcamo and Peñabaena-Niebles, 2022).

In the Croatian context, where the circularity rate is only 2.7%, compared to the EU average of 12.8%, the waste management sector represents a significant development opportunity (World Bank, 2022). However, the broader application of information technologies is hampered by a fragmented regulatory framework and the spatial fragmentation of the system. Despite these limitations, specific segments, such as waste tire and

sludge processing, show strong entrepreneurial potential, which is discussed in more detail in the following case studies (Erceg et al., 2024). EU-level estimates suggest that achieving circular economy goals in Croatia could bring economic benefits of €1-2 billion by 2030, primarily through reducing waste disposal costs and developing the market for recycled materials (Stojanović et al., 2025). Furthermore, the introduction of digital waste stream tracking could improve the efficiency of information systems, combining traditional approaches with technological solutions, as confirmed by comparative analyses of Croatia and Slovenia (Unukić, 2025). Social and environmental aspects further emphasize the importance of efficient waste management. It is estimated that inadequate practices in this area contribute to 5-10% of total greenhouse gas emissions in the European Union.

In comparison, the application of information technologies in targeted sectors can result in emission reductions of 15-25% (Neves et al., 2020). In Croatia, where tourism and agriculture account for a significant share of GDP, environmentally sustainable waste management strategies help preserve natural resources and increase the attractiveness of sustainable investments, thereby indirectly stimulating entrepreneurship (World Bank, 2022). To further strengthen these effects, it is recommended to strengthen the extended producer responsibility system, finance regional information technology centers, and systematically train relevant stakeholders (Sund et al., 2025).

Challenges and Policy Implications

Despite clearly identified development opportunities, macroeconomic constraints in waste management remain significant. Accelerated urbanization and industrialization worldwide, including in the European Union, could lead to municipal waste reaching about 3.4 billion tons by 2050. In conditions of insufficient waste segregation, Europe would have a significant share of this growth (Cárcamo & Peñabaena-Niebles, 2022). In the Croatian case, the lower level of GDP per capita, estimated at approximately 15,000 euros, compared to around 35,000 euros on average in the European Union, limits fiscal capacity, encourages reliance on bulk waste disposal and slows down the integration of information systems in the waste management sector (EEA, 2025a). In addition, the inconsistent implementation of European Union legislation deepens the differences in the efficiency of the systems across Member States (Costa et al., 2010). In this context, improving the waste recovery system requires targeted macro-

economic measures. These include directing EU funds towards the construction and modernization of waste treatment facilities, introducing fiscal incentives for the development and application of information technologies, and encouraging cross-border knowledge and expertise exchange (Stojanović et al., 2025). Such an approach aligns with the goals of sustainable development, with waste increasingly viewed as a source of innovation and a factor in strengthening economic resilience. In conclusion, waste management at the European Union level and in Croatia has significant macroeconomic potential when viewed through the lens of the circular economy and the application of information systems. Reducing differences in recycling rates and the effectiveness of public policy implementation could help bring Croatia closer to European standards and encourage the development of environmentally friendly, competitive business models.

GREEN ENTREPRENEURSHIP AND INDUSTRIAL SYMBIOSIS

One of the relatively new areas within entrepreneurship is green entrepreneurship (GE) (Muo & Azeez, 2019). According to the Green Project (Muo & Azeez, 2019), GE encompasses “activities that are consciously addressing environmental/social problems/needs through implementation of entrepreneurial ideas amidst high risks and expectation of net positive impact on environment and financial sustainability.”

In this context, green SMEs are defined as those that actively contribute to protecting the climate, environment and biodiversity through their products, services and business practices (Koirala, 2019 in Vasilescu et al., 2023). According to the same author, green SMEs can be classified into three groups: eco-innovators, who enter the market with radical and disruptive innovations; eco-entrepreneurs, who, similar to traditional entrepreneurs, recognize and exploit market opportunities while respecting environmental goals; and eco-adopters, whose actions are primarily based on compliance with existing environmental regulations (Koirala, 2019 in Va-

silescu et al., 2023). Among these groups, eco-innovative small and medium-sized enterprises are recognized as the most significant actors in GE, as confirmed by the extensive scientific literature focused on factors influencing the development of eco-innovations (Vasilescu et al., 2023). The increasing relevance of GE is also confirmed by the growing emphasis policymakers place on environmental protection and the efficient use of natural and recycled resources.

In this context, it is important to highlight IS as a concrete means of implementing GE. The keys to IS are collaboration and the synergistic possibilities [often] offered by geographic proximity.” Based on the above, it is evident that GE and IS complement each other, with the latter providing a concrete framework for achieving the environmental and economic goals of green entrepreneurs. The effectiveness of such models in practice is confirmed by numerous examples from different industries worldwide (Table 1).

Table 1. GE and IS examples. Source: Author's design

Company name	Short description	GE	IS
ECOALF	They began by producing clothes from recycled ocean plastic, then developed technology to recycle other materials, which they also use as resources in their production.	+	+
TOAST ALE	A company produces beer from old bread purchased from a baker. All their income is donated to a charity dedicated to reducing food waste.	+	+
MARITIMO RECYCLING	They collect caps from plastic bottles in the Adriatic Sea, recycle them, and use the recycled material to make sunglasses frames.	+	+
LEAF	They produce disposable plates from leaves, which are used instead of disposable plastic plates for the same purpose.	+	
HORTIRIVIERA	The company produces cleaning detergents from natural ingredients that are safe for humans and the environment.	+	
TINKTURA	They produce and sell cosmetic products that do not have a harmful effect on humans or the environment.	+	

The above table shows that some examples exhibit characteristics of both GE and IS, such as the companies Ecoalf, Toast Ale and Maritimo Recycling. In contrast, GE primarily emphasizes products and processes that do not harm the environment and that improve the community's quality of life. This approach is evident in examples such as Leaf, Hortiriviera, Tinktura and Include. The

key difference between these groups of companies is that those involving IS are characterized by recycling or reusing materials, in which waste or by-products serve as raw materials for producing new products. This further promotes the circular economy and more efficient use of resources.

METHODOLOGY & LIMITATIONS

This study applies a research design that integrates quantitative analysis of secondary macroeconomic data, a structured literature review and qualitative case studies. The aim is to explore the potential of IS to promote GE within the Croatian context. Given the empirical focus on Croatia, the study provides country-specific insights while recognizing that some conclusions may have limited generalizability across the broader European Union.

The first component of the research is based on secondary data on waste management in the member states of the European Union. Official statistical databases (Eurostat and the European Environment Agency) provide indicators such as total and per capita waste generation, recycling and recovery rates, disposal methods and selected measures of circular economy performance (Sund et al., 2025). The quantitative data are examined using descriptive statistics and cross-country comparative analysis. This macro-level perspective provides the context for understanding the framework conditions within which GE and IS initiatives emerge. The second component consists of a structured review of the academic literature on GE and IS (Neves et al., 2020). This review provides an analytical lens for

interpreting both macroeconomic patterns and case study evidence in terms of their relevance to GE. The third component of the research design comprises two qualitative case studies from Croatia that exemplify the implementation of GE grounded in IS. The cases are analyzed with respect to their business models, resource flows, governance arrangements, and observed environmental and local economic impacts to understand how IS is operationalized at the firm and regional levels.

Finally, the findings from the Croatian case studies are used to contextualize and illustrate the macro-level and theoretical patterns, enabling a triangulated assessment of the conditions, drivers and barriers for the development of GE based on IS in the EU and in Croatia. This integrated analytical strategy increases the robustness and practical relevance of the study's conclusions. Given the empirical focus on Croatia, the study provides country-specific insights while recognizing that some conclusions may have limited generalizability across the broader European Union.

CASE STUDIES

Gumiimpex LTD Varaždin

Gumiimpex-GRP is a leading Croatian manufacturer of rubber and technical products, specializing in the recycling of waste tires and the retreading of truck tires. The main activities include the sale of tires of renowned brands (Michelin, Goodyear, Bridgestone), the production of over 7,000 rubber and technical products per year, tire retreading using NEXT TREAD technologies, and tire repair services. A key investment was the opening of the first Croatian tire recycling plant in the Varaždin Free Zone in 2005, which was later expanded to Trnovec Bartolovečki (Gumiimpex, 2025).

Gumiimpex-GRP applies the principles of IS by converting waste car tires into resources through mechanical recycling: the tires are torn, shredded, and separated into granulate, steel, and textiles, without emissions or waste. Granulate of various sizes is used in construction (geotextiles, substrates), agriculture (livestock substrates), sports fields, children's playgrounds, and rehabilitation centers, thus preventing landfill waste and conserving natural resources. This process, scientifically proven to be ecologically superior to incineration, supports the circular economy and reduces environmental impact, enabling symbiotic

relationships with other industries (Citycircle, 2020). It turned the problem of used tires into a new source of income through recycling and the production of products from secondary raw materials (Gumiimpex, 2025; Jahić, 2025) and demonstrated entrepreneurial ability by perceiving an "unwanted" phenomenon (the accumulation of waste tires) as a market opportunity rather than just a cost. In this way, classic tire service and sales are complemented by a new business model based on the use of by-products and waste, a typical configuration for recognizing entrepreneurial opportunities in the context of the circular economy (Erceg et al., 2025). Gumiimpex, acting as a "symbiotic hub", connects various actors: waste suppliers (repairers, fleets, utilities) and users of secondary raw materials (construction, sports and recreation, public sector) (Jahić, 2025). The IS is manifested in (i) material flows: waste tires serve as an input raw material, yielding rubber granules, slabs, tartan surfaces, protective coatings for sports fields, children's playgrounds, and industrial floors (Gumiimpex, 2025); and (ii) spatial and logistical connections: recycling facilities and logistics infrastructure enable local waste collection and regional product

distribution, reducing transport-related costs and emissions (Erceg et al., 2025; Jahić, 2025).

Gumiimpex's entry into tire recycling and the development of products from recycled materials are, in essence, consistent with the definitions of GE, in which: (1) the environmental problem is the starting point of the business idea, and (2) the environmental benefit is integrated into the core of the business model, and not just in marketing activities (Melay & Kraus, 2012). In

Livit Belišće

Livit Belišće is an example of a company operating in the waste management chain. However, it also shows the limitations of IS when environmental and social aspects are not sufficiently aligned with the local community. Livit's business model can be interpreted as an attempt to turn an environmental problem (wastewater treatment sludge) into a business opportunity through IS. However, it faces severe limitations in the realm of GE.

Livit's starting point is the observation that disposing of sludge from industrial and municipal wastewater treatment plants is expensive, technologically demanding, and subject to regulatory pressure, creating a market for specialized service providers. The sludge that Livit takes on is generated as a by-product of wastewater treatment, including industrial processes such as paper production, and is typically incinerated or landfilled, both of which are expensive and environmentally problematic (Erceg et al., 2025). The company recognizes that sludge, a "chemical-laden mass" created, represents a constant waste stream that can be contractually tied and monetized through long-term processing contracts. In entrepreneurial terms, it is about identifying a "pain point" (the cost and risk of sludge disposal) and offering a technological solution (Luxverte technology) that converts waste into construction material, with the potential to sell that material on the market (Klancir, 2023). Livit's basic symbiotic

the broader context of Croatian and European circular economy policy, Gumiimpex can be seen as a concrete example of a company that operationalizes the goals of GE through IS - recognizes regulatory, technological and social changes as an opportunity, invests in innovative infrastructure and builds a new market segment based on recycled resources instead of linear consumption (Citycircle, 2020).

relationship is a triangle: (i) different (industrial and municipal plants) "produce" sludge as a source of waste; (ii) Livit is a waste processor that processes it into a composite building material; and (iii) the construction sector is a potential user of this material.

This theoretically achieves the "waste = raw material" scenario, in line with research recommendations on sustainable sludge management that emphasize the advantage of material recovery over classic disposal or exclusive incineration (Erceg et al., 2024). At a conceptual level, Livit can therefore be used as an example of IS in the sludge sector, like European projects that convert sludge into fuel or bituminous products (Đurđević et al., 2022). If one looks only at the model's design (material recovery, reduction of landfill use, potential substitution for primary building materials), the concept aligns with GE patterns in the waste and renewable resources sector (Đurđević et al., 2022). However, modern definitions of GE also include a social dimension – acceptability for the local community and transparent risk management. (Erceg et al., 2025) The Livit case can therefore serve as a didactic example of an "imperfect" IS and GE: the entrepreneurial opportunity and technological solution are recognized, but the lack of comprehensive management of environmental and social aspects can limit the venture's economic and environmental benefits.

CONCLUSIONS

Waste management is increasingly recognized as a strategic component of the transition toward a circular economy and a potential driver of sustainable economic development. Although the European Union has achieved notable progress in recycling and resource recovery, substantial disparities persist among Member States, particularly in countries such as Croatia, where circularity rates remain below the EU average. At the same time, waste streams represent an underutilized economic resource that can stimulate IS,

GE, and the development of secondary raw material markets. Strengthening institutional frameworks, improving policy implementation, and investing in modern waste management systems could therefore significantly enhance both economic efficiency and environmental sustainability. GE refers to entrepreneurial activities that address environmental and social challenges while ensuring environmental and financial sustainability. In this context, green SMEs contribute to environmental protection through sustainable

products, services, and business practices, and can be classified as eco-innovators, eco-entrepreneurs, or eco-adopters. IS represents a practical mechanism for implementing the GE principles through collaboration and the reuse of waste or by-products as production resources.

The case studies analysis shows how IS can stimulate the development of innovative business models,

especially in the waste, energy, and agriculture sectors, where there is significant potential to optimize resource flows. Research showed a connection between IS and GE, but also that not all IS is GE.

Further research is needed to quantify the impact of IS and GE on sustainability, especially in Croatia, and to extend this research to other neighboring and similar countries.

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Measuring What Matters: Knowledge and Competencies in CE and IS

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ABSTRACT

The increasing relevance of Circular Economy (CE) and Industrial Symbiosis (IS) in tackling contemporary sustainability challenges, such as resource scarcity and environmental degradation, calls for educational approaches that go beyond general awareness. In this context, the development of concrete competencies and practical skills becomes essential for the effective implementation of CE and IS practices. Empirical studies demonstrate a strong positive relationship between stakeholders' knowledge of CE practices and their sustainable attitudes and behavior, highlighting the importance of substantive understanding rather than superficial familiarity. Similarly, research conducted among students emphasises the need for a deeper comprehension of sustainability and circularity concepts in order to achieve established sustainability goals. However, despite the growing body of literature, research systematically addressing awareness of industrial symbiosis—particularly among younger populations—remains limited. Moreover, while several studies examine general awareness of CE-related concepts among young people, considerably fewer investigate their actual knowledge and the development of relevant competencies, thereby revealing a significant research gap in this field.

In response, this paper presents the development of a measurement scale aimed at assessing both knowledge and competencies in CE and IS. The goal is to reveal gaps between what young people currently think and know and the practical skills they need to apply these concepts effectively. To support this, a structured approach is proposed to develop a comprehensive competency map that highlights the key knowledge and practical skills essential to IS and CE contexts. Based on the existing literature, a conceptual assessment framework is introduced that distinguishes between awareness and conceptual knowledge, on the one hand, and practical skills and application, on the other. The measurement scale was constructed based on this framework, with items specifically designed to capture both respondents' understanding and their perceived ability to implement CE and IS practices.

By making this distinction, the framework not only identifies potential gaps in knowledge and skills among young learners but also contributes to the literature by providing a coherent, research-based model for evaluating learning outcomes in IS and CE education.

KEYWORDS

Industrial symbiosis • Circular economy • Awareness • Knowledge Assessment • Practical skills

INTRODUCTION

Contemporary global challenges, such as climate change, resource depletion, and increasing pollution, are fundamentally reshaping production systems and the ways in which resources are used and managed. In response, the development of the circular economy and industrial symbiosis introduces new approaches that redefine organizational and societal practices in production, consumption, and material flow management. The transition from the linear model of “take-make-throw” to circular systems is based on more efficient use of resources, extension of the life cycle of products and cooperation between different actors in order to reduce waste and negative impacts on the environment.

This transformation largely depends on the knowledge, skills and competences of individuals, especially in the context of the education of future professionals. Therefore, the assessment of the level of awareness, understanding and development of students’ competencies in the field of circular economy and industrial symbiosis can be of particular importance for educational institutions, curriculum creators and policy makers in the field of education, in order to develop effective strategies for integrating the principles of sustainability into the educational system.

Although recent research is focused on the analysis of the application of circular principles and technologies in various sectors, research dealing with the level of awareness, knowledge and competence of students in this area is still limited. The lack of studies that systematically differentiate and, at the same time, examine the relationship between awareness, knowledge, and practical skills and competencies, as well as their importance for understanding and potential application of the principles of circular economy and industrial symbiosis, is especially noticeable. Additionally, existing works rarely offer validated instruments for measuring these dimensions, especially in the context of the student population.

Accordingly, the goal of this paper is to present a conceptual framework for examining students’ awareness, knowledge and competencies in the area of circular economy and industrial symbiosis, as well as an initial proposal of dimensions that could be the subject of a future measurement scale. Starting from existing theoretical frameworks and identified competences in the literature, the work seeks to establish an integrated model that distinguishes these dimensions and enables their reliable measurement. In this way, the research contributes to the existing literature through the development of a theoretically based instrument

that can serve as a basis for further analysis and improvement of educational approaches in the field of circular economy and industrial symbiosis.

THEORETICAL FRAMEWORK

The development of the circular economy implies a shift towards the so-called “era R” (reuse, repair, remanufacturing), which is aimed at extending the life cycle of products, as well as “era D” (dismantling, disassembly, deconstruction, dematerialization), which is based on the application of modern technologies for efficient management of materials, where everything is viewed as a potential resource for further use. Industrial symbiosis implies the exchange of underutilized resources, such as materials, energy, water and by-products, between different industrial systems, thus extending their life cycle and reducing the negative impact on the environment. Developing awareness of these principles is the basis for further acquisition of more complex knowledge and skills.

Therefore, there is a need not only to change production and consumption patterns, but also to systematically invest in knowledge and skills that enable the preservation of natural and human resources. The growing importance of the circular economy and, additionally, industrial symbiosis has a direct impact on changes in the structure of jobs and required competencies. Contemporary research indicates the need to develop both general (transversal) skills, such as digital and environmental literacy and problem solving, as well as specific, professional knowledge related to certain functions and disciplines. Special emphasis is placed on non-routine jobs that require skills such as product repair and maintenance, but also the ability to understand and manage complex material flows between different systems. In this context, the implementation of these concepts requires the development of appropriate policies that encourage education, training and innovation (UNESCO-UNEVOC, 2021).

The development of the circular economy implies significant changes in the required knowledge and skills, especially in the STEM field, given their key role in technological innovation. However, there is still a limited understanding of what specific competencies are necessary for this transition and to what extent they are represented in existing educational programs. In this context, it is particularly important to examine not only the developed competencies, but also the level of awareness, knowledge and readiness of students to understand and apply the principles of the circular economy.

Awareness represents the initial level of understanding and refers to familiarity with the basic concepts, the importance and challenges of the circular economy, including the role of industrial symbiosis as one of the key mechanisms for more efficient resource use. In an effort to measure and quantify different levels of circular economy awareness, several studies have developed methodologies to identify key components of CE awareness.

In a study by van Langen et al. (2021) assessed the perception and level of awareness of the circular economy among three groups: researchers, economists and administrators. This research focuses on broadening understanding of individuals' perceptions of CE, so that researchers and policymakers can better understand its application across all three dimensions of sustainable development – environmental, economic, and social – to support the transition to a sustainable society. Indiran et al. (2025) apply the Knowledge–Attitude–Behavior (KAB) model. In the context of environmental sustainability and circular economy practices, the KAB model provides important insights, showing how an individual's knowledge of these concepts shapes their attitude, and attitude further influences engagement in sustainable behavior. The KAB model assumes that knowledge and attitude significantly influence behavior, which is particularly relevant in the application of CE.

The KAB model was also used to analyze students' awareness as a driver of changes towards the principles and practices of the circular economy (Wardani et al., 2025). The results indicate a high level of awareness about circularity among economics students in Indonesia. Similarly, a study by Łuka et al. (2025) conducted among Polish students shows differences in the level of knowledge and awareness, with awareness mostly limited to basic understanding of concepts. However, the examination of the application of certain circular practices showed better recognition, which is in line with previous research on consumers (Sijtsema et al., 2020; Almulhim & Abubakar, 2021).

The conclusion of these studies indicates that even among students there is a significant gap between the knowledge of the concept of circular economy and the recognition of environmental practices that are intrinsically related to CE, highlighting the need for further educational and strategic interventions to translate awareness into practical circular actions.

ANE & Ethica (2021) and Akyazi et al. (2023) point out that knowledge in the circular economy includes the ability to think systematically, understanding the interdependence between different systems, as well

as knowledge of regulations, policies and technologies in the field of resource and waste management. Perrin et al. (2023) emphasize the importance of understanding the basic principles of circular design and thinking based on the life cycle of products and supply chain characteristics as well as deep knowledge about materials, the distinction between biological and technical flows, and data collection and processing.

The Circular Economy Institute (2025) further indicates that the highest level is represented by skills and competencies, which enable the application of acquired knowledge in concrete situations. The authors point out that, in the context of the circular economy and industrial symbiosis, these competencies include applying circular design principles, identifying opportunities for more efficient resource use, and actively engaging in cooperation among different actors. Sumter et al. (2020), Schlüter et al. (2022) and Akyazi et al. (2023) emphasize that social and organizational skills, such as communication, negotiation, teamwork and managing relationships with stakeholders, are key competencies for the successful functioning of industrial symbiosis.

Sumter et al. (2020) and the Circular Economy Institute (2025) define competence in the circular economy as a set of abilities needed for decision-making in complex transition processes, where they particularly emphasize systemic thinking, design and seeing from multiple perspectives, integrated with innovative competences. Circular Economy Institute (2025), Renfors (2024) and Vitti et al. (2024) add that an interdisciplinary approach, entrepreneurial thinking, ability to solve problems and adapt to changes enable individuals to function in complex and dynamic systems characteristic of the circular economy. Karra Sillaman & de Colle (2024) point out that for the successful implementation of circular economy principles in an entrepreneurial context, it is crucial to develop strategic, innovative and interconnected competencies that enable organizations to adapt to complex regulations, include different actors and build sustainable ecosystems.

Research to date identifies potential CE skills, but without systematic prioritization. The Wu 2025 research highlights the synergistic importance of technical, strategic-cognitive and digital skills, with the most critical competencies being: circular product design (DfX principles), systems thinking, LCA and material flow analysis, holistic perspective taking and data analysis and interpretation.

This work is based on a qualitative research approach, applying a review of relevant scientific and professional literature in the field of circular economy and industrial

symbiosis. The literature review included works dealing with competencies, skills and knowledge levels necessary for the transition to a circular economy, with a special focus on youth and the educational context. Based on the review of the relevant literature, the key dimensions of competencies necessary for the transition to the circular economy and the application of industrial symbiosis were identified. In order to systematize different approaches, the selected competencies are grouped into thematic units.

The first dimension, Awareness and Understanding, forms the foundation for all further learning in circular economy (CE) and industrial symbiosis (IS). It includes familiarity with key concepts of CE and IS, comprehension of the principles of sustainability, and a general awareness of circularity. Developing this awareness is essential, as it provides students and professionals with the context necessary for applying more complex skills and competences.

The second dimension, Systems and Resource Thinking, emphasizes the ability to analyze and understand interconnections between different systems. This includes competencies such as systems thinking, material flow analysis, and the ability to view challenges and solutions from multiple perspectives. These skills allow individuals to assess resource use holistically and identify opportunities for efficiency and collaboration across systems.

The Technical and Practical Skills dimension focuses on the hands-on competencies needed to implement circular practices. It encompasses resource management, application of relevant technologies, engineering expertise, and the skills required for recycling and reuse. Mastery of these technical skills enables effective

intervention in product life cycles and resource optimization.

Circular Design and Business Thinking represents a combination of creative and strategic competences. This includes circular design, application of DfX principles, understanding circular business models, and fostering innovation. Professionals with these skills are able to design products and systems that extend life cycles, reduce waste, and contribute to sustainable business strategies.

The Digital and Data Skills dimension highlights the importance of modern digital literacy in CE and IS contexts. It covers data analysis and interpretation, digitization, and supply chain management skills. These competences are increasingly essential for monitoring, evaluating, and optimizing circular processes in data-driven environments.

Collaboration and Social Skills focus on interpersonal and organizational abilities that facilitate effective teamwork and stakeholder engagement. Key skills include cooperation with diverse actors, communication, soft skills, and cross-cultural awareness. These competences are particularly important for industrial symbiosis, where successful resource exchange relies on strong collaboration.

Finally, the dimension of Strategic and Sustainability-Oriented Thinking addresses higher-order competencies required for decision-making in complex and dynamic contexts. It involves strategic thinking, anticipatory and normative competences, ethical reasoning, and an understanding of sustainability. These skills enable individuals to plan and implement long-term solutions that align with both organizational goals and global sustainability objectives.

CONCLUSION

This paper addresses the growing need for a better understanding of the competencies required for the effective implementation of circular economy (CE) and industrial symbiosis (IS), particularly among younger populations. While existing literature emphasizes the importance of awareness, the findings confirm that awareness alone is insufficient without deeper conceptual knowledge and the ability to apply it in practice. Furthermore, despite the increasing relevance of these competencies, current educational systems do not integrate them adequately, highlighting the need for their systematic development and measurement. In this context, strengthening the understanding of key CE concepts and recognizing them as core competencies across business functions becomes essential,

particularly in sectors such as agriculture, automotive, construction, and electronics, where circular practices can generate significant economic and environmental benefits.

By synthesizing existing research, this paper develops a structured competency framework that clearly distinguishes between awareness, knowledge, and practical skills. This framework enables a more precise understanding of learning outcomes and provides a foundation for assessing individuals' readiness to engage in CE and IS practices.

The proposed measurement scale contributes to bridging the gap between theoretical understanding and practical application by enabling the identification of discrepancies between perceived knowledge and ac-

tual competencies. In doing so, the study responds to the identified research gap, particularly regarding the limited focus on industrial symbiosis awareness and competencies among young people.

The findings underline the need for a more systematic integration of CE and IS competencies into educational programs, with a strong emphasis on practical and

application-oriented skills. Future research should focus on the empirical validation of the proposed scale and its application across different educational contexts, in order to support the development of a workforce capable of driving the transition toward a circular and sustainable economy.

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Monitoring and Evaluating Awareness Impacts in Circular Economy Transitions: Bridging the Knowledge–Action Gap through Digital Tools and Industrial Symbiosis

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ABSTRACT

Many people agree that moving toward a circular economy is a key way to achieve sustainable development. However, its success depends not only on new technologies and ways of doing things, but also on the ability to turn awareness into real changes in behavior. Even though more and more attention is being paid to initiatives that raise awareness, there is still a knowledge-action gap, which means that being more aware of the environment does not always mean adopting circular practices. This study tackles the significant issue of assessing and tracking the effects of awareness in transitions to a circular economy by suggesting a comprehensive, data-driven framework that connects awareness initiatives to quantifiable results.

The study takes a conceptual and interdisciplinary approach by combining ideas from circular economy theory, industrial symbiosis, behavioral sustainability, and digital innovation through an integrative literature review. Based on these theoretical foundations, the study creates a multi-dimensional framework that links awareness inputs to behavioral proxies and measurable circular economy indicators. This framework is backed up by digital monitoring systems and feedback loops.

The findings indicate that conventional awareness metrics, including participation in training initiatives

or information dissemination, are inadequate for measuring genuine impact, as they do not accurately represent modifications in behavior and operational procedures. Data from both developing and developed economies shows that awareness only works when it is built into systems that allow for measurement, coordination, and ongoing feedback. For example, industrial symbiosis gives measurable signs like better use of resources and less waste, and digital technologies like AI and the Internet of Things make it possible to monitor things in real time and make evaluation processes more reliable.

The research enhances the literature by introducing a comprehensive framework that views awareness as a quantifiable and iterative process, rather than merely a cognitive result. The framework connects behavioral change to measurable circular economy performance indicators, making it a strong tool for policymakers and practitioners who want to create evidence-based sustainability programs. In the end, the results suggest that closing the knowledge-action gap requires a change to system-oriented and data-driven evaluation methods that turn awareness into an actionable and accountable driver of circular economy transitions.

KEYWORDS

The circular economy • The impact of awareness • The gap between knowledge and action
Monitoring and evaluation • Industry 4.0 • Industrial symbiosis

INTRODUCTION

The increasing strain on natural resources, along with worsening environmental damage and climate change, has made it even more important to change the way we make and use things. In this context, the shift to a circular economy has become a key part of modern sustainability strategies. The goal is to replace linear models that are based on extraction, use, and disposal with systems that are regenerative and restorative, focusing on resource efficiency, waste reduction, and the ongoing flow of materials through closed-loop processes. In this framework, enhancing awareness among individuals, organizations, and institutions is widely acknowledged as a crucial strategy for promoting the adoption of circular practices and facilitating sustainability transitions.

Nonetheless, in spite of the surge in awareness campaigns, educational initiatives, and policy measures, mounting evidence indicates that elevated levels of environmental awareness do not inherently result in corresponding behavioral modifications. This difference, which is often called the knowledge-action gap, is a major obstacle to putting circular economy strategies into action. Initial research has shown that pro-environmental behavior is shaped by a complex interaction of cognitive, social, and structural factors. Additionally, knowledge alone does not suffice to prompt action without conducive conditions such as incentives, institutional frameworks, and behavioral reinforcement mechanisms (Kollmuss & Agyeman, 2002; Meyer, 2015). Recent empirical studies further validate that heightened exposure to environmental education does not uniformly lead to elevated pro-environmental behavior, underscoring the constraints of awareness-based strategies when applied in isolation. Industrial symbiosis networks as platforms for measurable collaboration and performance improvement (Sgambaro et al., 2024; Ali et al., 2025; Vahidzadeh et al., 2025). Integrated behavioral frameworks underscore the significance of values, norms, and perceived control in influencing behavior, thereby highlighting the necessity to transcend solely informational strategies (Steg et al., 2014).

These limitations are especially clear in developing economies, where efforts to raise awareness often run into problems like a lack of technological infrastructure, weak enforcement of regulations, and a lack of integration of sustainability goals into industrial systems. In these situations, the difference between being

aware and taking action becomes clearer because just knowing more does not always lead to better resource use, less waste, or more circular practices. At the same time, recent developments in the implementation of the circular economy show that industrial symbiosis is becoming more important as a way for companies to put circular principles into practice by sharing materials, energy, and by-products, which leads to measurable environmental and economic benefits (Castellet Viciano et al., 2022). Simultaneously, progress in digital technologies, such as artificial intelligence, the Internet of Things, and data analytics, is generating novel opportunities for real-time monitoring and evaluation of sustainability performance, facilitating a transition from perception-based assessment to data-driven decision-making (Ali et al., 2025).

Even with these changes, there is still a big gap in the research on how to systematically measure the effects of awareness in transitions to a circular economy. Current research predominantly emphasizes either behavioral determinants or technical and operational indicators, failing to sufficiently connect awareness initiatives to quantifiable outcomes via integrated evaluation frameworks (Godinho et al., 2024; Sgambaro et al., 2024; Ali et al., 2025; Vahidzadeh et al., 2025). There is a notable deficiency in methodologies that integrate behavioral insights, circular economy metrics, and digital monitoring systems to evaluate the efficacy of awareness initiatives in effecting substantial and enduring modifications in practices.

In response to this gap, this study seeks to create a comprehensive framework for assessing and tracking the effects of awareness in circular economy transitions, specifically targeting the knowledge-action gap through digital tools and indicators of industrial symbiosis. The study proposes a conceptual model that connects awareness inputs to behavioral proxies and measurable outcomes, utilizing insights from circular economy theory, industrial symbiosis theory, behavioral sustainability, and data-driven monitoring systems, all underpinned by continuous feedback mechanisms. The paper enhances both theory and practice by proposing a more robust and operational framework for assessing awareness initiatives, while also equipping policymakers and practitioners with a structured instrument to improve the efficacy of circular economy strategies.

METHODOLOGY

This study employs a theory-building and conceptual modeling methodology based on an integrative literature review, aiming to establish a comprehensive and functional framework for assessing and monitoring awareness impacts during transitions to a circular economy. The research adopts an interdisciplinary analytical framework that integrates circular economy theory, industrial symbiosis theory, behavioral sustainability, socio-technical transition theory, and digital innovation. This approach facilitates the systematic amalgamation of various yet complementary strands of literature that are conventionally addressed in isolation. The integrative review methodology is chosen because the research problem is exploratory and conceptual. This allows for the inclusion and synthesis of empirical evidence, theoretical models, and policy-oriented studies to build a coherent and analytically sound framework. Circular economy theory establishes the macro-level conceptual framework by characterizing economic systems as regenerative and restorative, emphasizing resource efficiency, waste reduction, and the preservation of materials within closed-loop cycles. In contrast, industrial symbiosis theory translates these principles into practice at the meso-level by conceptualizing industrial systems as networks of interdependent actors involved in the exchange of materials, energy, water, and by-products, thereby yielding quantifiable environmental and economic advantages (Castellet Viciano et al., 2022). These symbiotic interactions yield quantifiable metrics such as material flow efficiency, waste valorization rates, reductions in virgin resource inputs, and enhancements in environmental performance. These metrics are particularly pertinent to this study as they serve as objective proxies for assessing the efficacy of awareness-driven behavioral change within organizational and industrial frameworks (Fussone et al., 2025). In parallel, the framework incorporates established behavioral theories, including the knowledge action gap perspective (Kollmuss & Agyeman, 2002), the Theory of Planned Behavior, and the Value Belief Norm theory (Steg et al., 2014), which collectively explain the limited capacity of awareness based interventions to generate action in the absence of enabling conditions, such as institutional support, incentives, and monitoring mechanisms, thus highlighting the need to move beyond cognitive indicators toward measurable behavioral and operational outcomes. This perspective is further supported by empirical evidence showing that increased education does not necessarily lead to higher levels of pro environmental behavior (Meyer, 2015; Ghisellini

et al., 2016; Godinho et al., 2024). These behavioral insights are further integrated within the overarching framework of socio-technical transition theory, particularly the multi-level perspective, which characterizes sustainability transitions as dynamic interactions among niche innovations, established regimes, and broader socio-economic contexts. This underscores the necessity of connecting micro-level awareness initiatives with macro-level systemic transformations and scalable evaluation frameworks.

Based on these theoretical foundations, the study creates a multi-dimensional analytical framework made up of three interconnected layers: awareness inputs, behavioral proxies, and measurable outcomes. Awareness inputs include things like educational programs, communication campaigns, and training initiatives. Behavioral proxies show changes in practices that can be seen, like adopting circular production processes, joining industrial symbiosis networks, and changing how people consume and manage resources. Measurable outcomes are quantifiable indicators that come from circular economy and industrial symbiosis practices, such as lower raw material use, higher recycling and reuse rates, better resource productivity, and better environmental performance. The relationships among these layers are conceptualized as a causal chain in which awareness inputs influence behavioral proxies that in turn generate measurable outcomes, thereby addressing the limitations of traditional input based evaluation approaches and enabling a more rigorous assessment of impact (Ghisellini et al., 2016; Godinho et al., 2024). A key methodological innovation of this study is the use of digital technologies as tools for ongoing monitoring and evaluation. Technologies like artificial intelligence, the Internet of Things, and advanced data analytics make it possible to track material and energy flows in real time, collect data automatically, and predict how well a system will work, changing evaluation processes from static and retrospective assessments into dynamic, adaptive, and data-driven systems (Ali et al., 2025). These digital monitoring systems improve the reliability, validity, and temporal resolution of measurement by giving objective data and making self-reported indicators less important. They also let you see performance through dashboards and analytical platforms that help with decision-making and transparency. The framework also includes feedback loop mechanisms that are in line with adaptive governance and data-driven sustainability management. These mechanisms allow for ongoing

evaluation, learning through trial and error, and changes to awareness strategies based on what has been seen, which strengthens behavioral change and makes interventions more effective over time. The result of this multi-level and integrative analytical process is a conceptual model that makes the causal links between awareness inputs, behavioral proxies, measurable circular economy outcomes, and digitally enabled monitoring and feedback mechanisms clear. This model is a structured and scalable way to measure the effects of

RESULTS

The analytical synthesis of the literature demonstrates that the efficacy of awareness initiatives in circular economy transitions is significantly hindered by the enduring knowledge-action gap, as conventional evaluation methods predicated on participation rates, educational exposure, and self-reported attitudes inadequately reflect genuine behavioral change, thereby yielding an incomplete and frequently deceptive assessment of impact (Kollmuss & Agyeman, 2002; Meyer, 2015). Evidence from emerging economies further underscores this limitation, illustrating that while awareness campaigns and sustainability education programs have fostered heightened environmental awareness, their conversion into quantifiable circular practices remains inconsistent and heavily reliant on contextual factors such as institutional capacity, technological infrastructure, and policy enforcement. For example, in China, even though there is strong policy support and a lot of awareness campaigns promoting circular economy principles, measurable results like better resource efficiency and less waste vary a lot from region to region. This is because technology adoption and regulatory implementation are not consistent. In India, on the other hand, awareness programs aimed at sustainable consumption and waste management have gotten more people involved, but they have not always led to widespread adoption of circular practices because there are not enough monitoring systems and infrastructure support. In Brazil, industrial symbiosis initiatives in eco-industrial parks have demonstrated that awareness, when integrated with collaborative industrial networks, can yield quantifiable results such as diminished waste disposal and enhanced reuse of industrial by-products, thereby underscoring the necessity of connecting awareness to operational systems. In the European Union, particularly in nations with sophisticated digital infrastructures like Germany and the Netherlands, the amalgamation of digital monitoring tools with circular economy strategies has facilitated more

awareness. This approach conceptualizes awareness not as a fixed cognitive state but as a quantifiable and improvable process integrated within larger socio-technical systems. This effectively connects behavioral theory with circular economy performance metrics, providing a scientifically robust framework suitable for various sectors, industrial systems, and institutional settings.

accurate tracking of material flows and environmental performance, fostering a more effective synchronization between awareness and action. These findings align with behavioral sustainability theories, including the Theory of Planned Behavior and the Value Belief Norm theory, which assert that awareness primarily facilitates cognitive and attitudinal shifts, but does not inherently result in behavioral change without supportive conditions such as incentives, institutional backing, and feedback mechanisms (Steg et al., 2014). In this context, the combination of circular economy theory and industrial symbiosis theory is a big step forward because it adds measurable system-level indicators that can be used as objective proxies for behavioral change. This lets us evaluate the effects of awareness through observable outcomes instead of inferred intentions (Castellet Viciano et al., 2022). Industrial symbiosis networks exemplify how awareness-driven collaboration can be actualized through measurable exchanges of materials and energy, yielding indicators such as by-product exchange efficiency, reductions in virgin resource consumption, enhanced recycling and reuse rates, and improvements in environmental performance. Collectively, these indicators provide a solid foundation for evaluating the efficacy of awareness initiatives (Fussone et al., 2025). Moreover, digital technologies serve as a crucial enabling factor in this process, as tools utilizing artificial intelligence, the Internet of Things, and advanced data analytics facilitate continuous and real-time monitoring of resource flows and production processes. This transformation shifts evaluation systems from static, perception-based methodologies to dynamic, data-driven, and evidence-based models (Ali et al., 2025; Palagonia et al., 2025). This digital transformation improves the accuracy, objectivity, and temporal resolution of measurement. It also makes it possible to see patterns in behavior over time, which makes it easier to tell the difference between short-term changes and long-term changes

in circular practices. In this context, an integrated perspective emerges where awareness initiatives are systematically connected to measurable circular economy indicators through a structured causal chain linking awareness inputs to behavioral proxies and ultimately to quantifiable outcomes. This is supported by digital monitoring systems and industrial symbiosis metrics, and it also includes feedback loops that allow for continuous learning, transparency, and adaptive governance. Theoretically, these findings enhance socio-technical transition theory by illustrating that awareness initiatives, generally positioned at the niche level, can facilitate systemic transformation solely when integrated within technological infrastructures and institutional frameworks that permit measurement, coordination, and feedback across various system levels. From a policy and management point of view, the results show that awareness initiatives should be

redesigned as parts of integrated evaluation systems instead of stand-alone programs. This will require investments in digital infrastructure, the creation of standardized circular economy indicators, and the promotion of industrial symbiosis networks as platforms for measurable collaboration and performance improvement (Sgambaro et al., 2024; Vahidzadeh et al., 2025). The study shows that to close the knowledge-action gap, we need to move away from evaluations that focus on inputs and perceptions and toward evaluations that focus on systems, outcomes, and data. In these new evaluations, awareness is constantly tracked and directly linked to measurable circular economy performance indicators. This changes awareness from a symbolic goal to an operational and accountable process during sustainability transitions.

CONCLUSIONS

This research has tackled the significant issue of assessing and monitoring awareness effects in circular economy transitions, emphasizing the shortcomings of conventional awareness-based methods and suggesting a more comprehensive, cohesive, and data-driven framework. The results show that awareness-raising efforts are important for changing people's attitudes and increasing their knowledge, but they are not enough on their own to cause long-term changes in behavior. This is shown by the knowledge-action gap that has been found in behavioral sustainability research (Kollmuss & Agyeman, 2002; Meyer, 2015). This gap is especially clear in developing economies, where structural problems, a lack of technological infrastructure, and weak institutions often make it hard to turn awareness into measurable circular practices.

The primary contribution of this study is the formulation of an integrated conceptual model that connects awareness inputs to behavioral proxies and quantifiable circular economy outcomes, underpinned by digital monitoring systems and indicators of industrial symbiosis. The study integrates insights from circular economy theory, industrial symbiosis theory, behavioral models, and socio-technical transition frameworks, advancing a multidimensional perspective that conceptualizes awareness as a measurable and iterative process rather than merely a cognitive or symbolic construct. The utilization of industrial symbiosis indicators offers a concrete and measurable framework for evaluating the efficacy of awareness-driven collaboration. Concurrently, the incorporation of digital techno-

logies, including artificial intelligence and the Internet of Things, facilitates real-time monitoring, improved data accuracy, and ongoing feedback.

The study makes a theoretical contribution to the literature by connecting behavioral sustainability research with measuring the performance of a circular economy. It shows that awareness initiatives can only lead to systemic change when they are part of larger socio-technical systems that include measurable indicators, technological infrastructures, and institutional support mechanisms. The proposed framework presents a scalable and adaptable methodology for assessing awareness impacts across various sectors and economic contexts, especially in emerging economies where the demand for efficient monitoring tools is most critical.

From a policy and management point of view, the results show that awareness programs should be redesigned to be part of integrated evaluation systems instead of being separate programs. This necessitates the formulation of standardized circular economy indicators, investments in digital infrastructure, and the advancement of industrial symbiosis networks as frameworks for quantifiable collaboration and resource optimization. In addition, adding ways to give feedback and making decisions based on data is important for making things more accountable, open, and always getting better.

Even though these things are helpful, the study has some limits, mostly because it is based on ideas and secondary sources. Subsequent research ought to

concentrate on the empirical validation of the proposed framework via case studies, quantitative modeling, and sector-specific analyses, in addition to investigating the scalability of digital monitoring systems across diverse institutional and economic contexts.

This study illustrates that addressing the knowledge-action gap in circular economy transitions necessitates a fundamental transformation from input-oriented

and perception-based evaluations to system-oriented, outcome-based, and data-driven methodologies. From this point of view, the ability to systematically measure, monitor, and continuously improve awareness initiatives is a key factor in turning circular economy strategies from wishful thinking into effective, evidence-based drivers of long-term systemic change.

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Urban Waste Repurpose under the Concept of Industrial Symbiosis

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ABSTRACT

Urban waste management has become a pressing global challenge as rapid urbanization, population growth, and rising waste volumes place increasing pressure on cities. With nearly 70% of the world's population expected to reside in urban areas by 2050, effective waste strategies are essential not only for environmental sustainability but also for public health and economic resilience. This study reframes the discussion of waste-to-energy (WtE) technologies within the broader context of industrial symbiosis (IS), a collaborative systems approach in which the by-products, energy flows, and residuals of one process become valuable inputs for another.

The study presents cutting-edge solutions in diverse cities in the world that convert waste into useful energy while reducing environmental impacts and explores how these innovations can gain societal endorsement when embedded in transparent, participatory, and equitable IS frameworks. Diverse examples were addressed, not only in regards to the WtE practices but also to the industrial settings in distinct places in Europe, Asia, North and South America, and Africa. Comparing technical parameters such as energy efficiency

and scale, environmental impacts (namely emissions), and the socioeconomic dimension (for instance urban vs rural settings), actionable insights for implementing WtE-enabled industrial symbiosis are provided, underscoring also the role of public acceptance in advancing urban sustainability.

The work shows how WtE technologies support circular resource flows and strengthen the foundations of sustainable urban waste systems. At the same time, it emphasizes that the success of WtE-based symbiosis is shaped profoundly by societal perception and acceptance, including public trust, perceived risks and benefits, community engagement, and the social legitimacy of shared-resource infrastructures.

Challenges and opportunities on achieving trade-offs were identified, an approach for the role of innovation in achieving sustainable cities and complementing broader climate goals being put forth. Future research directions point to the development of new methods, technologies and policies; the wide application of tools such as LCA and S-LCA to measure impacts, and addressing technical and non-technical uncertainties.

KEYWORDS

Industrial Symbiosis • Waste-to-Energy • Societal Acceptance • Circular Economy • Urban Waste Management • Sustainable Resource Exchange

INTRODUCTION

The rapid increase in municipal solid waste (MSW) generation poses significant environmental, social, and economic challenges worldwide. Cities are now facing critical challenges in managing large volumes of waste while minimizing environmental impacts and maximizing resource efficiency (ISWA, 2024; Kaza, Yao, Bhada-Tata, & Woerden, 2018). Traditional waste management approaches, particularly landfilling, have become increasingly unsustainable due to their contribution to greenhouse gas emissions, land degradation, and inefficient resource utilization (Hoornweg & Bhada-Tata, 2012). In response to these challenges, cities around the world are adopting innovative waste management strategies that emphasize waste reduction, recycling, and resource recovery. Among these strategies, Waste-to-Energy (WtE) technologies have gained significant attention as a method for converting waste into useful forms of energy such as electricity, heat, and biogas (Ramos, 2023). These technologies include processes such as incineration with energy recovery, anaerobic

digestion, landfill gas capture, and advanced biogas upgrading systems (Ramos, 2026). The implementation of WtE technologies varies widely across cities depending on their economic conditions, waste composition, technological infrastructure, and policy frameworks. While many developed cities have established advanced waste management systems with integrated WtE facilities, developing cities often face challenges related to financing, technological access, and governance structures (World Bank Group, 2025; Lee, Khan, Bumbaugh, Jain, & Heneine, 2024; Lerpiniere, Wilson, & Velis, 2025). This paper examines worldwide case studies representing diverse waste management approaches and technological solutions as IS strategies. The analysis aims to identify key innovations, operational strategies, and lessons that can inform sustainable waste management policies and practices globally. The comparative framework allows the identification of patterns across cities with different economic and institutional contexts.

METHODOLOGY

Each case study was examined based on the following criteria:

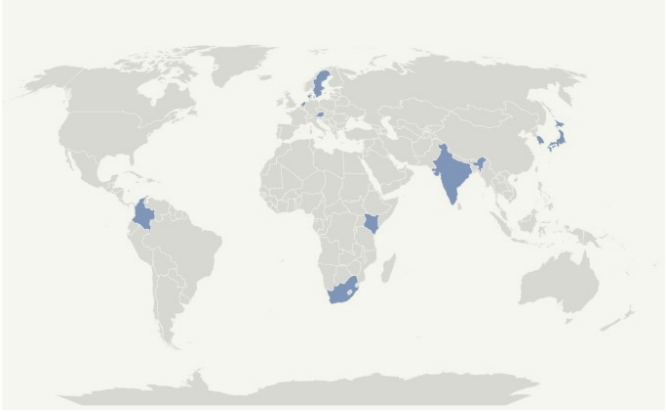
- Technology/Strategy
- Level of implementation
- Innovation characteristics

RESULTS

Case studies provide valuable insights into how cities implement and adapt these technologies within their local contexts. By examining real-world examples, policymakers and urban planners can better understand the practical challenges and opportunities associated with innovative waste management systems. Table 1

compiles the key aspects of the selected use cases. Cities such as Copenhagen and Vienna demonstrate how WtE facilities can be integrated into urban infrastructure and public spaces. In contrast, cities like Pune and Nairobi highlight decentralized approaches that rely heavily on community participation and low-cost technologies. The following sections examine these differences in detail.

Figure 1. World map with the use cases' location



Waste-to-Energy Technologies Diversity

The case studies reveal a wide range of technological approaches used to convert waste into energy or valuable resources. Incineration with energy recovery is one of the most widely used technologies, particularly in developed cities. For example, Copenhagen’s Copenhill facility converts approximately 440,000 tons of waste annually into electricity and district heating (Edo, 2021). With a net electricity efficiency of 17%, and net thermal efficiency of 83%, Copenhill can treat residues of up to 11.5 MJ/kg (lower heating value), showing a capacity of up to 560,000 tons per year, having supplied heat to 90,000 apartments (1.363 GWh) and electricity to 80,000 households (244 GWh) in 2020. The facility also demonstrates innovative infrastructure design

by integrating recreational spaces such as a ski slope and climbing wall on its roof (Edo, 2021). The environmental aspects related to odors, dust, and other emissions were crucial not only for the recreational features embedded into the facilities, but also for the social acceptance of the plant in the neighborhood. Indeed, Copenhill’s flue gas cleaning systems achieve 99% reduction of hydrochloric acid, total dioxin removal, 99.5% reduction of sulphuric acid, 96% removal of NOx, ashes being converted into construction agglomerate and enabling up to 5% of metal recovery. With the new addition of a carbon capture system, 500,000 tons of CO₂ annually emitted by Copenhill are captured lowering even further the plant’s emissions (Edo, 2021).

Table 1. Use case waste valorization features.

City	Region	Technology Category	Scale	Key Innovation Theme
Copenhagen	Europe	Thermal WtE (Incineration)	Large-scale urban plant	Energy infrastructure integrated with recreation
Vienna	Europe	Thermal WtE (Incineration)	District heating system	Public acceptance through architectural design
Tokyo	Asia	Network of WtE plants	Metropolitan infrastructure	Logistics and strict waste separation
Pune	Asia	Decentralized anaerobic digestion	Neighborhood level	Community-owned and low-tech solutions
Linköping	Europe	Anaerobic digestion + biogas	Citywide organic waste system	Waste powering public transportation
Amsterdam	Europe	Incineration+recycling+ CHP energy recovery	Municipal level	High-efficiency integration of waste streams
Bogotá	South America	Landfill gas recovery	Large landfill plant	Waste-to-grid electricity + social investment
Johannesburg	Africa	Landfill gas recovery	City-level approach	Low-cost climate mitigation
Seoul	Asia	Diverse WtE	Municipal level	Model for waste reduction and resource recovery
Nairobi	Africa	Anaerobic digestion	Community-scale	Decentralized solutions for developing cities

Similarly, Vienna’s Spittelau incineration plant processes municipal waste while providing district heating to more than 60,000 households, with circa one third slag production and < 2% ash production (Lindbauer, 2000). In 2017, the plant treated 250,000 tons of waste, supplying 504 GWh of heat, 120 GWh of electricity and 17 MWh of district cooling capacity, numbers four times higher than 4 years before that, which reveals a very good scalability and adequacy to the city needs (Bicer, 2019). The facility is notable not only for its energy production but also for its architectural design,

created by artist Friedensreich Hundertwasser, being seen as a work of art, perfectly integrated into the urban infrastructure, which enhances public acceptance and transparency (Bicer, 2019). It is a perfect combination of technological innovation, architectural integration, and public engagement, the acceptance being highly anchored in the architectural design, the strict emission controls, and a broad community engagement (Microcitygrid, 2025).

Tokyo represents another advanced example of incineration-based waste management. With its 9 million inhabitants spanning to 37 million when considering the whole metropolitan area, the city operates more than twenty waste-to-energy plants supported by strict waste separation regulations and efficient logistics systems (Kurishima, 2018). This integrated approach allows Tokyo to manage large volumes of waste, which is reduced by 20 times from the initial volume received at the facilities, while generating electricity and minimizing landfill dependency (Simić, Garić, Vučenov, & Sekulović, 2024). Waste is burnt at 800 °C, dioxins, dust, mercury, hydrogen chloride, and sulfur oxides being removed in the process. Also, bottom and fly ash are filtered and then recycled for construction, and solids and heavy metals in wastewater are removed before it is discharged into the sewer (Simić et al., 2024). In 2021, 1,240.50 MWh of electricity were generated, and 496,000 GJ of heat was delivered, the industrial symbiosis approach being even more highlighted in such a broad network.

Some cities combine multiple WtE technologies and waste management strategies within a comprehensive system. Seoul, South Korea, has developed a highly integrated waste management model that focuses on

reducing landfill dependency while recovering energy and valuable resources from waste streams (Development Asia, 2019). The city's approach includes recycling programs, WtE facilities, and policies aimed at promoting waste reduction. Amsterdam, on its turn, has integrated WtE systems within a broader circular economy framework. The waste management facility processes residual waste to generate electricity and heat while recycling significant amounts of materials. Once as many raw materials as possible are extracted from the waste, a residual flow is used to generate energy. With what remains of one ton of waste, approximately 628 kWh of electricity and 208 kWh of heat are generated and then supplied to the grid to heat approximately 30,000 houses in the North of Amsterdam. By combining different waste streams, including sewage treatment and incineration, the system achieves conversion efficiencies of up to 95% through combined heat and power technologies (AEB, 2026). This is taking industrial symbiosis to the next level as these integrated systems demonstrate the potential for cities to create circular waste management models that maximize resource recovery while minimizing environmental impacts.

Biological Waste Conversion Systems

In addition to incineration technologies, several cities rely on biological waste conversion processes such as anaerobic digestion, in a synergistic way. In Linköping, Sweden, food waste and sewage sludge are processed through anaerobic digestion to produce biogas. This biogas fuels the city's public buses and garbage trucks, creating a closed-loop system that links waste management with public transportation (Masebinu, Akinlabi, Muzenda, & Mbohwa, 2018; Molin, 2015).

Similarly, Pune in India has implemented decentralized anaerobic digestion systems that convert organic market waste into biogas used for cooking and lighting (Frankiewicz et al., 2018). In 2018, 2,100 m³ of MSW were produced daily which were then directed to more than 40 waste management sites, 26 of which are decentralized anaerobic digestors, treating 5–10 tons of organic waste per day. Each produces around 180 m³ of methane per day, generating electricity to power local street lighting (2 kWh on average per day), while the digestate is used as soil amendment to maintain local green spaces. These systems are developed through collaboration between non-governmental organizations and municipal authorities, demonstrating

how community-based initiatives can provide effective low-tech solutions in densely populated urban areas. Decentralization is key, as it reduces the risk of unprocessed waste piling up due to a temporary failure of a single facility, which has been one of the keys to replication, a number of other large and medium cities in India having conducted site visits to Pune to start their own models also.

Nairobi also employs anaerobic digestion through community-based programs that focus on scalable solutions for resource-constrained environments. These decentralized initiatives emphasize local engagement and participation, making them suitable for cities with limited financial and technological resources (Kenya Biogas Program, 2019). Kenya has now more than 20,000 bio-digesters installed across the country, scaling affordable clean energy for domestic use and bio-slurry fertilizer for increased agricultural productivity. These solutions contribute to food security, clean/sustainable use of energy and environmental conservation, therefore the initial industrial symbiosis approach has a much larger and significant output than just converting residues into energy.

Landfill Gas-to-Energy Projects

Landfill gas recovery is another important method for generating energy from waste. Bogotá's Doña Juana landfill project captures biogas and converts it into electricity with a capacity of approximately 30 MW, providing a solution for the disposal of around 2 million tons of household solid waste generated by almost 8 million inhabitants each year. This corresponds to 96% of the overall waste produced in Bogotá, representing almost 60-70% of the total potential gas that can be produced, an estimated greenhouse gas emission reduction of 14.8 million tons of CO₂ equivalent over the entire 22-year life of the project. This initiative represents the first large-scale project in Colombia that converts landfill waste into electricity delivered to the national grid (CEPS, 2014). In addition to environmen-

tal benefits, the project allocates part of its revenue from energy and carbon credits to social investments in surrounding communities, truly contributing to a sustainable approach.

Johannesburg has implemented a similar landfill gas-to-energy project that captures methane emissions from landfill sites and converts them into electricity (C40 Cities, 2020). In this case, a 19 MW share and 250,000 carbon credits are generated annually since 2007. These projects represent cost-effective solutions for cities where large landfill sites already exist and can serve as transitional steps toward more advanced waste management systems.

CONCLUSIONS

The analysis of international case studies highlights the diversity of approaches used by cities to manage municipal solid waste and recover energy. Waste-to-Energy technologies, combined with innovative waste management strategies, offer significant potential to address the environmental and energy challenges associated with increasing urban waste generation.

Developed cities such as Copenhagen, Vienna, Tokyo, and Amsterdam demonstrate advanced technological solutions that integrate WtE facilities with urban infrastructure and circular economy strategies. These cities emphasize high efficiency, strict waste separation systems, and strong regulatory frameworks to support sustainable waste management.

In contrast, developing cities such as Pune, Nairobi, Bogotá, and Johannesburg often focus on decentralized and community-based approaches that are better suited to local economic and institutional conditions. These initiatives highlight the importance of scalability,

local participation, and low-cost technologies in resource-constrained environments.

The case studies also show that successful waste management systems require more than technological solutions. Policy support, public engagement, and institutional coordination are essential for achieving long-term sustainability.

Overall, Waste-to-Energy technologies should be viewed as part of a broader circular economy framework that prioritizes waste reduction, recycling, and resource recovery. When combined with effective policies and community participation, WtE systems can play a crucial role in creating sustainable urban environments. Future efforts should focus on improving access to technology, strengthening policy frameworks, and promoting international collaboration to support the adoption of innovative waste management solutions worldwide.

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Analyzing Barriers to Industrial Symbiosis Adoption Using DEMATEL: KPI-Oriented Insights

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ABSTRACT

SMEs, while forming the fundamental building blocks of the economic system, face difficulties in adopting sustainable production practices due to their limited resources. In this context, this study aims to encourage the transition of these businesses to environmentally friendly production processes in line with sustainable development goals by addressing ways to integrate industrial symbiosis, an element of the circular economy, into SMEs. Industrial symbiosis (IS) is an important sustainability approach that contributes to reducing environmental impacts by increasing resource efficiency in industrial systems. However, the adoption of IS practices by industrial actors is limited due to numerous economic, operational, organizational, and institutional barriers. Although these barriers are widely defined in literature, studies that systematically analyze the interactions and relative importance of these barriers and transform them into measurable performance indicators are limited.

The aim of this study is to analyze the factors hindering the adoption of industrial symbiosis and to propose appropriate key performance indicators (KPIs) for these barriers. This study first identified key barriers to adoption, including high logistics and processing costs,

lack of inter-firm collaboration and trust, insufficient data transparency, supply-demand imbalance, policy and incentive deficiencies, and inadequate research and innovation, through a literature review and expert opinions. Then, using the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method, the cause-and-effect relationships between these barriers were revealed, and those barriers playing a critical role in the adoption process were prioritized.

The findings from the DEMATEL analysis were used as input to determine key performance indicators (KPIs) aimed at increasing the applicability of industrial symbiosis. The proposed KPIs, covering dimensions such as economic feasibility, logistical continuity, data quality and transparency, level of collaboration, and institutional support, aim to make the fundamental barriers encountered in IS applications traceable and comparable. This study provides a holistic assessment of the industrial symbiosis literature, analyzing adoption barriers using a DEMATEL-based approach and transforming these analysis results into KPI recommendations.

KEYWORDS

Industrial Symbiosis • Adoption Barriers; DEMATEL • Key Performance Indicators

INTRODUCTION

Industrial symbiosis is a collaborative model that has many positive environmental and economic impacts on SMEs. Since SMEs have more limited financial and technological resources compared to large businesses, they seek solutions that will increase resource efficiency, reduce costs, and minimize environmental impact. Industrial symbiosis allows SMEs to gain a cost advantage by offering their waste or by-products as raw materials to another business, while simultaneously reducing environmental impact as part of the circular economy concept (Chertow, 2007). However, there are also some challenges in implementing industrial symbiosis. SMEs often struggle to invest in symbiosis projects due to insufficient financial resources; this is particularly evident in developing countries (Paquin and Howard-Grenville, 2013). Furthermore, a lack of information and low awareness levels make it difficult for SMEs to recognize industrial symbiosis opportunities (Gibbs and Deutz, 2007). Studies by Henriques et al. (2021) and Golev et al. (2015) identified the facilitators and barriers to implementing industrial symbiosis using sectoral analysis, where factors were categorized into various sectors such as social, economic, environmental, geographic, and policy. Golev et al. (2015) assessed the barriers to industrial symbiosis using the Maturity Grid. Environmental regulations, lack of

cooperation between industries, lack of trust, and lack of information sharing were identified as the main barriers. Neves et al. (2020) and Zhang et al. (2015) identified the barriers through a literature review. Yang et al. (2022) used the Analytical Hierarchy Process (AHP) and the Topsis-Based Rank Preference Technique (TOPSIS) to assess the barriers to industrial symbiosis and found that technological, economic, and security barriers were the most significant. Taqi et al. (2022) investigated the broader challenges faced by Bangladesh's manufacturing sector without focusing on any particular sector.

Based on the statements made, it has been determined that the current study, which investigates the barriers to industrial symbiosis for SMEs and evaluates these barriers using DEMATEL, a Multi-Criteria Decision Making technique, will contribute to the literature. In this respect, the aim of the study is to identify the barriers to industrial symbiosis, a crucial step in the process of transitioning to a circular economy, for manufacturing sectors operating as SMEs in Turkey. After determining the importance weights of the identified barriers, KPIs will be developed to encourage SMEs to utilize industrial symbiosis.

METHODOLOGY

In this study, the barriers faced by SMEs were analyzed using the DEMATEL method. The DEMATEL method is a model analysis that reveals causal relationships using matrices and derives effect diagrams between a set of criteria (Bai and Sarkis, 2013). First, the total relationship matrix is obtained. Then, the sender and receiver groups are calculated. The sum of the columns in the S matrix (R) represents the sum of the rows in the S matrix (D). By calculating the D and R equations and using the D-R and D+R values, the effect of each criterion on the others and the level of relationship with the others are determined. Finally, weights are calculated using

the D+R and D-R values.

In the present study, the criteria listed in Table 1, i.e., the barriers preventing SMEs from implementing industrial symbiosis practices, were used. A questionnaire was created via Google Forms to analyze the degree of influence between these barriers. These forms were designed to gather opinions from experts, including competent individuals working in SMEs and academics working in this field. Twelve positive responses were received through this form. The general responses from the expert opinions were converted into matrices, the averages of these matrices were calculated, and final decision matrices were created.

Table 1. Barriers used in the present study

Code	Barriers to the Adoption of Industrial Symbiosis in SMEs
IS1	High logistics and processing costs
IS2	Economic and technological infeasibility
IS3	Low cost difference between raw materials and by-products
IS4	Low awareness of waste trading and lack of knowledge about industrial symbiosis mechanisms

IS5	Logistics and infrastructure constraints
IS6	Lack of inter-firm collaboration and trust
IS7	Absence of intermediary institutions to facilitate symbiosis
IS8	Supply-demand imbalance
IS9	Risk of loss of continuity
IS10	Lack of appropriate policies and incentives
IS11	Data/input quality and transparency issues
IS12	Lack of research and innovation

RESULTS

When the study was analyzed according to the DEMATEL method, a decision matrix was created based on the responses received, and then the total impact matrix (Table 2) was calculated. Subsequently, the

affected and influencing barriers, which are the sender and receiver groups, were determined (Table 3).

Table 2. Total impact matrix.

	IS1	IS2	IS3	IS4	IS5	IS6	IS7	IS8	IS9	IS10	IS11	IS12
IS1	0.526	0.584	0.533	0.501	0.538	0.519	0.526	0.535	0.553	0.522	0.462	0.511
IS2	0.602	0.497	0.528	0.507	0.528	0.500	0.518	0.525	0.545	0.498	0.439	0.515
IS3	0.540	0.512	0.407	0.457	0.474	0.455	0.474	0.483	0.501	0.444	0.396	0.451
IS4	0.594	0.568	0.524	0.431	0.511	0.509	0.527	0.524	0.549	0.509	0.448	0.500
IS5	0.633	0.610	0.547	0.516	0.469	0.525	0.537	0.551	0.574	0.521	0.455	0.526
IS6	0.608	0.583	0.534	0.504	0.528	0.443	0.527	0.534	0.561	0.507	0.454	0.514
IS7	0.623	0.602	0.546	0.529	0.546	0.531	0.467	0.548	0.576	0.525	0.465	0.525
IS8	0.588	0.562	0.515	0.490	0.504	0.495	0.505	0.444	0.541	0.493	0.430	0.496
IS9	0.538	0.523	0.459	0.432	0.460	0.445	0.462	0.476	0.419	0.446	0.392	0.439
IS10	0.657	0.640	0.566	0.553	0.583	0.553	0.565	0.575	0.606	0.475	0.484	0.568
IS11	0.569	0.550	0.491	0.481	0.491	0.488	0.498	0.505	0.516	0.467	0.363	0.474
IS12	0.658	0.632	0.585	0.555	0.575	0.555	0.563	0.566	0.597	0.548	0.482	0.476

Table 3. Analysis of affecting and affected barriers.

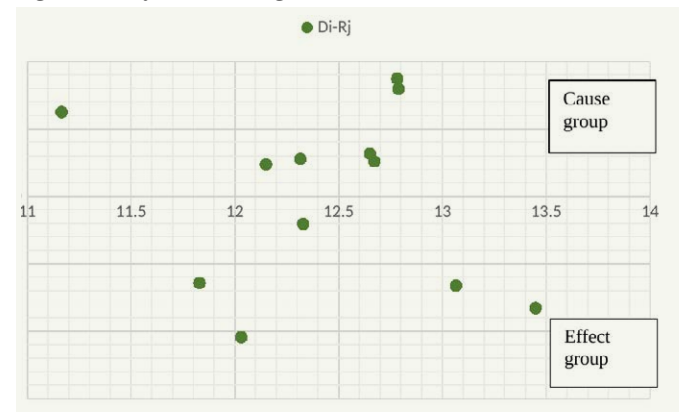
	Di	Rj	Di+Rj	Di-Rj	Impact Group
IS1	6.3105	7.138	13.449	-0.828	Affected
IS2	6.2011	6.8635	13.065	-0.662	Affected
IS3	5.5931	6.2363	11.829	-0.643	Affected
IS4	6.1933	5.9566	12.15	0.2367	Affecting
IS5	6.4656	6.2068	12.672	0.2588	Affecting
IS6	6.2965	6.0189	12.315	0.2776	Affecting
IS7	6.4835	6.1672	12.651	0.3162	Affecting
IS8	6.062	6.2667	12.329	-0.205	Affected
IS9	5.4928	6.5377	12.03	-1.045	Affected

IS10	6.8272	5.9549	12.782	0.8722	Affecting
IS11	5.895	5.2703	11.165	0.6248	Affecting
IS12	6.7923	5.9959	12.788	0.7963	Affecting

When the DEMATEL analysis results are examined (Table 3), the $Di+R_j$ values indicate the total interaction level of the barriers within the system. In this context, the barrier with the highest total interaction value is IS1 (High logistics and processing costs), which stands out as one of the most critical barriers in the system with a $Di+R_j=13.449$ value. This is followed by IS2 (Economic and technological infeasibility) (13.065) and IS10 (Lack of appropriate policies and incentives) (12.782). These results show that economic and structural factors significantly affect the development of industrial symbiosis applications. In contrast, the barrier with the lowest interaction value is IS11 (Data/input quality and transparency issues) (11.165), and its total impact on the system is seen to be more limited compared to other barriers.

When causality relationships are evaluated by examining $Di-R_j$ values (Figure 1), it is observed that positive values are classified as the influencing (Affecting-cause) group, and negative values as the influenced (Affected-effect) group. According to the analysis results, barriers IS4, IS5, IS6, IS7, IS10, IS11, and IS12 have positive $Di-R_j$ values and are identified as influencing factors. Among these barriers, the factor with the highest causality value is IS10 (Lack of appropriate policies and incentives) ($Di-R_j=0.872$), which is one of the strongest factors triggering other barriers in the system. Similarly, IS12 (Lack of research and innovation) (0.796) and IS11 (Data/input quality and transparency issues) (0.625) also have a significant guiding effect on the system.

Figure 1. Influence diagram



These findings show that improving policy support, innovation capacity, and data transparency plays a critical role in the widespread adoption of industrial symbiosis applications.

On the other hand, IS1, IS2, IS3, IS8, and IS9 have negative $Di-R_j$ values and have been identified as affected factors. In particular, IS9 (Risk of loss of continuity) ($Di-R_j=-1.045$) has the highest negative value and stands out as the factor most affected by other barriers in the system. Similarly, IS1 (High logistics and processing costs) and IS2 (Economic and technological infeasibility) are also among the resulting barriers due to the influence of other factors.

According to DEMATEL results, barriers in the “cause” group are particularly critical for developing KPIs. This is because these factors are the primary reasons that trigger other barriers in the system. Therefore, KPIs should both make the barrier measurable and enable monitoring of firm performance. Table 4 contains suggested KPIs based on DEMATEL findings.

Table 4. Proposed KPIs

Barriers	KPI	Definition	Method
IS1	Logistics cost ratio	Ratio of byproduct transportation costs to total production costs	(By-product logistics cost / total production cost)
	By-product processing cost	Cost of processing to make by-products reusable	\$/ton or €/ton
IS2	Technology investment ratio	Investments made by companies in resource efficiency and recovery technologies	(Sustainable technology investment / total investment)
	Recovery capacity	The company's capacity to utilize by-products	ton/year

IS3	By-product utilization rate	The ratio of by-products to total inputs used in production	(Amount of by-products / total input)
	Raw material substitution rate	The use of by-products in place of primary raw materials	%
IS4	Level of industrial symbiosis awareness	Employees' knowledge level on IS (Health, Environment, and Resources)	Survey scores
	Number of training programs	Number of training courses on IS or circular economy	Training pieces/year
IS5	Shared logistics utilization rate	The use of shared logistics systems between companies	%
	Average transportation distance	By-product transportation distance	km
IS6	Number of collaboration agreements	Symbiosis agreements between companies	agreement/year
	Number of joint projects	Sustainability or IS projects between companies	project/year
IS7	Number of symbiosis matches	Symbiosis collaborations established by intermediary institutions	match/year
	Platform usage rate	Level of use of digital symbiosis platforms	number of active users
IS8	By-product matching rate	Rate at which produced by-products are used by other companies	(by-products used / total by-products)
	By-product matching rate	Amount of unusable byproducts	ton
IS9	Supply continuity	Uninterrupted flow rate of byproducts	%
	Long-term contract rate	Long-term symbiosis agreements	%
IS10	Incentive utilization rate	Rate at which companies benefit from sustainable production incentives	%
	Number of publicly supported projects	Publicly funded symbiosis projects	project/year
IS11	Data accuracy rate	Accuracy of input-output data	%
	Digital data sharing rate	Sharing supply chain data on digital platforms	%
IS12	R&D investment ratio	Investment in circular economy or resource efficiency projects	%
	Number of patents / innovations	Innovation related to IS or recovery technologies	pieces/year

CONCLUSIONS

The DEMATEL analysis results revealed that some barriers played a triggering role within the system. Specifically, the lack of appropriate policies and incentives, insufficient research and innovation, issues with data/input quality and transparency, and the absence of intermediary institutions to facilitate symbiosis were identified as key factors influencing other barriers within the system. Conversely, factors such as high

logistics costs, economic and technological constraints, and the risk of loss of continuity were found to arise primarily as a consequence of other barriers. These results demonstrate that developing industrial symbiosis applications requires not only technical solutions but also strengthened policy support, institutional collaboration, and information-sharing mechanisms. In particular, improving policy and incentive

mechanisms, supporting research and innovation activities, and creating platforms for data sharing among firms will significantly contribute to the widespread adoption of symbiosis applications. The findings

contribute to academic literature and offer important implications for firms and policymakers regarding the development of industrial symbiosis applications.

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Turning by-products into partnerships: Albania's debut on Industrial Symbiosis

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ABSTRACT

Industrial symbiosis is a collaborative approach in which traditionally separate industries engage in the physical exchange of materials, energy, water, and by-products in ways that create mutual economic and environmental benefits. Within the broader framework of the circular economy, industrial symbiosis plays a crucial operational role by transforming waste streams into valuable inputs, thereby reducing resource extraction, minimizing emissions, and increasing overall system efficiency. By fostering inter-firm cooperation and closing material and energy loops at the regional or industrial-cluster level, industrial symbiosis supports key circular economy principles such as resource efficiency, waste prevention, and sustainable production.

This paper presents and analyses the first documented case of industrial symbiosis in Albania, involving a network of four companies that actively cooperate through the exchange and reuse of by-products. The study highlights how inter-firm collaboration enables

waste streams generated by one company to become valuable inputs for others, significantly reducing the need for virgin resources and disposal. To systematically capture and evaluate these interactions, the paper employs material flow chart analysis, mapping all material exchanges among the five participating firms. This analytical approach provides a comprehensive visualization of resource flows and interdependencies within the network, demonstrating how coordinated by-product sharing can lead to an almost zero-waste production system. There are currently very few studies directly linked to industrial symbiosis in Albania, so by documenting this pioneering Albanian experience, the paper contributes empirical evidence to the literature on industrial symbiosis and illustrates its practical potential for advancing circular economy objectives in emerging contexts.

KEYWORDS

Industrial Symbiosis • Material Flow Chart • Zero Waste • Case Study Analysis
IS Barriers • Business collaboration

INTRODUCTION

Industrial Symbiosis (IS) is a business-focused collaborative approach oriented towards resource efficiency that has been theorized and studied mainly over the last 25 years. The emergence of circular economy have been emphasized by numerous authors, analyzing different aspects of business cooperation within the new circular mode (Blomsma & Brennan, 2017). Recently, IS seems to have found a renewed impetus in the framework of the Circular Economy (CE), a novel approach to

sustainability and Sustainable Development (SD) that has been rapidly gaining momentum worldwide (Cecchin et al., 2020). By fostering inter-firm cooperation and closing material and energy loops at the regional or industrial-cluster level, industrial symbiosis supports key circular economy principles such as resource efficiency, waste prevention, and sustainable production. As a result, it is increasingly recognized as a practical mechanism for implementing circular economic

strategies, contributing not only to environmental performance but also to innovation, competitiveness, and regional sustainable development. Cross-industry networks of multiple supply chains have evolved in the circular economy model using approaches such as industrial and urban symbiosis (Tseng et al., 2018). These avantgarde models can provide excellent choices to further reduce waste and turning by-products into inputs for new businesses within the supply chain network. However, despite the clear benefits of industrial symbiosis in the era of Industry 4.0 and Industry 5.0, businesses have noted that social, environmental and economic perspectives are also highly appreciated in the cross-industry networks. In this logic, industrial Symbiosis (IS) is a collective approach to competitive advantage in which separate industries create a cooperative network to exchange materials, energy, water and/or by-products (Baldassarre et al., 2019).

The benefit evaluation of industrial symbiosis in industrial parks plays an important part in park management. Besides, classify industrial symbiosis according to the exchange of materials, water, and energy to conduct an in-depth analysis of diverse symbiosis (Chen et al., 2022). Industrial parks working under the industrial symbiosis framework should be analyzed in order to provide comprehensive analysis for both costs and benefits deriving from the cooperation between industries (Felicio et al., 2016). Other authors goes far proposing also the creation of Ecologic Industrial Parks (EIP) assessment index to better evaluate all the relevant indicators (Jung et al., 2013). The role of industrial

symbiosis is particularly crucial in specific sectors like energy, biowaste decomposition, water recycling, etc. Synergies among eco-industrial parks and the adjacent urban areas can lead to the development of optimized energy production plants, so that the excess energy is available to cover some of the energy demands of nearby towns (Butturi et al., 2019). Moreover, the experience from past and current ongoing projects can help better understand the industrial symbiosis concepts in specific industrial parks (Eilering & Vermeulen, 2004; Guo et al., 2016; Park et al., 2008; Yu et al., 2015).

This paper presents and analyses the first documented case of industrial symbiosis in Albania, involving a network of companies that actively cooperate through the exchange and reuse of by-products. The case study highlights how inter-firm collaboration enables waste streams generated by one company to become valuable inputs for others, significantly reducing the need for virgin resources and disposal. This analytical approach provides a comprehensive visualization of resource flows and interdependencies within the network, demonstrating how coordinated by-product sharing can lead to an almost zero-waste production system. There are currently very few studies directly linked to industrial symbiosis in Albania, so by documenting this pioneering Albanian experience. Previous studies emphasize the early stage of industrial symbiosis implementation in Albania, as well as numerous economic, social and technological barriers (Zani & Muñoz Puche, 2025; Zani & Muñoz Puche, 2026; Zani & Lleshaj, 2025).

OVERVIEWS OF THE INDUSTRIAL SYMBIOSIS CASE: AZ INDUSTRIAL PARK

Despite the negligible amount of business dealing with circularity and full implementation of industrial symbiosis, there is a particular case where an industrial park has been transformed into an 'almost zero waste' case. This project is the first swallow of broader industrial cooperation not only in Albania, but it represents the very first documented case of applying IS principles in the WB6 region. This industrial park located in North-western Albania part of the Lezha region serves as the main location of the cooperation between four compa-

nies sharing resources, by-products and waste management transformation into valuable products in food processing industry, food and beverages supply chain, animal food industry and biopharmaceutical industry. Throughout a closed loop between these companies, the value added and value creation starts with the process of recycling and reusing parts of livestock, cattle and slaughtered animals coming from Albania and other Balkan countries.

INCA Company

The first company that have been established in this circular initiative was established in 2008, almost two decades ago. However, the company did not have this crucial role until the idea to further develop the business circle, thus starting to implement the principles of green economy, sustainability and industrial symbi-

osis implementation. Driven by the 'zero waste' principle, the administrative board started to think about expanding their idea to step forward into advanced processing the waste left from the first production line. INCA is the first company starting the implementation of Industrial Symbiosis. The company's main activity is re-

lated to artisanal production on an industrial scale. The company is part of industry of natural casing in Albania. The production lines processes 100% animal by-products mostly from livestock, veal and swine by-products. The core part of the activity consists of reprocessing 3 – 7 varieties of small intestines and animal stomachs. The main inputs come predominantly from slaughterhouses in Albania [and some cases from Montenegro,

Kosovo and Macedonia].

The production line is barely automatized, with the level of manual labor work up to 90%. The products are being purchased via B2B channels, with an export level of approximately 60 – 70%, in some cases also in Asian markets (delicacy products). The waste and residual products do not get disposed – so here starts the process of closing the loop.

PET EAT

The second company that uses INCA's waste and by-products as input is the company PET EAT. It was established some years later than the first company. All the natural animal waste from swine, veal and livestock left after the first processing to produce natural casing, are now reprocessed under another treatment to produce natural dog chews. This product is 100% natural, as it also promotes sustainable products and completing a challenge: contributing to animals. This industrial

process requires less manual labor force, with reducing manual level of labor with additional 30% – 40%. However, there are still some waste and by-products left from the production line, still not disposed. The industrial park has a dedicated section to transport waste into another processing line and by-products transformation. The symbiosis of industries now has three companies dealing with mutual by-products and cooperating in the same loop.

AZ RENDERING

Is the third company that deals with the further processing of animal waste left from the first two companies. It also takes other by-products of different animals except the first three categories mentioned above, like poultry, fish and other small animals. Using rendering technologies, the production lines create two main categories of products, and what is more important: it is a process with zero waste, taking out only water and steam from production.

The first product is animal fat. The second main group of products is related to proteins, mostly producing Tallow and Meat Bone Meal (MBM), high-protein (typ-

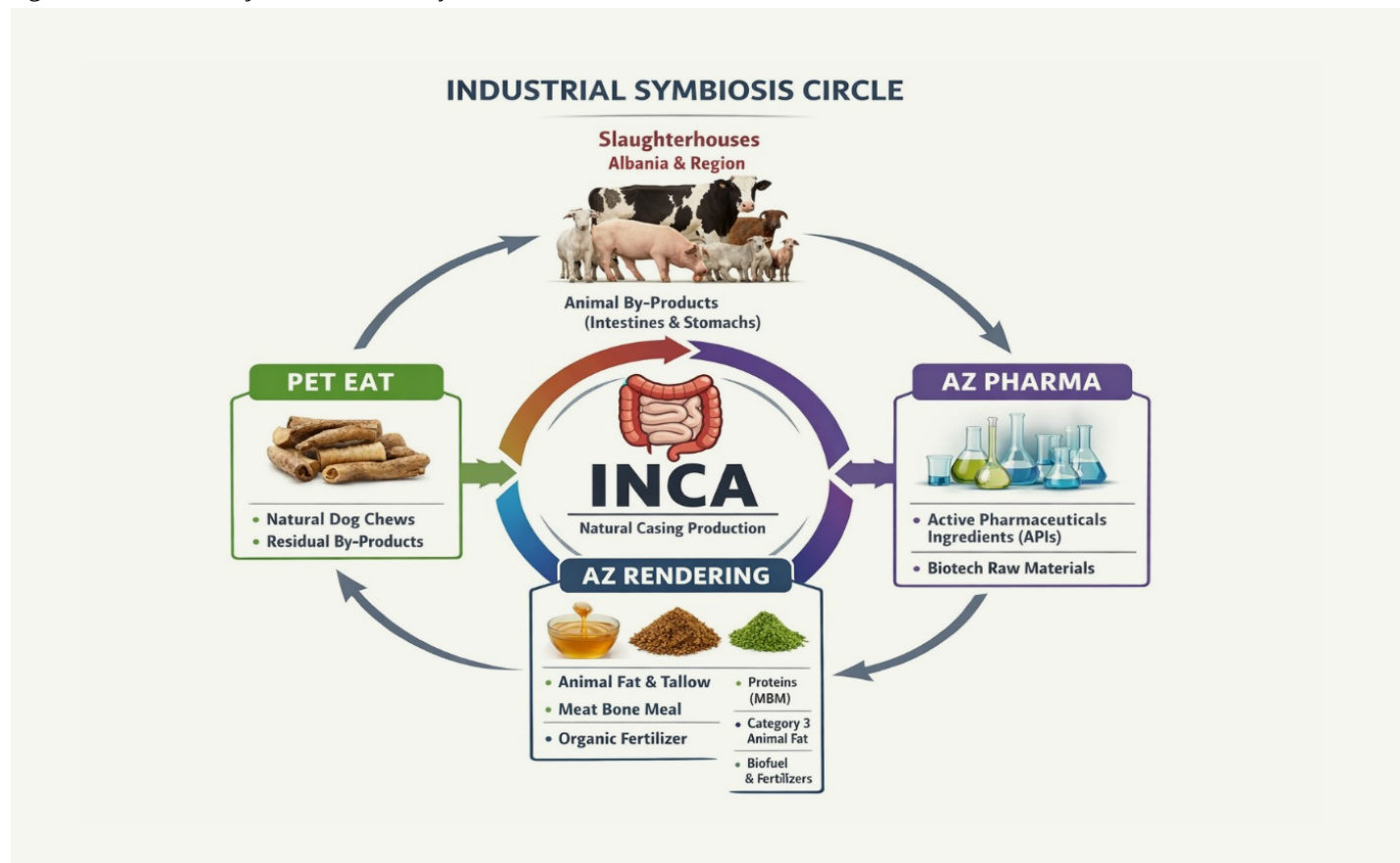
ically 48–52%) rendered product derived from animal by-products. This product is included in animal feed ration in order to create the optimal diet for them. Then, the tallow products are also used as Category 3 Animal Fat and are predominantly used for biodiesel for combustion. Furthermore, from protein further processing, the company produces fertilizers, with an AZ fertilizer product with 100% organic ingredients. The high investments for this production line are combined with almost 90% automatized work, eliminating the manual labor due to the special treatment of these products.

AZ PHARMA

The Industrial Park has currently a dedicated company for production of raw materials and staple of pharmaceutical products [the company is currently taking the certifications for the products]. The main goal is to produce Active Pharmaceutical Ingredients (APIs), extracting animal by-products to add value in this

industrial chain in the BioTech industry. The waste from this company is also 100% organic (only steam and water). In this logic, from INCA to AZ PHARMA the manual exclusive labor decreases, while the technology and investment level increases, closing the loop and complementing the industrial symbiosis circle.

Figure 1. Industrial Symbiosis Circle of AZ Industrial Park



CHALLENGES AND FUTURE OPPORTUNITIES

Besides the unique idea of AZ Industrial Park, there are several challenges that accompany the daily operations and the full business cycle of four companies. Deep interviews with the Head of Business Development of

the Industrial Park actually confirms some preliminary results from previous questionnaires shared to estimate the barriers and obstacles of IS implementation in Albania. There are three main barriers and challenges identified in this case.

Supply chain risks

The industrial symbiosis system creates strong interdependencies that, while efficient, also introduce a range of supply chain risks. One of the primary vulnerabilities lies in the upstream supply of raw materials. Since INCA depends heavily on animal by-products sourced mainly from slaughterhouses in Albania and partially from neighboring countries, any disruption in livestock production, cross-border logistics, veterinary regula-

tions, or disease outbreaks (e.g., livestock epidemics) can significantly affect the availability, quality, and consistency of inputs. Given that INCA operates with a high level of manual labor (up to 90%), labor shortages, skill variability, or operational inefficiencies may further exacerbate production instability and delay the entire downstream flow of materials.

Regulatory framework

Represents simultaneously a challenge and an opportunity, because it has an impact on the way the waste from slaughterhouses should be treated. In Albania nowadays, a lot of slaughterhouses refuse to give the animal waste (intestines, stomachs, etc.) due to their

disbelief in further processing, but at the same time the Albanian law obliges them not to dispose the waste, thus imposing an obligation to send them to the only park in country: AZ Industrial Park.

Culture

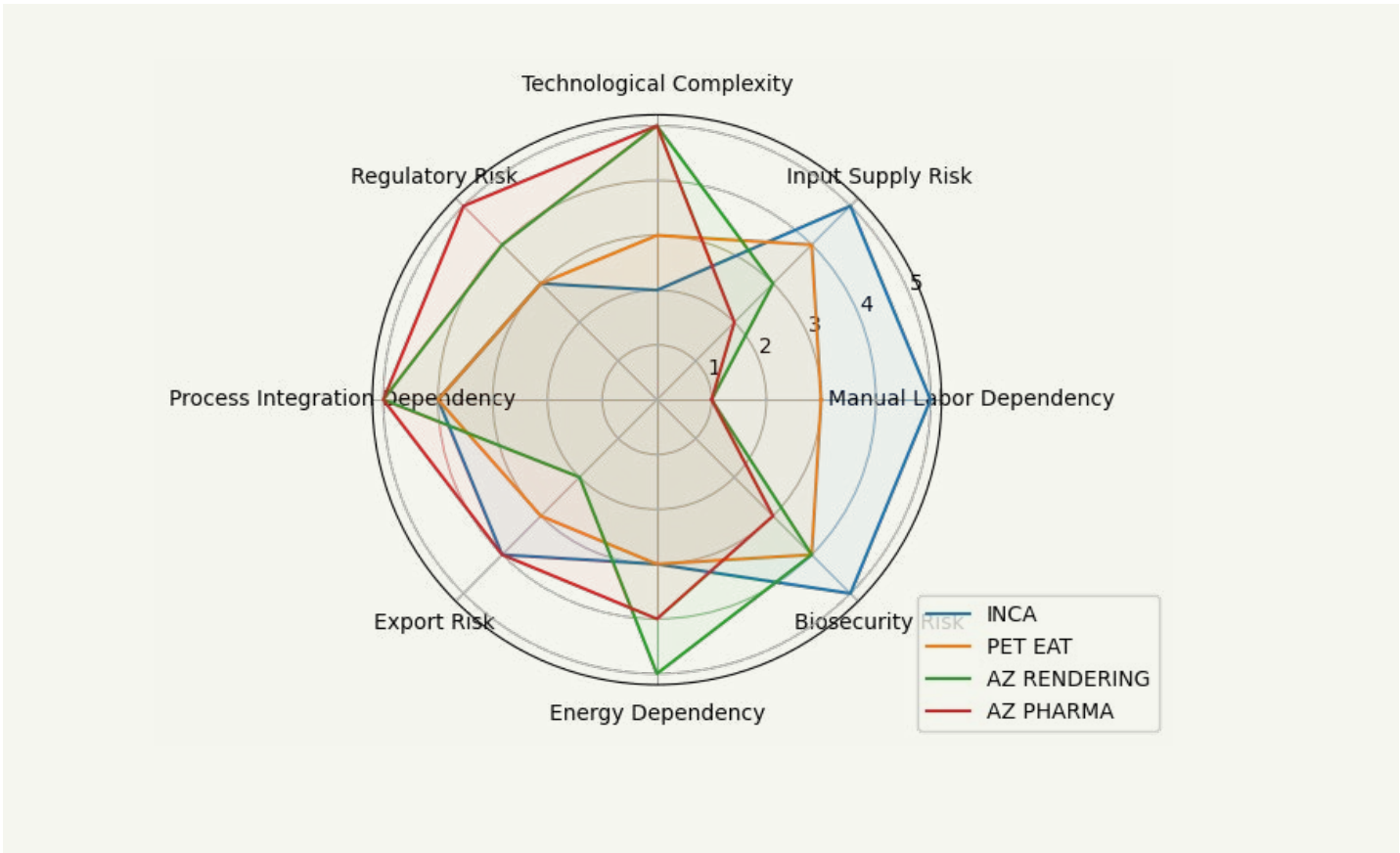
From the socio-economic perspective, the culture of accepting recycled organic products from animals (livestock) is still very low in Albania, reducing the ac-

ceptance of the products for daily use [i.e. natural dog chews or natural casing]. This imposes a major obstacle, thus hindering the advancement in production.

Table 1. AZ Industrial Park heatmap

Variable	INCA	PET EAT	AZ RENDERING	AZ PHARMA
Manual labor	90%	50% - 60%	15%	5% - 10%
Investment	Moderate	Moderate	High	Very High
Value added creation	Low	Moderate	High	Very High
Production Waste	Moderate	Low/ Moderate	Zero Waste	Zero Waste
Geo. Proximity	Very High	Very High	Very High	Very High
Type of products	B2B	B2B/ B2C	B2B/ B2C	B2B

Chart 1. Radar Map of factors influencing AZ Industrial Park



The case of AZ Industrial Park demonstrates how industrial symbiosis can be successfully implemented even in emerging economies with limited prior experience in circular practices. By creating a closed-loop system among four interconnected companies, the park achieves a high level of resource efficiency, transforming what would traditionally be considered waste into valuable inputs across multiple industries.

This integrated approach not only minimizes environmental impact through near zero-waste production but also enhances economic value creation by diversifying outputs from natural casings and pet products to biofuels, fertilizers, and potential pharmaceutical ingredients. The progressive shift from labor-intensive processes to highly automated and technology-driven operations further illustrates how industrial symbiosis

can stimulate innovation and industrial upgrading. However, the long-term sustainability and scalability of this model depend on addressing key structural challenges. Supply chain vulnerabilities, regulatory inconsistencies, and low cultural acceptance of recycled animal-based products remain significant barriers that could hinder further development. At the same time, these challenges present opportunities for policy intervention, awareness-raising, and institutional support

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to strengthen circular economy practices in Albania. As the first documented case of its kind in the region, AZ Industrial Park provides a valuable reference model, highlighting both the practical feasibility and the systemic requirements of industrial symbiosis. Its experience can inform future initiatives aiming to foster sustainable industrial development, not only in Albania but also across similar transitioning economies.

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