Proceedings Book

Industrial Symbiosis from a business perspective: **challenges and opportunities**

WG2 Workshop & Conference
Izmir, may 21 2025

LIAISE

Cooperation, development
and cross-border transfer
Of industrial symbiosis

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Almudena Muñoz Puche

Editors
Hasan Volkan Oral, PhD, İstanbul Aydin University,-Department of Civil Engineering, İstanbul, Türkiye
Istemi Berk, PhD. Dokuz Eylul University, Faculty of Business, Department of Economics, Izmir, Türkiye
Azemina Mashovic, Ph.D., American University of Europe – FON, Faculty of Economics, Skopje, North Macedonia

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Croatia, North Macedonia and Mauritius – Industrial symbiosis barriers comparison

Aleksandar Erceg
Josip Juraj Strossmayer University of Osijek, Faculty of Economics and Business in Osijek, Osijek, Croatia
aleksandar.erceg@efos.hr

Rajesh Sannegadu
University of Mauritius, Faculty of Law and Management, Department of Management, Reduit, Mauritius & North-West University, South Africa
r.sannegadu@uom.ac.mu

Marie Valerie Uppiah
University of Mauritius, Faculty of Law and Management, Department of Management, Reduit, Mauritius
m.uppiah@uom.ac.mu

Jovana Damoska Sekuloska
University of Information Science and Technology "St. Paul the Apostle" Ohrid, Ohrid, North Macedonia
ovanka.damoska@uist.edu.mk

Biljana Činčurak Erceg
Josip Juraj Strossmayer University of Osijek, Faculty of Law Osijek, Osijek, Croatia
bcincura@pravos.hr

Aleksandar Anastasovski6
International Balkan University, Faculty of Engineering, Skopje,
a.anastasovski@ibu.edu.mk

ABSTRACT

Industrial symbiosis (IS), a key field within industrial ecology, focuses on utilizing waste or by-products from one entity as resources for another, fostering environmental and economic advantages. Central to this concept is the reuse of resources and waste minimization, driven by collaborative opportunities and synergies often facilitated by geographical proximity (Chertow, 2000). IS is a systems approach to a more sustainable and integrated industrial system that identifies business opportunities that leverage underutilized resources (such as materials, energy, water, expertise, assets, etc.) (Domenech et al., 2019). These relationships are driven by numerous factors, such as resource-saving economic benefits that meet environmentally friendly requirements, e.g., reducing greenhouse gas emissions, natural resource scarcity and reducing waste that would otherwise end up in incinerators and landfills. The IS concept uses symbiotic collaborations and business connections to close the loop. The paper's main aim is to analyze possibilities for IS in Croatia, North Macedonia and Mauritius and to compare their current situation regarding IS. Methodologically, the research is based on statistical analysis of secondary data on waste management, geographical factors, regulatory framework and economic trends. In addition, a case study was used to investigate how existing industrial symbioses have overcome barriers and seized opportunities to establish mutually beneficial relationships between companies. The research results provide guidelines for policymaking and the development of strategies that encourage the establishment of industrial symbioses and can serve as a basis for future research aimed at its further application and development.

The paper analyzes previous research on opportunities and challenges for industrial symbiosis. The second part of the paper compares three countries and examines how their size, geographical position, regulation, and economy influence IS implementation. It tries to find similarities and differences in barriers and opportunities. Based on the research results, conclusions and recommendations for further research are given.

KEYWORDS
Industrial Symbiosis - Barriers - Croatia - North Macedonia - Mauritius - Similarities - Differences

INTRODUCTION

Industrial symbiosis (IS) represents a collaborative approach in which industries exchange materials, energy, water, and byproducts to foster mutual benefits, thereby enhancing resource efficiency and waste reduction while supporting the transition to a circular economy (Chertow, 2007; Domenech et al., 2019). This symbiotic relationship between industrial facilities or companies transforms waste into raw materials, significantly reducing environmental impact and promoting sustainable practices (Fallahi et al., 2024). The core of IS involves at least three entities exchanging at least two resources (Chertow, 2007; Albino et al., 2016). Despite its increasing recognition, the global adoption of IS remains limited (Neves et al., 2020).

Implementing IS is complex due to its reliance on multifaceted systems, diverse industries, and numerous stakeholders, which hinders its widespread adoption. Despite the success of IS initiatives (Oughton et al., 2021), their implementation often remains isolated, with limited guidance on best practices to overcome inherent challenges (Lybæk, 2021). Extensive reviews and studies have explored IS, focusing on its benefits, challenges, and case studies (Fraccascia et al., 2021), highlighting its positive impact on resource efficiency, cost reduction, and environmental sustainability. However, key barriers such as inadequate institutional support, economic disincentives, and technological limitations have been identified (Neves et al., 2019).

This paper investigates the potential for IS in Croatia, North Macedonia, and Mauritius, comparing their current IS situations. It synthesizes existing research on opportunities and challenges in IS. The analysis is divided into two parts: the first part examines the current state of IS in these countries, while the second part compares them, exploring how factors such as size, geographical position, regulatory frameworks, and economic conditions influence IS implementation. The study seeks to identify similarities and differences in barriers and opportunities across these countries. Based on the findings, conclusions and recommendations for future research are provided.

INDUSTRIAL SYMBIOSIS BARRIERS

When examining barriers to IS, literature often categorizes them into distinct subdivisions. The terms "barriers" and "challenges" are frequently used interchangeably to describe factors that impede the realization of initiatives (Henriques et al., 2021). Barriers are commonly classified into four categories: financial, technological, regulatory, and institutional (Fraccascia et al., 2021). However, more detailed classifications also exist, such as social, economic, political, managerial, informational, geographical, and intermediary facilitators and barriers (Henriques et al., 2021). Other studies list technological, financial, and informational barriers, a lack of trust between organizations, regulatory issues, and risk and uncertainty (Järvenpää et al., 2018).

Interestingly, each barrier category can also serve as a driver or enabler that promotes IS (Golev et al., 2014). Specific barriers to IS implementation include low waste disposal costs, confidentiality concerns, and a focus on core business strategies over sustainability (Van Beers et al., 2007). Institutional barriers, such as inadequate market incentives and regulatory issues, are also significant (Watkins et al., 2013). Other identified barriers include time lags in implementation, agricultural scale, and social governance issues (Olayide, 2015), as well as challenges related to regulatory, informational, community, economic, technological, cooperation, trust, and commitment to sustainable development (Corder et al., 2014). Social and informational issues, technical challenges, and policy framework barriers have also been noted (Afshari, 2017). Recent studies highlight the lack of urban strategy guidelines, insufficient waste-to-energy conversion, and low byproduct reuse as significant obstacles (Momirski et al., 2021). High start-up costs, complex supply chains, and difficulties in intercompany collaboration are significant hurdles (Jaeger & Upadhyay, 2020).

Based on the research on IS barriers (e.g., Golev et al., 2014; Rahman et al., 2016; Järvenpää et al., 2018; Erceg et al., 2024), they can be divided into several main categories (Figure 1).

Infrastructure and technology

The lack of technology and infrastructure readiness is the most significant barrier to implementing IS, especially in emerging economies (Hossain et al., 2024). This barrier relates to the need for advanced technologies enabling IS, such as novel treatment processes for byproduct extraction and valorization, water purification, and energy transformation (Branca et al., 2021). Infrastructure challenges are also a key obstacle. Companies often struggle with access conditions and infrastructure issues when exchanging waste and

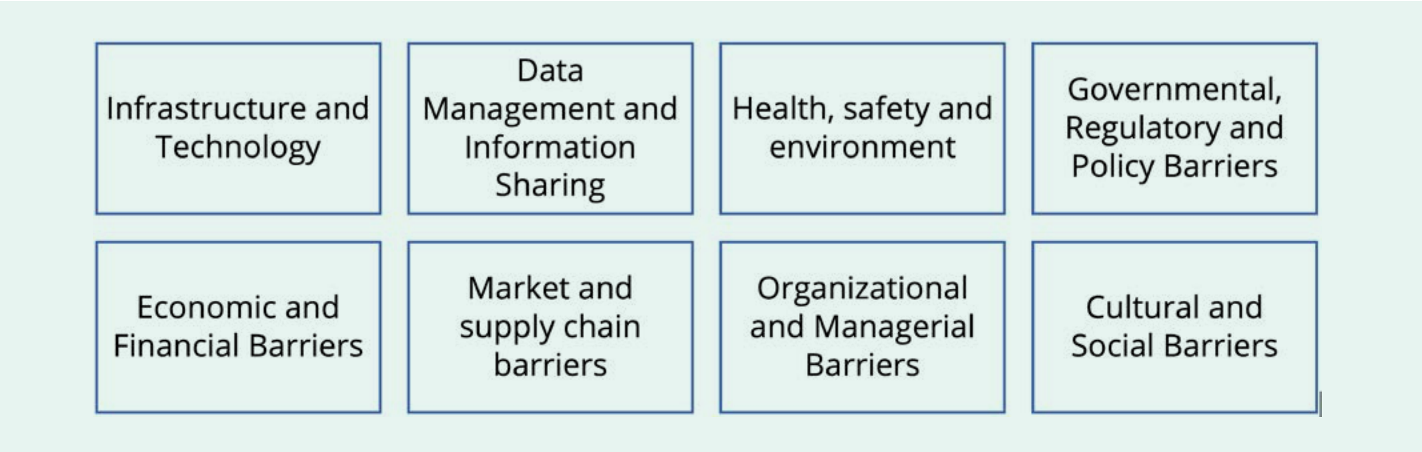

Figure 1 Main IS implementation barriers

byproducts with other co-located industries (Agudo et al., 2023). The absence of proper infrastructure can hinder the physical exchange of resources between companies, limiting the potential for symbiotic relationships. A crucial component of IS infrastructure is the tangible network facilitating material exchange. This encompasses pipelines, transport systems, and storage units that enable efficient movement and management of waste streams, byproducts, and other resources among companies (Berkel et al., 2009). In IS networks, water management infrastructure plays a vital role. This may include communal water facilities, shared utilities for alternative water supply, and systems for treating wastewater (Ramin et al., 2023). IS networks employ various infrastructure elements for inventory exchange and supply chain systems. These include tangible components such as shared pipelines, transportation networks, storage facilities, and digital systems for monitoring and controlling resource flows (Li & Shi, 2015). Within the IS framework, blockchain technology can optimize the sharing of resources, energy, and information across various industries, supporting sustainable development and circular economy concepts (Adams et al., 2017). Implementing blockchain technology in IS networks enables accurate tracking and verification of material and energy flows, increasing transparency and minimizing the potential for fraudulent activity or errors (Liu et al., 2020). Within IS, the IoT and smart systems fulfill various functions. IoT devices and sensors collect data from multiple sources in real time, enabling comprehensive monitoring of industrial processes and facilitating the discovery of potential cross-industry synergies and improved resource utilization (Kumar et al., 2020). Intelligent systems use the collected data to make informed decisions, leading to greater efficiency, safety and cost reductions in industrial operations. These improvements can include predictive maintenance, process control and energy management (Kumar et al., 2023). IoT-enabled systems contribute to efficient energy use and sustainable resource management, essential components of IS (Karad & Thakur, 2021).

Data Management and Information Sharing

Companies identify information scarcity as an obstacle, and a significant part of a facilitator's role in IS involves addressing this issue (Lombardi, 2017). This knowledge deficit impedes the recognition and execution of potential symbiotic connections between industries. The intricacies of knowledge sharing are seldom explored or implemented in IS endeavors (Kosmol, 2019), where most of the research concentrates on exchanging information/knowledge related to ICT, focusing on semantic web technologies. However, these tools are not incorporated into the overall business process for participating in IS activities.

Health, Safety, and Environment

The sharing and exchange of resources among industrial entities introduce complex operational and occupational health challenges and safety and environmental aspects due to differences in safety standards, potential protocol incompatibility, and varied risk management approaches. The interaction between industrial waste streams may lead to unforeseen health and safety risks due to chemical incompatibilities. Challenges in risk assessment related to the transfer of materials or processes between industrial contexts create health, safety, and environmental complications (Azevedo et al., 2021).

Governmental, Regulatory and Policy

A significant hurdle is the absence of explicit regulations and policies that promote IS. Many countries have no comprehensive regulatory framework to encourage or support IS activities (Buda et al., 2023). This lack of supportive policies can create uncertainty and reluctance among businesses considering IS projects. Moreover, current regulations may sometimes serve as barriers rather than facilitators for IS implementation (Neves et al., 2019). Waste regulations might limit the use of certain materials as inputs for other industries, thereby restricting potential symbiotic partnerships. While government backing is essential, a disconnect often exists between the supply side of green industrial policies (government objectives and actions) and the demand side (the needs of local green entrepreneurs) (Buda et al., 2023). This gap can lead to ineffective policies that do not meet the actual requirements of businesses involved in IS. The absence of government financial incentives is recognized as one of the most significant obstacles to IS adoption, especially in developing economies.

Economic and Financial barriers

Insufficient technology and infrastructure readiness are significant issues. This issue is often exacerbated by the high upfront costs of implementing IS systems, discouraging companies from engaging in such initiatives, particularly in emerging markets. Furthermore, while the commercial feasibility of IS opportunities is a concern for many businesses, they generally do not require assistance establishing this feasibility (Lombardi, 2017). Although economic barriers are widespread, they are not always the most crucial factors. This indicates that economic barriers frequently intersect with other challenges, creating complex difficulties for IS projects.

Market and supply chain

IS encounters numerous obstacles related to market dynamics and supply chains during its initiation and execution. A significant hurdle is the lack of information and awareness, with fewer than 0.1% of European businesses engaged in IS (Lombardi, 2017). This deficiency in information prevents companies from recognizing potential symbiotic partnerships and appreciating the advantages of such collaborations. The lack of inter-company collaboration and management backing causes the problem. Companies generally do not struggle with establishing the commercial feasibility of IS opportunities (Lombardi, 2017). They face difficulties in striking a balance between cooperation and competition. The issue of "coopetition" arises when businesses must collaborate to reduce waste disposal and input procurement costs while simultaneously competing to minimize their portion of additional operational expenses (Yazan & Fraccascia, 2020). This situation can create friction within the supply chain and impede the formation of symbiotic partnerships. Although both IS and traditional supply chains address waste management concerns, there is a notable lack of IS consideration within supply chain research (Bansal & Mcknight, 2009).

Organizational and Managerial barriers

A significant barrier is the absence of inter-company collaboration and management backing (Hossain et al., 2024). Companies frequently find it challenging to create and sustain the cooperative relationships essential for IS due to a lack of trust, information exchange, and partnership development (Agudo et al., 2023). The absence of a well-defined IS strategy at the organizational level further complicates its execution (Södergren & Palm, 2021). While companies usually do not struggle to establish the commercial viability of IS opportunities, they often need assistance tackling regulatory, organizational, and governance challenges (Lombardi, 2017). This indicates that the obstacles are more related to managerial and organizational factors than economic feasibility.

Cultural and Social barriers

These challenges often arise from organizational and interpersonal interactions, which can significantly influence the effectiveness of IS projects. A major cultural challenge is the lack of cooperation and trust between companies (Hossain et al., 2024). Hesitation to work together may originate from a culture of secrecy and individualism prevalent in many industries. Furthermore, the lack of support from management (Hossain et al., 2024) can pose a significant hurdle, as IS projects may find it challenging to gain momentum within organizations without backing from top-level executives. Building trust and fostering general reciprocity is vital in overcoming these challenges (Domenech & Davies, 2010). Establishing trust and integration within IS networks involves various stages of cooperation, which is crucial for facilitating effective exchanges. This highlights the importance of fostering a culture of collaboration and mutual benefit among the participating companies.

METHODOLOGY & LIMITATIONS

The research carried out in this paper is divided into two parts. First, a literature review on barriers to IS implementation was conducted to provide the basis for the second part of the paper, which investigates barriers to IS implementation in the countries studied.

Methodologically, the second part of the study analyzes secondary data on waste management, geographical factors, the legal framework and economic trends. In addition, case studies were used to examine how existing IS have overcome barriers and seized opportunities to build mutually beneficial relationships between companies.

The main limitation of the paper is that the research was only conducted in three countries – Croatia, North Macedonia and Mauritius – which are the authors' home countries. Therefore, the conclusions should not be generalized. On the other hand, it provides a good basis for further research on the implementation of IS in different countries.

BARRIERS FOR IS IN SELECTED COUNTRIES

In the next section of the paper, barriers to IS implementation in selected countries have been researched, and selected cases were presented to examine whether the barriers in the studied countries are similar.

North Macedonia

The concept of IS offers significant potential for promoting sustainable economic growth and improving environmental conditions in the Macedonian economy. The implementation of IS faces challenges regarding legal framework, public awareness and practical implementation. Many businesses fail to recognize the potential cost savings and waste reduction opportunities, resulting in missed chances to establish partnerships that could optimize resource efficiency (OECD, 2024). A key impediment is the lack of awareness and understanding of the circular economy among the public and businesses. According to the Regional Cooperation Council (2022), 77% of Macedonian citizens are unfamiliar with the circular economy concept. The Macedonian economy also encounters difficulties in advancing IS due to inadequate institutional and financial support. Companies struggle to implement IS effectively without targeted funding, technical assistance, or organizational backing. The absence of incentives—such as tax breaks or grants—further complicates their ability to capitalize on opportunities (OECD, 2024). To foster IS development, removing barriers and encouraging symbiotic partnerships is crucial. Although EU funding and international resources are available for sustainability projects, many Macedonian businesses find it challenging to access these funds due to limited guidance and concerns about eligibility.

The Macedonian economy relies heavily on the manufacturing, agriculture, and energy sectors, which present opportunities for IS. These sectors produce significant byproducts and waste that can be reused. An OECD (2024) analysis of the circular economy in North Macedonia identifies four key sectors—Construction, Biomass and Food, Textiles, and Mining and Metallurgy—and outlines measures for various stakeholders at different stages of the life cycle.

The application of IS in the Macedonian economy dates back to the 1950s, particularly in the food and biomass sector. A prime example of this model was found in the Pelagonia Agro-Industrial Park (AIP) (Figure 2), where various food industries were strategically located and interconnected throughout their production processes. The Sugar Factory in Bitola served as the central hub of this symbiosis, utilizing waste and byproducts from sugar production as inputs for other food industry operations.

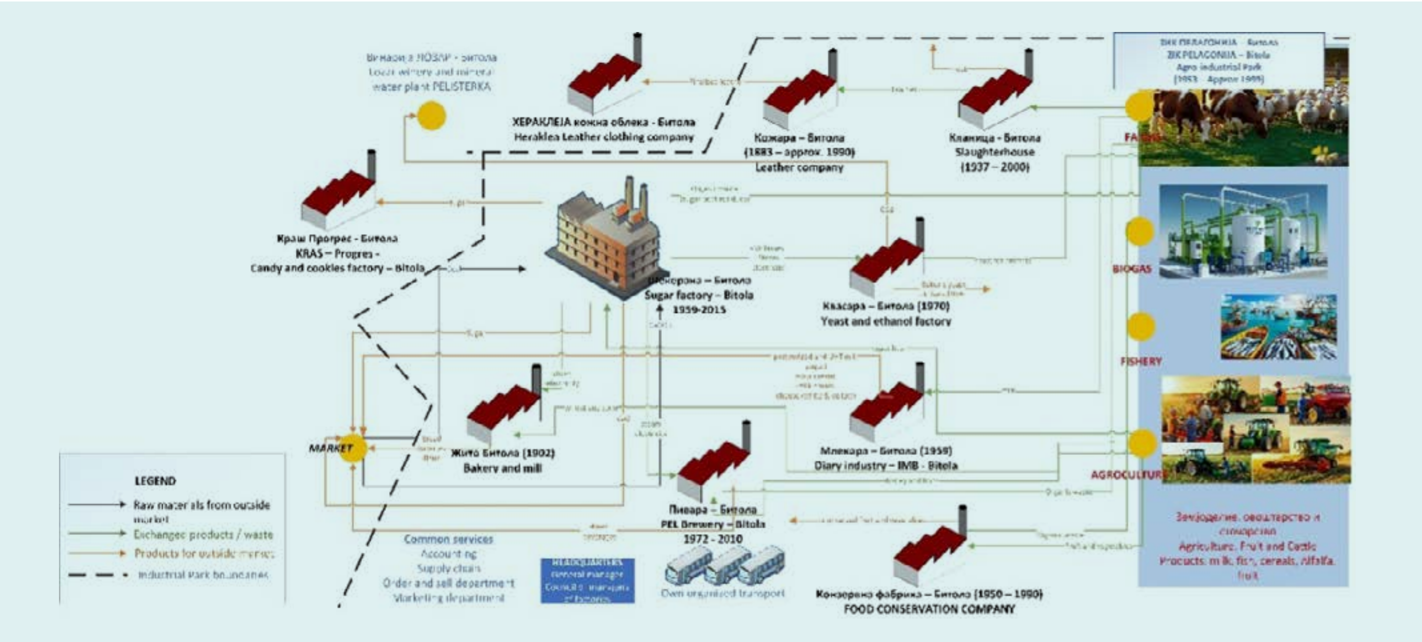

Figure 2 Agro-Industrial Park Pelagonija – Bitola

This AIP consisted of two main parts: industrial production facilities and the agricultural sector, which has farms. The agricultural sector produced the primary raw materials for factories in AIP and surplus for other markets. The industrial sector of AIP had a secure source of raw materials of controlled quality (AIP Pelagonija 1983). Moreover, these factories had their byproducts and waste exchanged between all units (by needs). Sugar-extracted sugar beets have been used as high-quality food for cattle molasses to produce yeast and ethanol. Anaerobic (alcoholic) fermentation produces pure CO2 that can be the only source of sparkling drinks for the food industry. Partially, yeast was produced as feed for animals (extra quality meat). Low flexibility, bad technical solutions and investments, and changeability of quality are some reasons for destroying this system. So, it can be said that IS barriers can be created during the existence of IS and can be a reason for the collapse of the system that already works. Such barriers with strong influence are economic barriers, lack of awareness/knowledge, technological readiness of each unit, scale and proximity. AIP has been a predecessor of the Pelagonia Agricultural Waste to Biogas Project, a contemporary example of successful IS, effectively transforming agricultural waste into biogas. This initiative addresses waste management, reduces methane emissions, and provides renewable energy for local use.

Effective textile waste management is crucial, particularly in North Macedonia, where many cutting processes remain unoptimized. When recycling is not an option, textile waste can be “downcycled” into lower-quality products. According to Switchmed (2020), most recycling efforts in the textile industry are focused on producing insulation materials for the automotive and construction industries. This situation allows the Macedonian textile industry to create new value from waste. A prominent example is “Netam,” a company dedicated to producing various textile products while actively collecting and recycling textile waste to develop new items, such as insulation sheets and geotextiles. They are tackling the issue of textile waste, which represents about 15% of total gross textile production. However, the owners have identified establishing a financial support environment as a substantial barrier to these targeted IS practices.

To facilitate a transition to a circular economy, North Macedonia should strengthen stakeholder cooperation, raise awareness, and educate citizens and municipalities (OECD, 2024). Despite the regulatory and logistical challenges, IS holds significant potential for economic growth and environmental sustainability in the Macedonian economy. By leveraging existing opportunities, increasing awareness, and implementing supportive policies, the economy can foster a thriving IS ecosystem that benefits businesses, society, and the environment.

Croatia

Although there are no classic eco-industrial parks in the Republic of Croatia that are cited as examples of IS, some examples of successful IS in Croatia include, for example, the companies NEXE, which uses alternative fuels produced from waste (NEXE, 2022; Jutarnji list, 2024), CEMEX, which uses byproducts and waste in cement production (CEMEX, N/A), ŽITO uses farm manure, silage and other organic residues in biogas plants and creates biogas, and also uses digestate, a byproduct of biogas production, as organic fertilizer (ŽITO, N/A). Livit (N/A) uses sludge from water treatment plants and fly ash from thermal power plants to produce soil for landfills, forest roads, and building protection against floods.

While specific examples of IS in Croatia are not extensively documented in the available sources, there has also been no comprehensive research in the Republic of Croatia, which poses a significant problem for detecting barriers to IS. However, the country's academic and industrial sectors actively explore the concept.

Furthermore, direct sources detailing the barriers to IS in the Croatian context are unavailable. We believe that here, too, we are dealing with typical barriers to IS: regulatory barriers - lack of an appropriate legal framework and bureaucracy; economic barriers - lack of financial incentives. Organizational barriers include a lack of trust, insufficient knowledge about IS, and weak connections between industrial sectors. We would also mention the lack of education as a potential barrier.

Various research and literature highlight the lack of an appropriate legal framework as one of the most significant barriers to IS (Södergren & Palm, 2021; Herath et al., 2023). In the European Union, IS is not often explicitly mentioned. However, the concept is embedded within the EU's regulations on the circular economy, waste management and protection of the environment, such as Waste Framework Directive (OJ L 312, 22. 11. 2008 and OJ L 150, 14. 6. 2018), Communication "A new Circular Economy Action Plan for a cleaner and more competitive Europe" (European Commission, 2020a) and Communication "A New Industrial Strategy for Europe" (European Commission, 2020b). European Union policies encourage industries to adopt circular and sustainable practices, with IS playing an increasingly vital role. Croatian Waste Management Act (Official Gazette of the Republic of Croatia, 84/2021) transposes the Waste Framework Directive into Croatian legislation. In addition to the Waste Management Act, the legal framework in the Republic of Croatia relevant to IS can also be linked to the provisions of the Waste Management Plan of the Republic of Croatia for the period 2023-2028 (Official Gazette of the Republic of Croatia, 84/2023), Waste Management Ordinance (Official Gazette of the Republic of Croatia, 106/2022, 138/2024). Croatia does not have specific policies dedicated to circular economy, therefore neither for IS, although it is the topic on the policy agenda. Also, various Croatian national strategies have the potential to promote circular economy initiatives. (SwitchMed, 2020; ETC, 2024).

At a workshop held as part of the COST LIAISE (CA22110) project in Osijek in 2024, representatives of Croatian industries pointed out that the legal framework for waste and byproduct management is not flexible enough to encourage IS and that excessively long bureaucratic procedures and complicated permit obtaining make cooperation between industries difficult.

It is known that investments in waste recycling and reuse technologies require significant financial resources, and the return on investment is not always fast. In Croatia, there are initiatives to support private investments, but these are not focused on green and circular businesses (SwitchMed, 2020). Although specific data for Croatia are unavailable, implementing IS requires initial investments, and the lack of financial incentives can be a barrier for companies considering such projects.

Although the Croatian Chamber of Economy has a system called the Waste Exchange (The Croatian Chamber of Economy, 2025), which is a specialized waste and secondary raw materials classifieds site where various types of waste and secondary raw materials can be offered or sought, we are not sure about its practical functioning. Therefore, we can say that no organized platforms and initiatives would encourage the exchange of waste and byproducts between companies. Also, companies are often unaware of the possibilities for IS with other sectors. We believe many companies are not sufficiently educated about the advantages of IS and their application and are unaware of the possibilities for IS with other sectors. As stated in the Research Infrastructure Development Roadmap of the Republic of Croatia 2023-2027, research infrastructure ecosystems are generally underdeveloped and very poorly connected with the industry (Ministry of Science and Education, 2023: 5). In this sense, it is necessary to carry out information, consultation and education about IS, which would help in the implementation of this kind of business model.

Activities are being carried out to develop the secondary raw materials market to define common criteria and quality standards. A key step in this process was the adoption of the Ordinance on Waste Management, which specifies the conditions for acquiring the status of byproducts. Since every production process creates byproducts in addition to the main product, it is important to clearly define when a material becomes waste to avoid environmental risks and unnecessary costs. The growing number of registered producers of byproducts and the increase in their quantities from 2015 to 2020 indicate a growing awareness of business entities about the advantages of such an approach (Official Gazette of the Republic of Croatia, 84/2023). Unfortunately, most industrial waste is still landfilled instead of recycled or used for other purposes. The lack of adequate facilities for recycling and processing byproducts makes it challenging to implement IS.

In Croatia, technical barriers to IS implementation include waste management infrastructure and stream quality challenges. The lack of advanced waste processing and recycling technologies can hinder the efficient exchange of materials between industries, limiting the potential for symbiotic relationships (World Bank, 2019). Additionally, the suboptimal planning of waste management systems and insufficient separate waste collection practices in Croatia can further complicate the implementation of IS initiatives (World Bank, 2019). These technical challenges highlight the need for improved infrastructure and technological capabilities to support the development of IS in Croatia.

Mauritius

Since the country's independence in 1968, the island of Mauritius has undergone significant economic transformations. These economic transformations have enabled Mauritius to reach the status of a high-income country in 2020 (World Bank, 2020). With the country's rapid economic development, the amount of waste generated is rising. The list below provides for the causes for the increase in the volume of waste in Mauritius:

The population is increasing (presently, the population of Mauritius is around 1.3 million compared to 1.2 million and 900,000 in 2000 and 1980, respectively).

Increase in economic activities (14.74 billion USD in 2018 and 4.73 billion USD in 2000)

Increase in lifestyle - High consumption of packaged goods and other disposable items Industrialization - Constructing Smart Cities and other industrial buildings produces more industrial waste.

Improvement in the standard of living leads to increased demand for products.

Increase in the number of tourists visiting the country (from 732,000 in 2000 to approximately 1.3 million in 2024- this industry is considered one of the significant generators of waste throughout the different activities of the value chain such as accommodation and hospitality, transport, recreational facilities as well as organization events and festivals).

The main types of waste (Figure 3) generated in the country are household items, industrial byproducts, wastewater, industrial effluent, medical waste and gases produced from industrial processes (Erceg & Sannegadu, 2025).

Waste disposal is done at Mare Chicose Landfill, the only landfill in the country. With the increasing volume of annual waste, the authorities have enacted legislation and regulations to address waste management more effectively and efficiently. Table 1 summarizes the two main legislative frameworks for waste management in Mauritius:

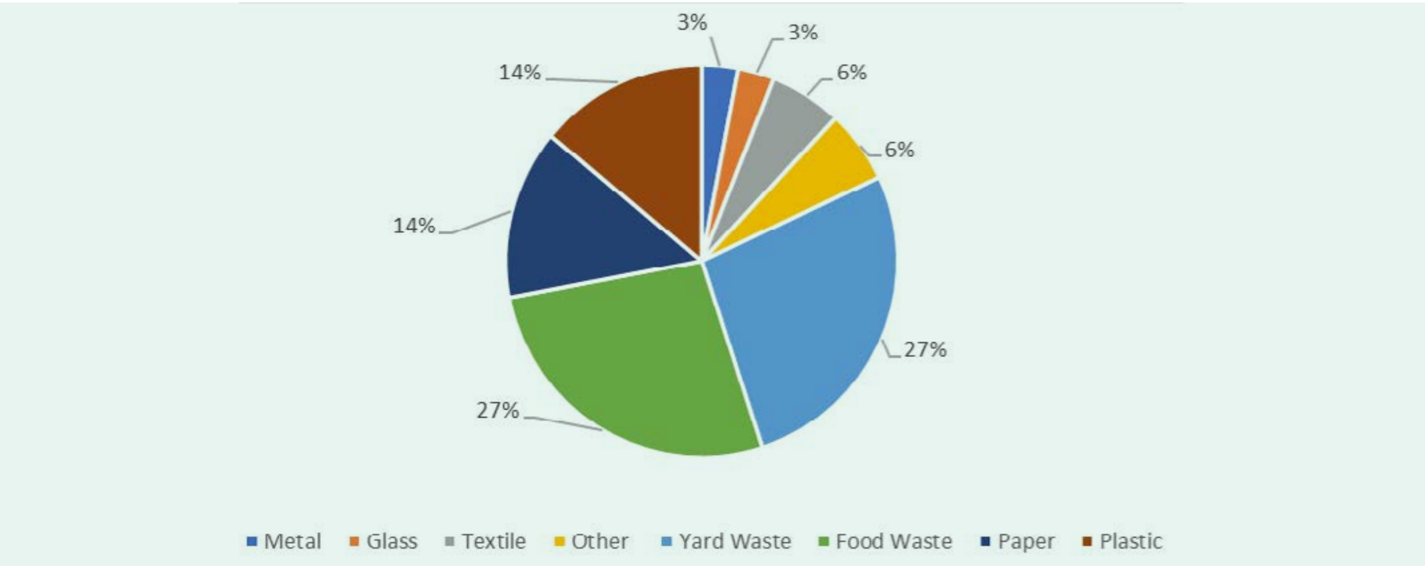

Figure 3 Main waste types in Mauritius
Source: Ministry of Environment, Solid Waste Management and Climate Change (2023)

Legislation	Purpose
Waste Management and Resource Recovery Act 2023	• The first legislation in Mauritius to expressly regulate waste management • Create the National Waste Management Coordination Committee, whose purpose is to coordinate and review the progress of waste management at a national level • Outline key waste management measures for Mauritius, namely: - Integrated Waste Management and Circularity Principles - National Solid Waste Management Strategy and Action Plan - Duties and Obligations of Waste Generators and Institutions - Public Consultation
Environment Act 2024	• Design national policies and priorities for the protection of the environment. • Create Committee and environmental monitoring bodies such as 'L'Observatoire de L'Environnement.' • Regulate: oil spill, plastic management, coastal and maritime zone management, circular economy, and extended producer responsibility.

Table 1. Main legislative framework in Mauritius

The other policy frameworks for waste management in Mauritius are The Local Government Act 2011, Environment Protection (Standards for Hazardous Waste) Regulations 2001; Local Government (Dumping and Waste Carriers) Regulations 2021; Local Government Act (Registration of Scavenging Contractors) Regulations 2004; Environment Protection (Collection, Storage, Treatment, Use and Waste Oil) Regulations 2006; Local Government Act (Registration of Recycler and Exporter) Regulations 2013. It must be noted that no official statistics regarding the number of cases brought to court under these legislations and regulations are available.

The introduction of IS in Mauritius has already been studied. One of the studies identified the primary polluting industries (Mauthoor et al., 2014), namely edible oil refineries, abattoirs and metal scrap recycling schemes. In a follow-up study, Mauthoor (2017) suggested how artificial intelligence can be implemented and focused on recycling electric arc furnace slag as concrete aggregate. The conceptual framework proposed by Van Assche et al. (2014) can help Mauritius find potential IS that can reduce waste and serve as an effective model to realize economic and environmental objectives. As far as barriers are concerned, Mauritius has both technical and non-technical barriers to IS implementation. Among the non-technical barriers, the most important are the legal provisions and the lack of knowledge about the possibilities of the IS. In addition, local authorities should continue to work closely with international institutions that provide technical and financial support and share technologies and best practices to promote the circular economy and ensure the well-being of future generations.

DISCUSSIONS

All three countries face almost the same obstacles to excellent IS implementation. Although technology and technical barriers play an important role in IS implementation, legal regulation as one of the non-technical barriers is the most significant barrier in all countries (Table 2).

Legislation	Purpose
Waste Management and Resource Recovery Act 2023	• The first legislation in Mauritius to expressly regulate waste management • Create the National Waste Management Coordination Committee, whose purpose is to coordinate and review the progress of waste management at a national level • Outline key waste management measures for Mauritius, namely: - Integrated Waste Management and Circularity Principles - National Solid Waste Management Strategy and Action Plan - Duties and Obligations of Waste Generators and Institutions - Public Consultation
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Table 1. Main legislative framework in Mauritius

As mentioned above, the European Union recognizes IS as an important tool for promoting a circular economy. According to Neves et al. (2020:15), the development of IS varies across European countries due to differences in economic development and national policies. Domenech Aparisi (2010) further explains that while legal frameworks and enforcement differ across Europe, EU regulations provide a common ground for national governments and industries to tackle environmental challenges. The author points to the problem of waste classification, noting that the lack of a clear distinction between waste and secondary materials in EU legislation hinders the exchange, reuse and recycling of materials. Special permits and licenses are required for materials classified as waste, creating obstacles for companies wishing to reuse them. Legal obligations related to waste management, reuse and recycling further complicate the exchange and reuse of materials (Domenech Aparisi, 2010). This can also be observed in two other countries studied – North Macedonia and Mauritius - which face the same problems regarding the legal process for converting waste into resources.

The most effective approach to support green and circular businesses is through economic instruments such as taxes and levies that discourage pollution and positive incentives and subsidies that encourage circular practices. These are all current non-technical barriers in all three countries, but they can become enablers and drivers for IS implementation. Extended producer responsibility is crucial to accelerate the transition to a circular economy by holding producers accountable for sustainable waste management and prevention. EU Member States must introduce EPR schemes for specific waste streams, including packaging, batteries and electronic waste (WEEE). However, it can be challenging for companies investing in eco-innovation to obtain funding (SwitchMed, 2020). No financial incentives exist in all three countries, which is a significant barrier. The lack of knowledge and information is a major obstacle to financial barriers, as stakeholders are unfamiliar with IS and do not know how to take advantage of the opportunities available.

Technical barriers to IS adoption in all three countries include waste management infrastructure and power quality issues. The lack of advanced waste processing and recycling technologies can hinder the efficient exchange of materials between industries and limit the potential for symbiotic relationships. This is compounded by sub-optimal planning of waste management systems and inadequate segregated waste collection practices. These technical challenges highlight the need for improved infrastructure and technological capabilities to support the development of the information society in all three countries.

To facilitate the transition to a circular economy, all three countries should strengthen stakeholder collaboration, raise awareness and educate citizens and municipalities. Despite the regulatory and logistical challenges, the information society holds significant potential for economic growth and environmental sustainability in their economies.

CONCLUSIONS

Industrial symbiosis offers a promising approach to enhancing resource efficiency and reducing waste by leveraging industry collaboration opportunities. However, its implementation faces numerous barriers across different regions. This study highlights the similarities and differences in IS barriers among Croatia, North Macedonia, and Mauritius, emphasizing infrastructure, regulatory frameworks, economic conditions, and geographical positions.

Although all three countries studied are different – one is part of the EU, one is trying to become part of the EU, and one is representative of SIDS – they all face similar or the same barriers to implementing IS. In each country, some examples of IS have arisen by accident and were not caused by a planned development. All three countries have significant potential for IS implementation, but some barriers must be overcome.

Based on the research, it can be concluded that the lack of advanced technologies and infrastructure readiness is a significant barrier, especially in emerging economies. Insufficient policy measures and regulatory support hinder the introduction of information services, create uncertainty and discourage companies from engaging in symbiotic partnerships. On the economic and financial side, high start-up costs and insufficient financial incentives from governments are significant obstacles, especially in developing countries. Finally, the lack of cross-company cooperation and trust makes it difficult to build sustainable IS relationships. To address the technical barriers, investing in advanced technologies and infrastructure is crucial for facilitating resource exchange and symbiotic relationships. If Croatia, North Macedonia and Mauritius address these challenges and adopt supportive policies, they can create a more favorable environment for IS and thus contribute to sustainable economic growth and environmental protection.

Further quantitative research should be conducted to determine the impact of the current IS and the potential for further IS implementation in all three countries. On the other hand, research should be conducted to propose a plan to overcome the identified barriers.

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Technical and non-technical barriers and challenges in industrial symbiosis implementation in the economic and technological context

Blisard Zani
Faculty of Economy, University of Tirana, Tirana, Albania
blisard.zani@unitir.edu.al

Llesh Lleshaj
Faculty of Economy, University of Tirana, Tirana, Albania
lleshlleshaj@feut.edu.al

ABSTRACT

Industrial symbiosis (IS) demonstrates the concept of resource-sharing of a by-product or service that in other circumstances would have been disposed of or underused. Industrial symbiosis appears to be crucial for fostering circular economy, enabling industries to share resources, waste reduce management, and enhance sustainability. However, IS implementation and adoption faces barriers like limited awareness, weak collaboration, and restrictive policies. Technical challenges, including technology integration, data sharing, and infrastructure gaps, further complicate efforts to implement this transformative approach. Moreover, non-technical obstacles also accompany all the processes. This study analyzes these challenges, providing recommendations to implement industrial symbiosis in accordance with circular economic goals, ultimately maximizing economic and environmental benefits while fostering more sustainable industrial ecosystems. The study gathers 67 expert interviews from 16 EU and 15 non-EU member countries. The data are collected using Likert scales, multiple-choices and open-ended questions, combining quantitative and qualitative methods, by analyzing correlative and factorial statistical models, and providing insights into expert perspectives on industrial symbiosis challenges and opportunities. High technology costs, lack of innovation, outdated infrastructure, and limited access to advanced recycling technologies are key barriers to industrial symbiosis, significantly hindering its adoption and limiting industries' ability to embrace sustainable resource-sharing practices. Also, the absence of fiscal incentives, insufficient funding, high upfront costs, stakeholder integration challenges, and complex regulations significantly issue for industrial symbiosis adoption. Addressing these barriers through supportive policies, funding mechanisms, and collaborative frameworks is essential for advancing sustainable industrial practices. In this context, governments should provide clear policies, funding, and incentives to promote circular economy, while universities and research centers advance innovation and knowledge transfer. Educational programs must enable the workforce with skills to support industrial symbiosis initiatives effectively.

KEYWORDS
Industrial Symbiosis - Circular Economy - Resource Sharing - Technological Barriers
Cultural Obstacles - Stakeholder Collaboration and Awareness

INTRODUCTION

Dynamic economic transformations in the last decades have imposed various economic challenges, creating an unsecure environment for some economic sectors. The concept of linear economic cycles is now a reality that developed countries have started to abandon, in order to create a more sustainable economic framework. In that context, circular economy and the cooperation between industries are becoming more present, imposing barriers and challenges related to their implementation. As a crucial part of it, industrial symbiosis implementation has created a brand-new environment for the vast majority of industries, willing to collaborate and apply this modern concept.

Industrial symbiosis (IS) demonstrates the concept of resource-sharing of a by-product or service that in other circumstances would have been disposed of or underused. Industrial symbiosis appears to be crucial for fostering circular economy, enabling industries to share resources, waste reduce management, and enhance sustainability. However, IS implementation and adoption faces barriers related to fiscal and economic framework, cross-border cooperation, regional barriers, changes in the legal context, technical and non-technical challenges, etc. Technical challenges, including technology integration, data sharing, and infrastructure gaps, further complicate efforts to implement this transformative approach. Moreover, non-technical obstacles also accompany all the processes.

This study analyses these challenges, providing recommendations to implement industrial symbiosis in accordance with circular economic goals, ultimately maximizing economic and environmental benefits while fostering more sustainable industrial ecosystems. The study gathers 67 expert interviews from 16 EU and 15 non-EU member countries, in order to provide a comprehensive viewpoint and to emphasis the differences and mutual aspects of countries. High technology costs, lack of innovation, outdated infrastructure, and limited access to advanced recycling technologies are key barriers to industrial symbiosis, significantly hindering its adoption and limiting industries' ability to embrace sustainable resource-sharing practices. Also, the absence of fiscal incentives, insufficient funding, high upfront costs, stakeholder integration challenges, and complex regulations significantly compound pivotal non-technical barriers for industrial symbiosis adoption in selected countries.

LITERATURE REVIEW

The rise of the industrialization process and urbanization in the last decades has led to an increase in carbon dioxide emission (Dong, et al., 2014) . This has increased the attention of researchers trying to find alternative ways of cooperating, to reduce carbon emissions, also contributing to the reduction and waste management. Pioneers such as Chertow and Desrochers has predefined the concept of industrial symbiosis, as an alternative viewpoint of economy as a whole, as industrial symbiosis engages traditionally separate entities in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products (Chertow, 2000) (Desrochers, 2004). Lawal and other authors has also emphasized the importance of industrial symbiosis and its relation to sustainability and industrial ecology (Lawal, Alwi, Manan, & Ho, 2021). Industrial symbiosis has now been documented in all continents, with sporadic or standardized cases (Lombardi, Lyons, Shi, & Agarwal, 2014). Chertow and Ehrenfeld developed a 3-stage theory for IS, beginning with the synergy of the actors involved in IS (Chertow & Ehrenfeld, 2012).

As the economic cycles are considered now more and more dynamic, the implementation of IS faces significant barriers and challenges. These obstacles are related to all phases of implementation, starting from understanding the importance of IS, technical aspects of implementation, socio – cultural barriers, etc. The barriers and obstacles of IS are analyzed from several authors, emphasizing the role of governments and learning from case studies, thus reducing the implementation challenges (Lybæk, Christensen, & Thomsen, 2021). Previously, Islam et. Al has also emphasized the importance of clear policies to support IS implementation (Islam, Rahman, & Islam, 2016). Neves et. Al noticed that the diversity of industries, geographical proximity, facilitating entities and legislation, plans, and policies are shown to be the main barriers of IS implementation (Neves, Godina, Azevedo, Pimentel, & Matias, 2019). From the business perspective, the organizational challenges are most significant in the journey towards IS (Taqi, et al., 2022). In addition, during IS Implementation, some firms are oriented by maximizing their own profit creating bilateral agreements (Akhtar, et al., 2022). Moreover, the latest studies also mention the lack of technology and infrastructure readiness as one of the most important barriers on IS implementing, especially in manufacturing industry (Hossain, et al., 2024).

METHODOLOGY AND RESULTS

This section provides the methodological aspects of the data collection, and then analyzes the results derived from the survey. Even though it is challenging to collect data related to industrial symbiosis, primary data always guarantees a more in-depth perception of the variables.

Methodology

This study uses primary data collected via a detailed questionnaire created by authors, in order to analyze the main challenges and obstacles for IS implementation. In separate sections, the survey has detailed questions for identifying technical and non-technical barriers. The study gathers 67 expert interviews from 16 EU and 15 non-EU member countries, to provide a full range of perceptions about IS implementation. The data are collected using Likert scales, multiple-choices, and open-ended questions, combining quantitative and qualitative methods, and providing insights into expert perspectives on industrial symbiosis challenges and opportunities. Through cross correlation questions, we can understand and identify some of the most important barriers and obstacles from researchers, experts from the business sector, public employees, etc.

Results

Since the Industrial Symbiosis is a complex economic process that integrates all the economic actors, the first questions in the survey analyzed the importance and impact of some macroeconomic and general indicators to the industrial symbiosis implementation. The chart below represents as Likert scales, the importance of GDP growth, unemployment rates, local culture, population age distribution and the level of investments in industry.

Chart 1 Importance of general indicators for IS implementation

More than fifty percent rank the importance of GDP growth as vital to IS implementation. In addition, the level of unemployment has a neutral impact. Since the IS implementation is also related to recycling, the local culture has a high or very high importance for more than 65%, emphasizing the circular economy and recycling processes awareness. The level of investments in industry has also a very high importance on IS implementation, while the population age distribution has a low – moderate impact on it. Maybe an in-depth analysis by country can give us a more complex understanding of these indicators, especially regarding the local culture of recycling.

Technical barriers on IS implementation:

Latest studies have listed several technical barriers that are directly or indirectly linked to the overall or specific aspects of IS implementation. The questionnaire and interviews conducted with experts affirms that technology costs, the lack of technological innovations, and difficulties in integrating new technologies are the most important technological barriers slowing the IS implementation. Furthermore, several other obstacles like lack of skilled HR to operate technologies, rapid obsolescence of current technology, and insufficiently developed infrastructure have also a negative impact hindering industrial symbiosis.

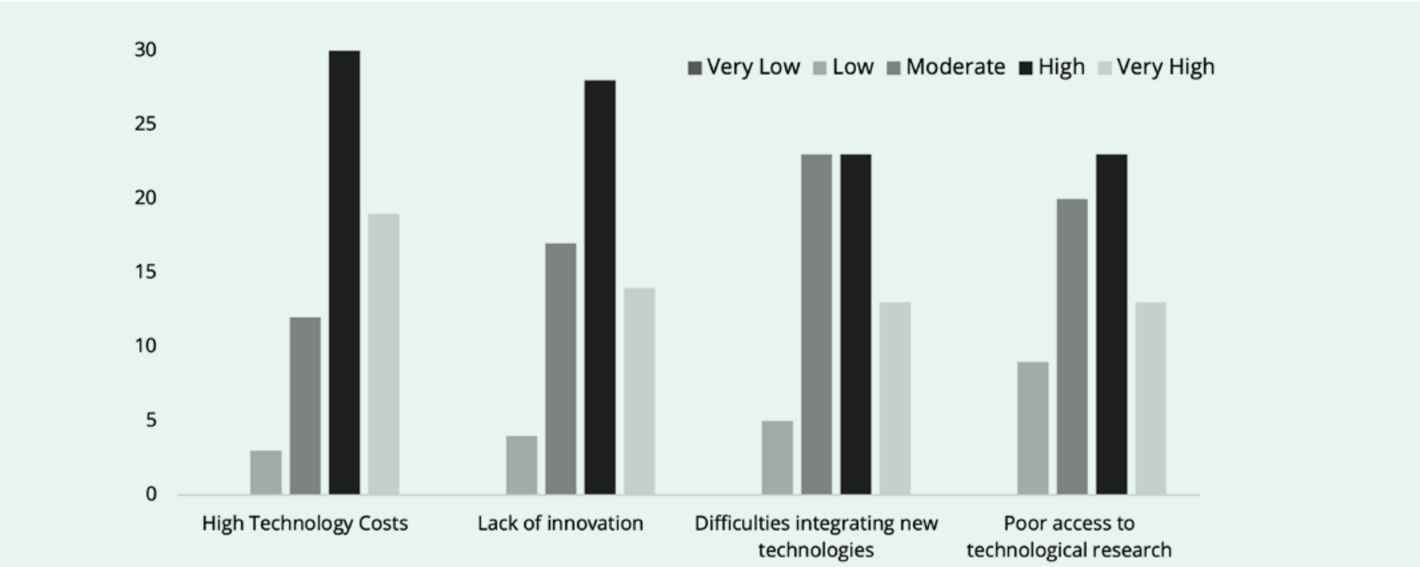

Chart 2 Technical barriers on IS implementation

The majority of respondents rated high technology cost as significantly or very significantly impactful. High costs are a major obstacle to acquiring the necessary technologies for effective IS implementation, especially for smaller businesses. Furthermore, lack of innovation was rated as significant or very significant by more than 75% of the experts. Industries report that a lack of cutting-edge technological solutions limits the scope of IS, preventing the adoption of advanced practices. The vast majority of respondents rated difficulties in integrating new technologies as significantly impactful. Integrating new, advanced technologies with outdated systems poses operational challenges, slowing down IS adoption across industries. Lastly, poor access to technological research and development split between moderately and significantly, indicating that limited access to R&D is a notable barrier. Without strong support for innovation and technology development, industries struggle to adopt newer IS-compatible technologies.

Non-technical barriers to IS implementation:

Industrial symbiosis adaption to the current economies also requires social understanding and involvement of all economic actors. However, a lot of socio-economic and cultural barriers [here referring as non-technical] tend to slow down the industrial symbiosis implementation, especially in underdeveloped and developing economies with low culture on circular economy. This study identifies six main barriers such as lack of infrastructure, lack of funding, inadequate regulations, insufficient human resources, lack of public awareness, and insufficient business collaboration. These obstacles create significant barriers to implement IS. (Chart 3)

The lack of infrastructure has moderate to high impact for more than 75% of the experts, as one of the main barriers. Moreover, dominantly the lack of funding is highly ranked as important, accompanied by insufficient business collaboration. Since businesses do not have significant know-how on IS processes, they have insufficient collaboration in order to adapt IS. The inadequate regulations and law are seen as predominantly with moderate importance, as well as the insufficient human resources working and researching in industrial symbiosis aspects.

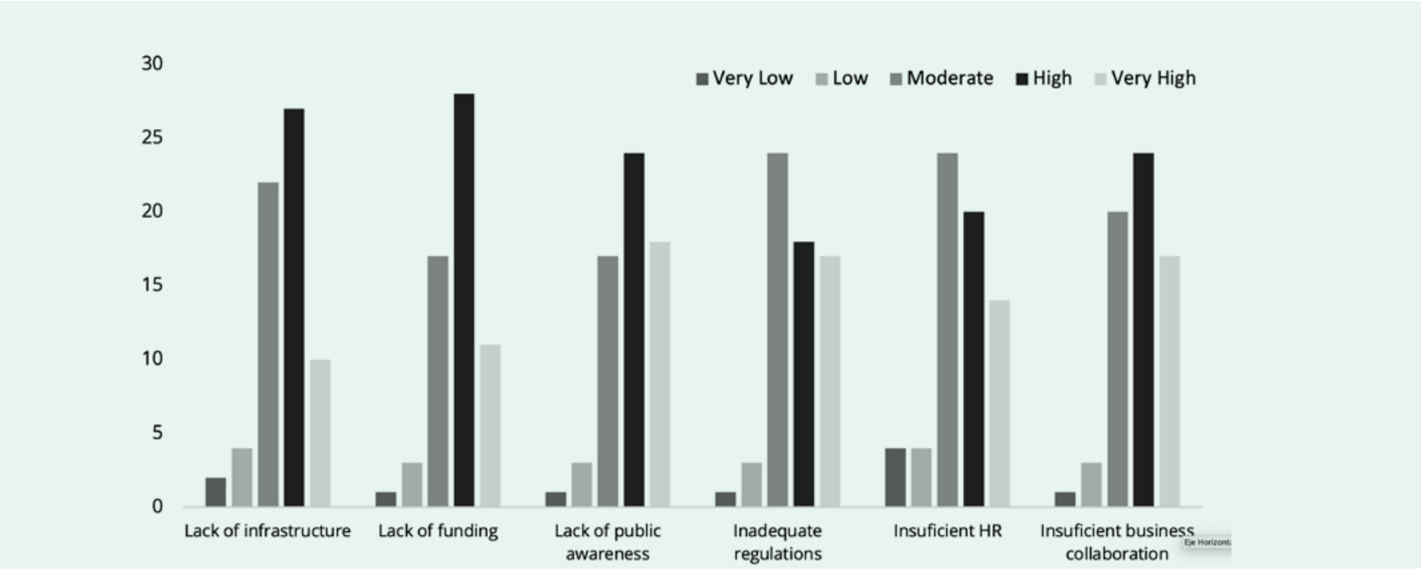

Chart 3 Non-technical barriers on IS implementation

CONCLUSIONS AND RECOMMENDATIONS

Industrial symbiosis, as a relatively new economic concept is closely related to the circular economy. The collaboration between industries and businesses in local and regional context is seen as vital in the near future to prevent waste management, carbon emission reduction and other consequences with climate and environmental impacts. However, industrial symbiosis implementation in different countries face several barriers and obstacles. For analytical purposes, this study classifies them as technical and non-technical barriers on IS implementation. Technological barriers to IS implementation are significant and multifaceted. High technology costs and a lack of innovation make it difficult for industries to adopt advanced solutions. Many organizations face insufficiently developed infrastructure and limited availability of advanced recycling technologies, hindering resource exchange. Additionally, the difficulty in integrating new technologies into existing systems and the lack of skilled personnel to operate and maintain them further complicate adoption. Poor access to technological research and development and the rapid obsolescence of current technologies add to the challenges, leaving industries behind in technological progress for IS. In a broader context, the implementation of IS faces numerous non-technical barriers. These include lack of fiscal incentives and insufficient funding, making IS financially challenging. High-cost investments in infrastructure, coupled with outdated equipment, further complicate adoption. Integration of regional stakeholders and regulatory issues hinder collaboration, while cooperation and coordinating change across sectors remain difficult. Additionally, insufficient information about IS, geographical barriers, and transversal skill gaps pose significant challenges. Know-how protection, a lack of functioning networks/platforms, and sector-specific skills gaps, alongside a shortage of a skilled workforce, further impede progress in IS implementation.

EU countries have made significant progress on IS regulations and implementation in several industries in the agricultural sector, service industry, processing industries, etc. Meanwhile, non-EU countries still face highly important barriers related to the factors mentioned above, combined with the slow adaptation culture of circular economy and recycling. High promotion of IS via media and other channels, fiscal incentives for companies adapting processes of IS, increased capacities and technologies for IS implementation are highly recommended, to ease the implementation of industrial symbiosis.

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3

The importance of the inter-correlation between industrial symbiosis and security symbiosis for ensuring the macro-social sustainability

Serghei Sprincean
Moldova State University, Institute of Legal, Political and Sociological Research, Chisinau, Republic of Moldova
sprinceans@yahoo.com

ABSTRACT

The aim of the work consists in the need to substantiate that ensuring macro-social sustainability depends the most on the inter-correlation between IS and SS for better promotion of the prospects for overcoming the global crisis. The concept of Security Symbiosis (SS) is designed as an extension of the concept of Industrial Symbiosis (IS), which involves a significant number of actors of safety symbiotic relations, which are simultaneously participants in the process of interrelation and cooperation in the security field. The process of ensuring the macro-social sustainability can be much more successful through a closer inter-linkage between the SS and the IS, in which the SS comes to support the IS by activating such actors as: institutions specialized in the field of ensuring national and individual or private security, the state itself as an institution and foundation of the security macro-system, the normative-legal framework, active civil society, in all forms of its organization, mass media as an important factor and actor in SS and in promoting IS goals, the academic environment, international institutions, inter-state organizations, multinational corporations with a significant impact on maximization for military and security potential, institutions specialized in providing logistics service for ensuring, supporting and backing, redirecting, allocating and transferring knowledge, resources or materials. In the perspective to overpass contemporary global crisis through ensuring the macro-social sustainability has an important role the concept of interceptor as an entity endowed with the ability to detect and counter security risks, dangers and threats, indispensable also for the proper functioning of the SS for discovering the full potential of IS. As a result of the ensuring the macro-social sustainability, by interrelationship of various actors of IS and SS, by optimizing mutual synergies and exchange synergies between these actors, mutual advantages can be obtained, both in terms of overcoming the global crisis and the evolution of methodologies and applicability of IS and SS. Thus, the inter-correlation between IS and SS becomes a minimum necessary condition for sustainable social progress and overcoming global crises, which can potentially threaten humanity with its irreversible degradation and eventual disappearance in a foreseeable future.

KEYWORDS
Industrial Symbiosis - Security Symbiosis - Synergy - Interceptor

INTRODUCTION

In the era of increasing global problems and world crisis, the level of insecurity increases, including political ones, manifesting itself in all constitutive spheres of political life, ultimately affecting the quality of democracy and the proper functioning of socio-political systems.

The need for personal safety and security of man is among his first vital needs, after biophysiological ones, such as nutrition, the need for shelter and survival, in the hierarchical pyramid of needs developed by psychologist Abraham Maslow in 1943. Personal safety transcends physical safety and the fear of being attacked and calls for economic and financial security: the need for a guaranteed minimum income, job security, the security of the psychological comfort necessary for effective activity free from the anxieties of everyday life. Personal safety also refers to socio-political security, through which man seeks to live in a comfortable, fair and stable hierarchical system, safe from the violence of wars, revolutions and coups with clear and fair rules in which progress and prosperity can be possible through honest work, loyalty and perseverance. In this context, the concept of Security Symbiosis (SS) comes to complement and adjust to the needs and imperatives of the era, and it is designed as an extension of the concept of Industrial Symbiosis (IS).

The diversity of security challenges raises new questions and generates new perspectives for researchers of security phenomena and processes, especially of the democratic processes as well of the securing good governance. So that security research, for a more in-depth understanding of it, acquires important new and novel conceptual-methodological valences in correlation with the general desideratum of the survival of democracy by enhancing good governance, in conditions of the contemporary unprecedented security crisis on a global level, after the Second World War. Security becomes a way, a fundamental condition, an important resource for the foundation of a new framework of analysis in a security context, modeled and flexible, depending on the optimal course towards achieving the general goal of the academic community and the whole society, that of solving sustainable security issues. Thus, the expansion of the conceptual-theoretical framework of the field of security in correlation with the methodological set of human security is able to present, analyze and find viable solutions to contemporary complex and interdisciplinary challenges. Also, in the context of the theory related to Security Symbiosis, an extension of the concept of Industrial Symbiosis, human security becomes an important part of the international security system.

Therefore, the efficiency of security processes is directly correlated with the system of social values, with the system of moral norms, dominant in society, on the one hand, and on the other, it depends very much on the competence, professionalism and degree of respect for professional ethics specific to officials involved in organizing public debates, as well as on the individual morality and conscientiousness induced through education and socio-behavioral models that determine manifestations in the public space, examples to follow that determine and influence behavior both in the context of security processes and in the socio-political space, in the broadest sense of the term. Thus, for greater efficiency of security processes, by moralizing and bringing them into line with the norms and standards common to the international community, stricter control over compliance with legal norms is required by state bodies responsible for organizing and administering security processes, prompt legal sanctioning of violations committed, on the one hand, and on the other hand, more thorough monitoring is required, under conditions of fair transparency and legal and moral sanctioning, in case of deviations, through mass media bodies, by increasing publicity and media coverage of cases of unacceptable behavior.

METHODOLOGY

The concept of Security Symbiosis involves a significant number of actors of Security Symbiosis relationships, who are simultaneously participants in the process of inter-relationship and cooperation in the security field. Thus, we will note such actors in the Security Symbiosis process as: institutions specialized in the field of ensuring state and private security, the state itself as an institution and foundation of the national security macrosystem, the normative-legal framework, active civil society in all forms of organization, the media as an important factor and actor in security symbiosis, responsible for promoting strategic public relations, the academic environment, international institutions, inter-state organizations, multinational corporations with an important impact on the development of an important military and security potential, institutions specialized in providing logistics services, with the function of ensuring, supporting and backing, redirecting, allocating and transferring knowledge, resources, material, intellectual, human or military potential.

As a result of the ensuring the macro-social sustainability, by interrelationship of various actors of IS and SS, by optimizing mutual synergies and exchange synergies between these actors, mutual advantages can be obtained, both in terms of overcoming the global crisis and the evolution of methodologies and applicability of IS and SS.

RESULTS

The perception of system insecurity by the citizen can generate such distortions of political behavior as electoral absenteeism, can amplify the effect of the phenomenon of irrational voting or can contribute to the increase in the general dissatisfaction of the electorate regarding the political process, resulting from the impossibility of exercising its main function within the democratic system of redistribution of state power as a result of blocking the functionality of the democratic principle of adopting decisions by majority consensus, given the need to ensure systemic security by temporarily establishing mechanistic-authoritarian partnerships between the rulers and the ruled in order to facilitate the efficiency of the system in the natural fight against the dangers to it.

As a result of the interrelationship of the various actors of security symbiosis, synergies are inevitably created between these mutual actors, but also between the system and individualized actors. These can be grouped into: mutual synergies and exchange synergies. Namely, synergies can evolve to the level of coagulating and coordinating factors for the entire security system that is driven in its activity by security symbiosis, mutually advantageous for each participating actor of the system. In this context, mutual security synergies are those that are based on mutual interest and have the ability to mutually amplify the potential of the participants, and exchange synergies represent the relationships prolonged over time that connect generations of various actors of the security synergy, transmitting from the oldest and most obsolete, the experience, memory, accumulated know-how to the newer actors, who come to replace the actors that tend to become less active.

An important concept from the perspective of the proper functioning of the security symbiosis can become the concept of the interceptor as an entity endowed with the ability to detect and counteract security risks, dangers and threats, being an integral part of the subsystem of interception and resolution of dangers and threats, as an integral part of the security system.

Security in general can be typified by several criteria. For example, depending on the model adopted, security can be linear, but also circular. The linear one concerns the use of resources until exhaustion. Circular security denotes a greater concern for the reuse and more rational use of resources that are important for ensuring security. In this context, the importance of circular security management is highlighted, which coordinates and balances the circular security system in order to achieve greater efficiency, given that resources are exhaustible or difficult to regenerate, and the competition for supremacy between opposing security systems is increasingly fierce, the efficiency of these systems having the potential to make a difference.

The concept of security sustainability, in addition to that of the resilience of security systems, or resilience in the field of security, has the task of reflecting the perspective in which systems have the capacities and resources to pursue and achieve their goals in the medium and long term. Security sustainability comes to evaluate both the efficiency of security efforts and the resistance and solidity of the results obtained through these efforts to ensure security.

However, a fundamental problem for the entire field of security is the question of whether security itself can be understood, in turn, as a resource, and if so, what kind of resource it represents: exhaustible, reusable, renewable, transmissible, etc. The specifics and characteristics of security as a resource, likewise, is a subject of crucial importance.

We believe that security, in a certain context, can and must be understood as a resource for strengthening the well-being of society, of man and of the community environment. As a resource, security can maximize the results in other areas of social life, provided that it is well managed and proportionally distributed, depending on priorities and security needs.

Sources of security can be multiple: human, natural resources, favorable circumstances, a series of successful, inspired or well-calculated decisions, the cultivation by society of leaders capable of assuming decisions of historical importance for the security of society and the community, etc., but, despite this, security proves to be an extremely volatile and mobile resource, fragile and fine, easy to unbalance but difficult to recover.

Certainly, security is a transferable resource, however, human society has not yet managed to perform a completely rational and predictable management of security as a resource for achieving well-being, stability and prosperity.

Naturally and logically, a series of new concepts such as Security Symbiosis, as an extension of the concept of Industrial Symbiosis, have been deduced and built regarding the safeguarding of humanity by overcoming the impasse in which human civilization finds itself at the contemporary stage of evolution, divided into several directions and approaches, depending on civilizational and political factors. Consequently, a series of domains and disciplines have been highlighted, with a normative character, with a real praxiological and applicative potential as practical institutional mechanisms with a significant social impact in the process of forming the political behavior of the human person.

CONCLUSIONS

Given the amplification of the global crisis and its threat to the existence of man on Earth, solving the problem of humanity's survival in decent conditions, ensuring all the necessary premises for a high standard of living for each individual, but also for humanity as a whole, in the subsequent periods after overcoming the crises that threaten contemporary civilization, depends largely on finding a functional formula for establishing efficient social control, including through various mass media sources, over the social management process, especially in the case of the managerial process using advanced biological and informational technologies, to which the vast majority of the population does not have access, in order to ensure a sustainable development of the entire human civilization under conditions of equity. Thus, a series of mechanisms that must be implemented to achieve this goal, being in a systemic interdependence, can be noted.

However, a fundamental problem for the entire field of security is the question of whether security itself can be understood, in turn, as a resource, and if so, what kind of resource it represents: exhaustible, reusable, renewable, transmissible, etc. The specifics and characteristics of security as a resource, likewise, is a subject of crucial importance.

We believe that security, in a certain context, can and must be understood as a resource for strengthening the well-being of society, of man and of the community environment. As a resource, security can maximize the results in other areas of social life, provided that it is well managed and proportionally distributed, depending on priorities and security needs. Thus, the inter-correlation between IS and SS becomes a minimum necessary condition for sustainable social progress and overcoming global crises, which can potentially threaten humanity with its irreversible degradation and eventual disappearance in a foreseeable future.

The importance liberty in the formation and streamlining of democratization is crucial in the context of deepening of the global crisis. In the article are emphasized several important aspects regarding the specific of the contemporary global crisis in the perspective of overpassing the insecurity for achieving a fair level of liberty and democratization in the society. The stringent necessity of overcoming the global menaces imprint a special character to the political processes, creating new forms of political behavior. In this piece of work is discussed the contribution of security conceptions to the facilitation and increasing the democratization of the society.

The process of ensuring the macro-social sustainability can be much more successful through a closer inter-linkage between the SS and the IS, in which the SS comes to support the IS by activating such actors as: institutions specialized in the field of ensuring national and individual or private security, the state itself as an institution and foundation of the security macro-system, the normative-legal framework, active civil society, in all forms of its organization, mass media as an important factor and actor in SS and in promoting IS goals, the academic environment, international institutions, inter-state organizations, multinational corporations with a significant impact on maximization for military and security potential, institutions specialized in providing logistics service for ensuring, supporting and backing, redirecting, allocating and transferring knowledge, resources or materials. In the perspective to overpass contemporary global crisis through ensuring the macro-social sustainability has an important role the concept of interceptor as an entity endowed with the ability to detect and counter security risks, dangers and threats, indispensable also for the proper functioning of the SS for discovering the full potential of IS.

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Breaking barriers and driving circular innovation: industrial symbiosis in Kenya's textile manufacturing industry

Dinah Awino Kawino
Department of Environmental studies and community development, Kenyatta University Nairobi, Kenya
kawinoawino19@students.ku.ac.ke

ABSTRACT

The textile industry in Kenya, represented by Rivatex East Africa and Thika Cloth Mill, contributes approximately 56% of industrial pollution, highlighting its significant environmental footprint. Industrial symbiosis (IS) and circular business models (CBMs) offer transformative solutions to reduce this impact through resource sharing and waste minimization across industries. This research explores current IS practices in these mills, identifies non-technical barriers to their expansion, and proposes strategies for integrating formalized circular models. The study employed a mixed-methods approach, combining qualitative interviews with quantitative analysis of resource utilization data. SPSS was used to evaluate practices, barriers, and demographic influences on sustainability efforts. Key IS practices identified include the repurposing of coffee husks from local factories as boiler fuel, converting textile offcuts into car seat covers, using boiler ash for construction, and transforming spinning waste into industrial cleaning mops. These practices have enhanced operational efficiency by 30% and reduced waste disposal costs by 22%. The study highlighted both components of industrial symbiosis: the resource-sharing relationships between industries (e.g., utilizing coffee husks and boiler ash in the textile sector) and the circular management of raw materials (e.g., repurposing textile offcuts and spinning waste). These symbiotic relationships fostered collaboration across energy, agriculture, and construction sectors, demonstrating the potential for scaling IS practices across industries. Despite these achievements, barriers persist. Surveys revealed that 65% of management lacked awareness of IS concepts, and 70% cited insufficient governance frameworks and weak cross-industry partnerships as challenges. Additionally, the absence of enabling policies and formal collaborations hinders broader adoption. The findings underscore the need for targeted capacity-building initiatives, digital monitoring tools, and policy interventions to strengthen IS practices. By formalizing IS and enhancing cross-sector partnerships, the textile sector could improve sustainability and operational performance by up to 53%, positioning itself as a leader in Kenya's green transition. This study concludes that leveraging IS and CBMs is essential for fostering environmental and economic resilience while contributing to global sustainability goals.

KEYWORDS
Industrial Symbiosis - Circular Business Models - Textile Sector - Green Economy - Resource Efficiency - Kenya

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[1] *An international Framework for Eco-Industrial Parks Version, World Bank Group, 2021*
[2] *EU Commission*

Circularity and industrial symbiosis in industrial parks: tools for green transition in Romania

Aida Szilagyi
National Centre for Sustainable Production and Consumption, Timisoara, Romania
aidaszilagyi@cnpcd.ro

Florica Manea
Faculty of Industrial Chemistry and Environmental Engineering, Timisoara, Romania
florica.manea@upt.ro

Emma Szilagyi
National Centre for Sustainable Production and Consumption, Timisoara, Romania,
emmaszilagyi@cnpcd.ro

Haakon Skar
Thamsklyngen, Orkanger, Norway
haakon@thamsklyngen.no

Pawel Krzeminski
Norwegian Institute for Water Research (NIVA), Oslo, Norway
pawel.krzeminski@niva.no

ABSTRACT

Industrial symbiosis (IS) and circular economy (CE) are emerging as transformative strategies to address global sustainability challenges. This study, conducted as part of the CATALYST project, examines how IS and CE principles can facilitate a green transition within Romanian industrial parks. The project focuses on enhancing resource efficiency, reducing waste, and fostering collaboration among co-located companies. The research employed a mixed-methods approach combining qualitative and quantitative analysis. This approach included a comprehensive literature review, surveys, capacity-building initiatives, and a pilot project. A survey of 30 Romanian industrial parks was conducted, utilizing quantitative analysis to assess stakeholders' perceptions of IS and identify opportunities and barriers. Survey data were analyzed statistically to determine trends and correlations between knowledge of IS and perceived challenges in adopting IS practices. The findings from the survey informed the design of targeted educational programs, leading to the successful training of 22 professionals on IS and CE principles, and their practical application. The educational program's effectiveness was evaluated through qualitative analysis of participant feedback and post-training assessments, indicating a significant enhancement in participants' understanding of IS and their ability to act as facilitators within their organizations. The study also initiated a pilot implementation of IS practices in a selected industrial park, using mixed-methods analysis to assess the park against the global framework of eco-industrial park criteria (World Bank Group 2021)[2]. This included resource mapping, qualitative stakeholder engagement, and quantitative data analysis to identify actionable symbiotic opportunities. Preliminary results from the pilot indicate the potential for significant resource optimization and environmental benefits, including reduced greenhouse gas emissions and cost savings, which were quantified through energy and material flow analysis. Key findings reveal a strong interest in IS among industrial park stakeholders, albeit with limited prior knowledge. The educational programs significantly enhanced participants' understanding of IS, equipping them to act as facilitators within their organizations. Preliminary results from the pilot implementation suggest a potential for resource optimization and environmental benefits, including quantifiable reductions in greenhouse gas emissions and cost savings. This research contributes to advancing the European Green Deal objectives by demonstrating the scalability and impact of IS practices in emerging economies. It highlights the critical role of stakeholder engagement, capacity building, and policy support in mainstreaming IS practices (European Commission, 2020)[2]. The study also underscores the importance of international collaboration, exemplified by knowledge exchange between Romanian and Norwegian partners, in adapting and implementing IS practices effectively.

KEYWORDS
Industrial Symbiosis - Circular Economy - Resource Efficiency - Green Transition

INTRODUCTION

The growing urgency of climate change, environmental degradation, and unsustainable resource consumption has compelled governments, industries, and civil society to re-evaluate conventional models of industrial development. In response, the circular economy (CE) and industrial symbiosis (IS) have emerged as transformative strategies to decouple economic growth from environmental harm. The European Green Deal places circularity at the core of its sustainable growth strategy, identifying it as "a prerequisite to achieving climate neutrality by 2050" (European Commission, 2020). Within this framework, industrial symbiosis offers a practical and systemic approach to implementing CE principles by enabling the exchange of materials, energy, water, and by-products between co-located firms (Chertow, 2000) (Paquin, 2012).

Eco-industrial parks (EIPs), as defined by the United Nations Industrial Development Organization (UNIDO), operationalize these principles by creating communities of manufacturing and service businesses located together on a common property, seeking enhanced environmental and economic performance through collaboration (UNIDO, 2022). Globally, EIPs have demonstrated benefits, including resource efficiency, cost savings, emissions reductions, and improved regional development. Despite their recognized potential, the implementation of IS in emerging economies remains limited due to structural, regulatory, and capacity-related barriers.

Romania, a member state of the European Union, faces significant challenges in aligning its industrial development with the EU's circular economy transition goals. Although the country has made notable progress in waste management and environmental regulation, its industrial parks largely operate under linear economic models. A national strategy for the circular economy was adopted only recently, and concrete instruments to foster IS are still lacking (Government of Romania, 2023).

In this context, the CATALYST project (2024–2025), funded through the EEA and Norway Grants, was launched to explore how industrial symbiosis and circular economy principles can be practically applied in Romanian industrial parks. Implemented by a consortium including the National Centre for Sustainable Production and Consumption (CNPCD) and its partners: Politehnica University of Timișoara (UPT), the Norwegian Institute for Water Research (NIVA), and Thamsklyngen Industrial Cluster, the project aimed to foster knowledge exchange, build stakeholder capacity, and initiate pilot IS projects.

This article builds on research conducted within the CATALYST project to address the following questions: (1) How can industrial symbiosis and circular economy practices accelerate the green transition in Romanian industrial parks? (2) What are the key barriers and enablers for implementing IS in Romanian parks, based on stakeholder perceptions and pilot experiences? (3) To what extent can targeted educational programs enhance stakeholder capacity and readiness to implement IS and CE strategies?

METHODOLOGY

Through a mixed-methods approach—comprising a literature review, stakeholder surveys, training programs, and a pilot implementation—this study contributes through empirical evidence and policy insights on scaling IS in emerging economies. The findings are intended to inform both academic discourse and practical policymaking, offering lessons for Romania and other countries navigating similar industrial sustainability transitions.

The methodology consisted of four interrelated components: literature review, stakeholder survey, training and capacity-building activities, and a pilot implementation in a selected Romanian industrial park.

Literature review: A comprehensive review of academic and policy literature was conducted to establish a theoretical foundation and contextualize industrial symbiosis and circular economy practices. Key frameworks included the European Circular Economy Action Plan (European Commission, 2020), the UNIDO Eco-Industrial Parks (EIPs) framework (UNIDO, 2022), and prior studies on industrial symbiosis adoption in emerging economies.

Stakeholder survey: A structured questionnaire was disseminated to over 100 industrial parks across Romania and Norway. The Romanian sample included 30 parks, of which 22 provided complete responses. The survey gathered data on stakeholder awareness of IS and CE, current practices, perceived barriers and opportunities, and readiness for implementation. The survey design incorporated both closed- and open-ended questions and was analyzed using descriptive statistics and qualitative coding of narrative responses.

Training and capacity building: Based on the survey findings, a training curriculum was developed targeting park administrators, company representatives, and local authorities. The curriculum focused on IS concepts, resource efficiency strategies, and stakeholder engagement techniques. A total of 22 professionals completed the training program, which included two days of online sessions.

Pilot implementation: A Romanian industrial park was selected for a pilot IS intervention based on stakeholder interest and readiness. The pilot involved an in-depth assessment using the UNIDO Eco-Industrial Parks criteria, mapping of material and energy flows, and identification of potential symbiotic exchanges. Participatory workshops were organized to engage local stakeholders in co-designing implementation pathways.

This multi-phase methodology ensured that the study combined theoretical grounding with empirical investigation and applied learning. The integration of cross-national insights, particularly from Norwegian partners with established IS practices, provided a comparative dimension that enriched the research outcomes.

LITERATURE REVIEW

Industrial symbiosis (IS) refers to the cooperative exchange of materials, energy, water, and by-products among different industries, forming an interconnected industrial ecosystem. The Kalundborg symbiosis in Denmark is one of the most widely cited examples, demonstrating significant environmental and economic benefits (Jacobsen, 2006). IS operationalizes circular economy (CE) principles by creating closed loops of resource use between firms. CE, in turn, represents a systemic shift from linear "take-make-dispose" models to sustainable systems focused on resource efficiency, reuse, and waste minimization (European Commission, 2020).

EIPs provide an institutional framework for implementing IS and CE at scale. UNIDO (2022) defines EIPs as communities of co-located businesses collaborating to improve their environmental and economic performance. These parks integrate shared utilities, infrastructure, and waste-to-resource exchanges, facilitating the transition to CE models while supporting regional development goals. Scholars such as (Korhonen, 2005) have conceptualized these industrial ecosystems as dynamic and evolving entities, often requiring enabling infrastructure and long-term governance structures.

IS implementation in emerging economies has been documented in various contexts, including China, India, Brazil, and parts of Eastern Europe. Geng et al. (Geng, 2014) provided an energy-based assessment of IS in the Shenyang Economic and Technological Development Zone, highlighting resource efficiency and emissions reduction but also underlining the critical role of local governance and data availability. Similarly, Iacondini et al (Iacondini, 2015) analyzed feasibility conditions in Italy, emphasizing regulatory and institutional constraints as major bottlenecks.

In South Asia, Hossain et al (Hossain, 2024) explored the apparel industry in Bangladesh, revealing that limited awareness, insufficient infrastructure, and weak inter-firm cooperation remain significant barriers. In contrast, Brazil has shown encouraging signs through industrial clusters that benefit from public-private partnerships and network facilitation (Sellitto, 2021). In Eastern Europe, Romania faces similar barriers to those seen in other transitioning economies, such as fragmented regulatory support and limited financial incentives. These examples collectively suggest that IS success in emerging contexts hinges not only on economic rationale but also on institutional design and governance.

The literature highlights that the absence or weakness of national IS strategies hinders wider uptake. Henriques et al. propose strategic incentive frameworks that integrate IS into national CE plans, including tax benefits, grants, and regulatory simplification (Henriques, 2022). Their applied assessment framework identifies risk factors associated with IS implementation and provides mitigation pathways to build business confidence. Countries like Portugal have adopted national roadmaps for CE with embedded IS incentives, which are instructive for Romania as it begins to implement its own CE strategy.

In Norway, recent qualitative studies by Havem and Karlsen (Havem, 2023) and field reports from the EYDE cluster (Kulia, 2021) underscore the importance of coherent national policies, regional facilitation, and infrastructure support in enabling industrial symbiosis in industrial parks. These insights demonstrate that IS ecosystems are most successful when multiple levels of governance are aligned.

Digital tools are emerging as critical enablers of IS. Grant et al. (Grant, 2010) argue that information and communication technology (ICT) solutions can foster

IS by facilitating data sharing, identifying synergies, and automating waste-to-resource matches. Recent studies, such as Mollica et al. (Mollica, 2025), reinforce the effectiveness of digital platforms through agent-based models that simulate decision-making in symbiosis networks. These technologies reduce transaction costs and uncertainty, especially for SMEs that may lack the capacity to participate in traditional IS systems.

Implementing IS requires not only material flows but also intangible flows of trust, information, and shared purpose. Walls and Paquin (Walls, 2015) review organizational perspectives on IS, emphasizing that facilitation, leadership, and inter-organizational trust are as critical as infrastructure. Training, workshops, and pilot projects have been repeatedly validated as effective tools for increasing IS literacy and stakeholder readiness (UNIDO, 2022), (Henriques, 2022).

The CATALYST project's approach—combining surveys, education, piloting, and exchange of experience—is consistent with these recommendations. By including academic institutions such as Politehnica University of Timișoara, CATALYST also aligns with the proposition by Gopalakrishnan and Bakshi (Gopalakrishnan, 2017) that universities can serve as hubs for interdisciplinary collaboration and innovation. Furthermore, stakeholder engagement has proven crucial in the Norwegian case of the Øra industrial park, where participatory governance structures fostered stronger symbiosis linkages (Hanssen, 2022)

Synthesis and relevance to Romania: the academic consensus is clear: IS thrives in environments where companies, facilitators, and regulators are aligned and incentivized to collaborate. In the Romanian context, this implies that beyond regulatory reform, investments must be made in education, facilitation mechanisms, and strategic networking platforms. The literature suggests that emerging economies like Romania can leapfrog traditional barriers by learning from early adopters, applying hybrid governance models, and leveraging ICT for coordination.

STAKEHOLDER SURVEY

To understand the current awareness, practices, and readiness of Romanian industrial parks for adopting industrial symbiosis, the CATALYST project conducted a national stakeholder survey in 2024. The survey targeted representatives of industrial parks, including park administrators, sustainability officers, and technical managers. It aimed to identify existing resource flows, assess potential synergies, and uncover perceived barriers and drivers to IS implementation.

The survey was designed collaboratively by the project partners and included eight thematic sections: (1) personal and institutional data, (2) general park information, (3) current IS practices, (4) resource management, (5) collaboration and communication mechanisms, (6) perceived limitations and opportunities, (7) future plans, and (8) consent and feedback. The questionnaire was distributed via email to 82 industrial parks selected from a national registry, followed by direct phone outreach and awareness-raising Info Days to increase engagement.

A total of 22 industrial parks completed the survey in Romania providing a diverse representation of industrial sectors including automotive, mechanical processing, logistics, construction, agriculture, and renewable energy. Respondents were primarily public or mixed public-private entities, with parks hosting between 5 (newly planned parks) and over 100 companies. According to Romanian legislation (Law no. 186/2013), industrial parks benefit from specific incentives such as exemptions or reductions from local taxes, fees, and charges, aimed at promoting sustainable industrial development and attracting investments.

KEY FINDINGS

Only three parks reported existing IS measures such as shared utilities or by-product exchanges. Most participants had limited or no engagement in IS, indicating a need for structured facilitation and awareness. Solid waste was the most commonly reported waste stream (91%), followed by liquid waste, hazardous waste, and gaseous emissions. While most parks recycle certain waste fractions, 64% also send some waste to landfills.

Water sourcing was largely dependent on municipal supply (over 80%), though some respondents used groundwater or surface water with basic filtration systems. Wastewater is predominantly discharged into public sewage systems, with only one respondent reporting the integration of nature-based treatment systems. Regarding energy, solar panels were the most frequently reported renewable source, but only one park reported energy infrastructure sharing—a core IS principle.

Communication practices were generally ad hoc. Only 26% of respondents reported frequent communication with co-located companies about resource sharing, while 30% communicated rarely or not at all. Meetings (42%) and emails (36%) were the most common forms of communication; dedicated online platforms were seldom used.

The most frequently cited barriers to implementing IS were lack of information (59%), legal uncertainty (41%), and financial constraints (41%). Other challenges included a lack of know-how, an absence of trust among companies, and infrastructure gaps. Conversely, stakeholders expressed optimism about IS, citing the potential for resource efficiency (86%), waste valorization, and environmental impact reduction as key opportunities.

Although IS was not yet widespread, 36% of respondents expressed clear interest in developing IS practices in the near future. Several parks also reported intentions to develop integrated waste treatment systems, shared utilities, and collaborative water management frameworks.

The survey results highlight both the latent potential and existing gaps in the Romanian industrial ecosystem for implementing IS. The limited current practice contrasts with a strong conceptual interest among stakeholders, emphasizing the need for targeted interventions such as technical training, policy guidance, financial support mechanisms, and trust-building platforms. The findings also validate the CATALYST project's focus on capacity-building and bilateral knowledge exchange, suggesting that systematic stakeholder engagement, combined with regulatory and financial incentives, can significantly enhance IS uptake in Romania's industrial parks.

NORWEGIAN STAKEHOLDER SURVEY

In parallel with the Romanian survey, the CATALYST project conducted a stakeholder consultation with Norwegian industrial parks and clusters to gather insights from a more mature industrial symbiosis context. The objective was to identify enabling conditions, successful models, and perceived challenges that could inform policy learning and capacity-building in Romania. The Norwegian survey was administered to 32 industrial parks across all of Norway. It included structured interviews and questionnaires focused on the following areas: (1) current IS and CE practices, (2) cooperation and governance models, (3) key success factors, (4) perceived limitations, and (5) recommendations for future development.

KEY FINDINGS

Respondents reported a high degree of awareness and engagement in IS practices, including shared energy infrastructure, heat recovery, industrial water reuse, and material side-stream valorization. A prominent example cited was the use of residual heat from industrial processes for district heating, demonstrating environmental and economic co-benefits. The Norwegian context also emphasized strong public-private partnerships, consistent policy support, and active facilitation by industrial cluster managers.

Challenges included the complexity of coordinating across firms with differing business models, maintaining economic viability for low-margin resource exchanges, and the need for continuous facilitation and innovation to sustain IS networks.

TRAINING AND CAPACITY BUILDING

As a central pillar of the CATALYST project, training and capacity-building activities were designed to address the gaps in knowledge, institutional readiness, and facilitation skills identified during the stakeholder survey. Two distinct training programs were organized, both aimed at enhancing the practical understanding and implementation capacity of industrial symbiosis (IS) and circular economy (CE) principles in Romanian and Norwegian industrial parks.

Training 1: Norwegian expertise the first training session was conducted by experts from the Norwegian industrial cluster Thamsklyngen and NIVA. The program focused on theoretical and technical aspects, introducing the circular economy concept, methodologies for identifying symbiotic opportunities, using resource-mapping tools, and sharing the Norwegian experience in implementing IS practices within industrial parks and clusters. Romanian participants were introduced to integrated waste-to-resource systems, industrial heat recovery, shared water treatment models, and stakeholder engagement strategies. Participants engaged in practical exercises and simulations, allowing them to apply the learned concepts to their local contexts.

Training 2: International Synergies approach - the second session was delivered by International Synergies, a UK-based leader in IS facilitation and implementation. This training was more hands-on in implementing IS real practices within industrial regions, providing real-world examples of successful collaboration, infrastructure sharing, and environmental performance. This training emphasized the role of facilitation, public-private partnerships, and long-term vision in enabling industrial symbiosis.

In total, more than 40 professionals from industrial parks, universities, and relevant institutions completed both or part of the training series. The participants acquired knowledge not only in IS theory and international best practices but also in practical facilitation techniques applicable in their home organizations. The curriculum spanned both online and in-person formats and included interactive workshops, case studies, and peer-to-peer exchange.

Evaluation feedback indicated a marked increase in participants' understanding of IS principles, confidence in facilitating IS discussions, and willingness to initiate symbiotic collaborations. The training also laid the foundation for building a national network of IS facilitators in Romania, contributing to long-term capacity building in the sector.

PILOT IMPLEMENTATION

The pilot implementation of the CATALYST project followed a structured three-phase approach, aligning with established eco-industrial park (EIP) and industrial symbiosis (IS) methodologies. This included an initial qualitative assessment, detailed data analysis, and a collaborative international workshop for synergy identification. Each phase integrated best practices in the circular economy (CE) to ensure the pilot was methodologically sound and informed by proven success factors.

In the first phase, a qualitative evaluation of the pilot industrial park was conducted using the UNIDO Eco-Industrial Park framework and tool The International EIP Framework defines performance benchmarks across four key categories – *park management, environmental performance, social performance, and economic performance* – encompassing a comprehensive set of 51 criteria.

Together with the park management team, the project team systematically reviewed each benchmark to assess the park's current alignment with these EIP criteria. For areas where a criterion was not fully met, the team brainstormed improvement opportunities and potential initiatives needed for compliance. This qualitative diagnosis established a baseline of the park's sustainability performance and helped prioritize focus areas. By using the UNIDO EIP criteria as a lens, the pilot ensured consistency with international best practices for sustainable industrial parks, encouraging the park to exceed mere regulatory compliance and pursue higher standards of environmental and social performance. The outcome of this phase was a clearer understanding of existing gaps and strengths in the park's operations, forming the foundation for targeted interventions in subsequent phases.

The second phase involved data collection and analysis; wherein quantitative information was gathered to complement the qualitative assessment. Data for calculating key performance indicators (KPIs) related to resource use, waste generation, and emissions were collected from tenant companies and park facilities. The project employed standardized tools and templates to capture enterprise-level resource efficiency and cleaner production metrics, enabling the team to compute indicators for resource productivity and pollution intensity.

This data-driven approach allowed the pilot to establish a baseline of material and energy flows within the park. By mapping these resource flows (e.g., energy streams, water usage, waste outputs), the team could visualize their performance as well as potential points of intersection between companies – a critical step in identifying symbiotic linkages. This systematic analysis was aided by digital tools, provided by the SYNERGie® software platform, for resource mapping and exchange evaluation, ensuring that data on quantities, qualities, and temporal availability of resources were rigorously analyzed. By the end of this phase, a catalog of resources ("waste" streams, surplus energy, water, materials) and needs (resource demands) was compiled, setting the stage for matchmaking in the next phase.

The third phase centered on synergy identification, which was conducted through a facilitated workshop that leveraged Norwegian expertise in industrial symbiosis. A study tour and workshop were organized in Trondheim, Norway, bringing together the Romanian industrial park stakeholders and Norwegian and British IS experts providing valuable information and practical case studies. They also confirmed the importance of establishing trust, fostering communication, and ensuring long-term institutional commitment—insights that were subsequently applied to the design of training programs and pilot implementation in Romania.

In a hands-on session, Romanian and Norwegian participants jointly used the SYNERGie® software platform to input the previously collected resource data and identify matches between waste streams and resource needs. This exercise operationalized international best-practice methods for synergy discovery: by systematically scanning for overlaps in the resource maps, the tool highlighted where one company's excess resource (for example, waste heat, steam, or an organic by-product) could serve as another company's input. Participants actively documented available resources and demands within their industrial parks, and the software assisted in pinpointing viable synergy pairs. This collaborative mapping technique, championed by International Synergies' methodology, ensured an objective and thorough exploration of potential exchanges.

This lesson resonated with the Romanian participants, who recognized that establishing mutual trust among companies and engaging local authorities are just as important as identifying technical synergies. The workshop's international context thus not only transferred knowledge of specific techniques but also instilled an appreciation for the governance and community aspects of eco-industrial development.

Action Planning: facilitators worked to prioritize the synergy opportunities based on criteria such as feasibility, expected benefits, and stakeholder interest (mirroring the UNIDO EIP toolbox approach of rating opportunities by achievability and impact). For each high-potential synergy, initial action steps were defined – including assigning responsibilities, outlining required investments or technologies, setting targets for the outcomes, drafting the action plan, aligned with the UNIDO EIP framework's guidance on planning and monitoring EIP initiatives, ensuring a clear roadmap with measurable targets.

Through the above process, several promising synergy opportunities were identified for the pilot industrial park. These reflected common industrial symbiosis themes and were inspired by the best practices observed:

- Renewable energy shares and advanced use. Opportunities to capture surplus energy from one process and use it as an input for another were highlighted. For example, renewable energy produced by the park and some tenants could be used to produce heating for its own facilities and the neighboring facilities or as such by other tenants.
- Water reuse and recycling: The pilot identified strategies for reusing water within and between facilities. One idea was to treat and recirculate industrial wastewater from one company for use in another company's cooling systems or for irrigation in green spaces. Harvesting rainwater from building rooftops and storing it for industrial use or for firefighting purposes was another viable synergy.
- Industrial waste repurposing synergies were pinpointed, where the waste or by-products of one firm could serve as raw material for another. Examples include using plastic waste from some companies to produce new plastic objects that could be used as furniture components.

Each identified synergy was evaluated in terms of technical requirements and benefits ensuring they align with both the park's sustainability targets and the business interests of the companies involved. By grounding the pilot's synergies in real-world examples and best practices, the project increased stakeholder confidence in their viability. These examples also serve as demonstrative projects for the wider region – showcasing how industrial symbiosis and eco-industrial park concepts can be practically implemented in Romania.

FINDINGS

The findings of the CATALYST project illustrate a nuanced understanding of the challenges, opportunities, and readiness for implementing industrial symbiosis (IS) and circular economy (CE) principles in Romanian industrial parks. Data from surveys, training feedback, and pilot implementation activities revealed three key themes: low initial awareness, high latent potential, and significant capacity gains through targeted intervention.

The stakeholder survey revealed that while awareness of IS concepts among Romanian industrial park managers and tenants was initially limited, there was a high degree of interest and willingness to engage once the benefits were clarified. Only a minority of parks reported existing resource-sharing initiatives, yet over 80% of respondents recognized the potential of IS to reduce costs and improve environmental performance. Notably, solid waste, energy, and water emerged as the most promising resource categories for future synergy development.

The two training sessions, delivered by Thamsklyngen, NIVA, and International Synergies, resulted in measurable improvements in participant knowledge and confidence. Post-training evaluations indicated an increased understanding of IS principles, with many participants stating they felt equipped to initiate IS processes within their parks. Participants especially valued the practical exercises using the SYNERGie® tool, as well as exposure to successful case studies from Norway. This highlights the critical role of experiential learning and peer exchange in driving behavioral and institutional change.

The pilot implementation at the Cluj Innovation Park demonstrated the practical applicability of IS in a Romanian context. The UNIDO EIP assessment framework helped identify systemic gaps and guided the prioritization of improvement actions. Through resource mapping and KPI-based monitoring, several synergy opportunities were identified, including energy cascading, water reuse, and industrial by-product exchange.

Collectively, these findings affirm that Romanian industrial parks possess both the motivation and foundational capacity to adopt IS practices—provided they receive adequate technical guidance, institutional support, and continued exposure to proven international models.

DISCUSSION

Industrial symbiosis (IS) implementation in Romania and Norway presents both common challenges and distinct differences shaped by each country's context. In Romania, barriers to IS are pronounced: a lack of information and awareness is the most frequently cited hurdle alongside financial constraints and regulatory obstacles. Companies in Romanian industrial parks often struggle with limited knowledge of symbiotic opportunities and face uncertainties in navigating environmental regulations, which discourages collaboration. A pervasive lack of trust between firms – rooted in competitive culture and fear of sharing data – further hampers inter-company cooperation, making businesses hesitant to pursue resource exchanges. Norway faces its own challenges, albeit of a different nature. Norwegian industrial parks report that insufficient economic incentives and infrastructure limitations are the primary impediments to expanding IS. Even with higher environmental awareness, many Norwegian companies find it difficult to justify symbiotic projects without clear financial benefits or when the necessary logistics (e.g. pipelines, storage facilities) are not in place. Both countries also grapple with regulatory and legal uncertainties – for instance, unclear classification of secondary materials can create bureaucratic delays in both Romania and Norway.

Conversely, several enablers and drivers are propelling industrial symbiosis forward in both Romania and Norway, offering lessons on how to overcome the above hurdles. Romanian stakeholders emphasize the importance of external support mechanisms: financial incentives and supportive legislation rank as the top drivers for IS engagement in Romanian industrial parks. The promise of grants, tax breaks, or favorable policies (such as streamlined permitting for waste reuse) is seen as crucial to nudge companies toward collaboration. Improved communication channels and technological advancements (e.g. better data on waste streams) were also noted as catalysts in Romania, suggesting that as information flows and tech solutions (like material matching platforms) improve, so will symbiosis opportunities.

In Norway, the motivation landscape is somewhat different. A strong sense of environmental responsibility and pursuit of competitive advantage stand out as key motivators for Norwegian companies to engage in IS. Many Norwegian firms recognize that reducing waste and sharing resources not only aligns with corporate sustainability goals but also lowers operating costs and can open up new business opportunities, thus improving their market positioning.

Importantly, both countries acknowledge the role of government support as pivotal. Regulatory pressure (such as stricter waste management rules in the EU context) and the prospect of efficiency gains are driving interest in IS in both Romania and Norway.

The bilateral visit to Norway under the CATALYST project proved to be a pivotal learning experience, shedding light on practical lessons and best practices for industrial symbiosis. Romanian industrial park managers and company representatives were able to witness first-hand how Norwegian clusters implement resource exchanges and overcome everyday challenges. Participants observed functioning examples of symbiosis, seeing these exchanges in action provided tangible proof of concept; what had previously been abstract ideas (like "waste-as-resource") became concrete projects with measurable benefits.

In discussions with Norwegian stakeholders, the Romanian visitors learned about the operational practices that made these successes possible. A recurring theme was the importance of open communication and trust: Norwegian companies highlighted how regular forums and cluster meetings helped break down barriers between firms, enabling them to share sensitive information about waste streams and resource needs securely. This exchange of experiences not only broadened the technical understanding of IS (e.g. how to set up a heat exchange loop or manage a shared utility) but also underscored the human and institutional factors vital for IS. Notably, Norwegian experts and cluster managers pointed out the role of industrial symbiosis facilitators or brokers – individuals or organizations dedicated to coordinating symbiotic activities – in driving projects forward. Romanian participants recognized that this sort of facilitation has been largely missing in their context and that establishing similar roles could be a game-changer.

A critical insight from both the bilateral exchanges and the project activities is the central role of training, supportive policy frameworks, and active facilitation in overcoming barriers to IS adoption. Technical and economic solutions alone are insufficient if companies lack the know-how or institutional support to implement them. The Norwegian experience strongly reinforces the value of this approach: many Norwegian clusters attribute their IS successes to having coordinators or cluster managers whose job is to facilitate collaboration across companies.

Clear and stable policies are essential to give companies the confidence to invest in symbiosis. At present, Romanian companies often cite bureaucratic uncertainty as a deterrent – for example, ambiguity in permits for using another company's waste or in liability for resource-sharing can stall potential synergies. Learning from Norway, where policy has gradually evolved to accommodate circular practices, Romania can work towards harmonizing its regulations with EU circular economy directives and Norwegian best practices. This could include creating standardized templates for inter-company contracts, guidelines for symbiotic resource use, and clearer classification of secondary materials. Additionally, financial and policy incentives are pivotal to overcoming the initial cost barriers. From this perspective, the Romanian Industrial Parks Law no. 186/2013 could be amended to grant these parks additional incentives, such as further tax exemptions or financial support, thus directly promoting sustainable and circular economic development.

When considering the applicability of Norwegian IS models to Romanian industrial parks, it is evident that context matters – strategies must be adapted to fit different regulatory, financial, and infrastructural realities. Norway's industrial symbiosis initiatives often operate within a mature ecosystem supported by decades of policy refinement and economic stability. Norwegian industrial parks typically benefit from well-developed infrastructure and a coordinated cluster approach where companies are geographically and operationally linked. By contrast, Romanian industrial parks may lack some of these foundational elements. Infrastructure in many Romanian parks is still developing; dedicated systems for water treatment, waste exchange or energy sharing might need to be built from scratch.

Policy frameworks also differ – Romania is still aligning its environmental regulations with EU norms and has historically placed less emphasis on circular economy practices. One important principle is integrating symbiosis into the planning and management of industrial parks.

Another transferable practice is fostering a culture of collaboration – the Norwegian emphasis on community, shared vision, and even pride in sustainable industrial districts is something Romanian parks can cultivate through regular stakeholder forums and public-private partnerships. Romanian authorities and park managers might start by encouraging small-scale symbiotic exchanges (like sharing waste management services or by-product reuse between a couple of companies) to build trust and demonstrate success. Over time, these can scale up to more complex networks as seen in Norway.

In adapting such models, Romania will need to ensure regulatory support and financial instruments are in place – potentially by introducing targeted pilot programs or leveraging EU funds dedicated to circular economy transitions. The differences in context (legal definitions, market maturity, infrastructure gaps) must be carefully accounted for in policy design. Ultimately, the Norwegian experience serves as both a benchmark and a guide: it shows the level of industrial symbiosis that is achievable and the multi-faceted support structure required to sustain it.

CONCLUSION

The CATALYST project's investigations and interventions provide a comprehensive look at industrial symbiosis readiness in Romania, revealing both significant challenges and promising momentum for change. Overall, the findings indicate that industrial symbiosis in Romania is still in an early developmental stage – many industrial parks are only beginning to consider resource-sharing initiatives, and baseline data showed relatively low engagement. This gap underscores the work ahead for Romania in catching up to international best practices. Key barriers – from informational and skill gaps to financial and legislative hurdles – have so far limited the widespread adoption of IS in the Romanian industry. At the same time, the project has identified and begun to strengthen the building blocks for progress. Encouragingly, there are clear signs of growing interest and commitment: several industrial parks have outlined concrete future plans such as developing shared utilities or waste-to-resource facilities.

These developments suggest that Romania's readiness for industrial symbiosis is on the rise, provided that supportive measures are put in place to maintain this momentum. In contrast, Norway's more advanced IS landscape – characterized by established projects and higher company engagement – has served as a valuable comparative benchmark, highlighting both the potential benefits Romania can attain and the critical success factors required. The comparative insights reaffirm that while Romania faces an uphill journey, it can accelerate progress by learning from what has worked elsewhere. In summary, the CATALYST project has not only diagnosed the current state of industrial symbiosis in Romania but also catalyzed initial improvements in capacity and enthusiasm, laying a foundation for more systemic adoption of IS in the coming years.

Building on these findings, targeted policy and practical actions are needed to convert industrial symbiosis from isolated pilot efforts into a mainstream practice across Romanian industrial parks. The study's outcomes and the lessons drawn from the Norway collaboration inform several clear policy recommendations for decision-makers and industry leaders in Romania:

1. Develop clearer regulations and guidelines that explicitly support industrial symbiosis. This includes harmonizing definitions of waste and by-products with circular economy principles (so that companies can more easily exchange materials without legal ambiguity) and integrating IS objectives into national and regional development strategies.
2. Alleviate the financial barriers to IS by implementing incentives such as grants, subsidies, or tax breaks for companies engaging in approved symbiosis projects. Dedicated funding lines (e.g. under green innovation or EU structural funds) should be established to support infrastructure investments like shared waste processing facilities, energy connectors, or recycling equipment.
3. Create and institutionalize roles or bodies that actively facilitate IS development. For example, appoint Industrial Symbiosis Facilitators at the industrial park or regional level – trained experts who can identify synergy opportunities, broker partnerships between companies, and help navigate administrative procedures. These facilitators could be part of an existing structure (such as park management teams or local environmental agencies) or new dedicated units. In addition, forming a national or regional IS network or working group would enable facilitators and interested companies to exchange knowledge, tools, and even resources across different parks, amplifying the impact of individual efforts.
4. Support the deployment of key infrastructure that enables symbiosis. This may involve building common utilities or interconnections – for instance, pipelines for steam or hot water transfer between plants, centralized waste sorting and pre-processing centers in industrial zones, or hub facilities where one company's by-product can be collected and treated for use by others. Alongside physical infrastructure, invest in digital tools such as resource exchange platforms or databases that allow companies to list available by-products and find matches.
5. Continue the momentum of education and knowledge-sharing started by CATALYST. This entails scaling up training programs for both industry practitioners and policymakers – for example, workshops, seminars, or certification courses on industrial symbiosis and circular business models. Incorporating IS topics into university curricula or vocational training for industrial engineers and park managers can build

a pipeline of knowledgeable professionals. Regular **outreach and matchmaking events** (such as symbiosis roundtables or innovation challenges) can bring together companies to brainstorm and initiate new collaborations. Moreover, disseminating success stories and case studies will help shift mindsets by showcasing tangible benefits, thus building a stronger culture of collaboration and innovation.

6. **Translate policy into practice** through well-monitored pilot projects in select industrial parks. Government agencies and park authorities should identify a few strategic sites or sectors to implement **demonstration IS projects**, with technical assistance and measure their outcomes in terms of economic savings, waste reduction, and emissions avoided. Successful pilots will serve as a proof-of-concept, creating buy-in from other companies and investors.

By implementing these recommendations, Romanian policymakers and industrial park stakeholders can significantly **accelerate the scaling up** of industrial symbiosis. The next steps should focus on operationalizing these policy adjustments and support mechanisms in the short to medium term. Industrial parks could be encouraged (or required) to develop **resource synergy plans** as part of their licensing or development processes, ensuring that new park developments consider infrastructure for sharing utilities or reusing waste from the outset. Simultaneously, outreach to industry needs to continue, marketing the economic and environmental benefits of IS to attract broader participation – many companies may join symbiotic exchanges once they see clear examples of cost savings or revenue from waste.

With sustained effort and the collaborative approach advocated by the CATALYST project, Romanian industrial parks can progressively transition to more interconnected, resource-efficient systems. Such a transition promises not only environmental dividends (through waste reduction and lower emissions) but also economic and competitive advantages for the Romanian industry. In essence, the project's comparative insight and resulting roadmap provide a clear message: by combining enlightened policy, financial backing, and capacity building, industrial symbiosis can move from an aspirational concept to a **scalable reality** in Romania, driving the country toward a greener and more resilient industrial future.

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Assessing the potential for successful application of industrial symbiosis in Southeast European countrie

Anđelka Stojanović
Technical Faculty in Bor, University of Belgrade, Bor, Serbia
anstojanovic@tfbor.bg.ac.rs

Azemina Mašović
Faculty of Economics, American University of Europe-FON, Skopje, North Macedonia
azemina.mashovikj@fon.edu.mk

Merim Kasumović
Faculty of Economics, University of Tuzla, Tuzla, Bosnia and Herzegovina
merim.kasumovic@untz.ba

ABSTRACT

Industrial symbiosis presents the concept of interaction and cooperation for sharing mutual benefits within industrial sectors, cross-sector or geographically, and is one of the key strategies in achieving the goals of the circular economy. Industrial symbiosis is recognized by the European Union as a business model that would optimize the use of resources, increase the efficiency of material and energy use, and reduce waste. Many of the goals set in The European Green Deal can be supported by the application of industrial symbiosis, among them the reduction of CO2 emissions. To determine the potentials for the implementation of industrial symbiosis, it is necessary to examine the potentials of industrial sectors, but also the potentials of entire geographical areas in terms of capacity and needs for the exchange of energy, waste, and by-products. In this sense, it was observed that some countries and regions have already advanced far in meeting the goals of climate neutrality and those struggling and lagging behind. This paper proposes using indicators from existing databases and data on several countries collected using a unique methodology to perform a comparative analysis. The countries of Southeast Europe (Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Greece, Montenegro, North Macedonia, Romania, Slovenia, Serbia, and Türkiye) are analyzed and compared with Denmark, which represents the country that has advanced the farthest in the implementation of IS, and the EU average. The three sets of statistical indicators available in the Eurostat database had been selected: 1. resource and waste management, 2. energy efficiency and emissions, 3. socio-economic indicators, and based on them, draw a conclusion about the potentials and shortcomings of the SEE region for IS implementation. The analysis points to the conclusion that, above all, the monitoring framework is still not fully applied to countries that are not members of the EU, even though the carbon neutrality goals set in The European Green Deal and the new Industrial Emissions Directive (IED 2.0) are set as a condition in the accession process. Also, among SEE member countries of the EU, the results enable drawing different conclusions. The study's results can be significant for designing guidelines for the potential development of IS in SEE countries.

KEYWORDS

Industrial Symbiosis - Countries of Southeast Europe - IS Indicators - Potential for Application - Comparative Analysis - Eurostat Data

INTRODUCTION

Industrial symbiosis (IS) refers to the concept of interaction and cooperation for sharing mutual benefits within industrial sectors, across sectors, or geographically. It is one of the key strategies in achieving the goals of the circular economy. Industrial symbiosis implies the connection of different industries into functional networks for exchanging materials and energy to benefit companies, the natural environment, and society (Chertow, 2020; Fraccascia & Giannoccaro, 2020). The fact that the waste from one facility can be used as a specific input for another primarily contributes to reducing the amount of waste created, minimises the use of raw materials and water, and enhances energy efficiency, thereby decreases of all types of emissions, including greenhouse gases (Fraccascia & Giannoccaro, 2020). In addition, IS contributes to production as it requires the optimization and redesign of both processes inside the company and also the supply chains. Lombardi and Laybourn (2012) proposed a definition that positions industrial symbiosis more towards the business segment as a tool that can foster eco-innovation, eco-efficiency, as well as financial gain.

Industrial symbiosis is recognized by the EU institutions as a path towards a circular economy and efficient use of resources. The document, a new Circular Economy Action Plan (European Commission, 2020), emphasizes the necessity of facilitating industrial symbiosis and circularity in order to prevent waste generation and change consumption patterns. Many of the goals set in the European Green Deal can be supported by the application of industrial symbiosis, first of all in energy saving and diversification of energy sources and striving towards a green industrial revolution. However, it is necessary to emphasize that neither all EU member states nor countries in the process of accession, which must also meet the set targets, have equal starting positions and capacities to achieve climate neutrality by 2050.

This study aims to explore how industrial symbiosis can be implemented in the South and Eastern Europe region. The first step is to define the elements based on which it is possible to make this assessment. Given the great attention that the European Commission pays to progress in achieving the goals of decarbonization and the circular economy, a framework has been created for monitoring measures and contributions through a series of indicators and sub-indicators. The research addresses three sets of indicators: 1. resource and waste management, 2. energy efficiency and emissions, and 3. socio-economic indicators. In the framework of indicators, nine sub-indicators from the set of existing indicators on the circular economy were used to examine the potential of SEE countries to apply IS.

The second step is to assess to what extent the SEE countries can be compared with the most prominent EU countries regarding IS. The analysis covers 11 countries of the region (Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Greece, Montenegro, North Macedonia, Romania, Slovenia, Serbia, and Türkiye), and Denmark, which is known as a cradle of IS networking, was used as a benchmark.

LITERATURE REVIEW

In the literature dealing with Industrial symbiosis, it is not easy to find a unique list of indicators to measure the effects of implementation. Many indicators have different measurement ranges, definitions, applications, etc (Fraccascia & Giannoccaro, 2020; Neves et al., 2020). Alakaş et al. (2020) emphasized that several criteria must be considered to ensure that IS practice changes existing systems and leads those processes in the direction of sustainability. In their research, the authors used economic, social, environmental, and management criteria as the main criteria for determining IS sustainability, the significance of which was assessed by experts. Brondi et al. (2017) emphasized the use of Life Cycle Assessment (LCA) by many authors as a comprehensive methodology for determining ecological compliance from the perspective of industrial symbiosis and sustainable production. Industrial symbiosis is therefore associated with production, and the industrial sector, where the consumption of various resources can be monitored, analyzed and optimized in the direction of green industries. Also, Material Flow analysis (MFA), Material Flow Cost Accounting (MFCA), and many IT-supported solutions are related to IS assessment (Fraccascia et al., 2020; Lütje & Wohlgemuth, 2020; Kosmol et al.,2021; Fet & Deshpande, 2023).

METHODOLOGY

This paper proposes utilising indicators from existing databases that collect data on several countries using a unique methodology, allowing comparative analysis. The Eurostat database was used as a data source because it provides reliable, comprehensive, and up-to-date statistical data for the European Union member states and those in the accession process. Available data from 11 countries belonging to Southeast Europe and Denmark were collected. Denmark was used as a benchmark in the research because it represents the global leader in recycling and is the cradle of industrial symbiosis.

In order to monitor the development and success of IS, it is necessary to define a standardized set of indicators. In this paper, the goal is to systematically monitor quantitative indicators, which enables the analysis of the potential for industrial symbiosis in the countries. It is proposed to monitor three groups of indicators: 1. resource and waste management, 2. energy efficiency and emissions, and 3. socio-economic indicators, and their sub-indicators, which are presented in Figure 1.

In order to achieve a better focus, this research primarily covers the field of waste management, which represents the essence of Industrial Symbiosis. Waste is considered any discarded material or object with no further function. It is the loss of resources that can be found in different forms. The waste generation indicator measures the waste generated in a country per capita. Waste that is treated in order to be recovered into material for further use, meaning it is not used for energy generation or for disposal, is measured with the recycling rate. The recycling rate indicator is expressed as a percentage and represents the ratio of recycled waste to total treated waste without major mineral waste. Related to this is the measure of the share of recycled material that is returned to use, which contributes to reducing the extraction of raw materials. Therefore, in the resource and waste management segment, efficient recycling and reuse of materials play a key role in reducing the ecological footprint and preserving natural resources, indicating the IS capacities (Fraccascia & Giannoccaro, 2020).

Considering that Industrial Symbiosis, because it enables better use of resources and more energy-efficient processes between industries, contributes to the reduction of energy consumption and emissions, it is important to target this segment as well (Park & Behera, 2014; Lütje & Wohlgemuth, 2020). In order to identify the source of emissions, the emission of greenhouse gases is monitored. In the context of Industrial Symbiosis, reducing the need for raw materials and energy contributes to reducing greenhouse gas emissions, thereby establishing the prerequisites for a sustainable industry. Additionally, monitoring industrial symbiosis and its effects includes tracking energy flows. In addition to the fact that IS can imply a direct exchange of energy, it contributes to energy productivity because it increases resource efficiency and reduces total energy needs. Energy productivity measures the amount of economic output per unit of gross available energy. Final energy consumption refers to the energy used by end users for various purposes. This indicator can be considered an economic indicator, as it also reflects the energy efficiency of the state's economy. In this segment, the share of renewable energy consumption in total energy consumption is monitored.

Industrial symbiosis means that several entities, whether industrial or public, jointly realize some interests by exchanging energy, materials, and by-products that are waste and cannot be further used by the entity that generates them to achieve certain benefits (Chertow, 2020). Those benefits, among others, can be economic, but also other types, such as social. Industrial symbiosis offers economic benefits by redirecting waste to other industries, reducing disposal costs, and generating additional revenue from waste sales. Socio-economic indicators assess how industrial symbiosis has the potential to contribute to social and economic sustainability (Ibáñez-Forés et al., 2019; Lütje & Wohlgemuth, 2020). The implementation of industrial symbiosis fosters the creation of new jobs in the recycling and logistics sectors, along with new workplaces for green technologies. In this sense, IS encourages innovation because new ways of using materials and energy are being explored.

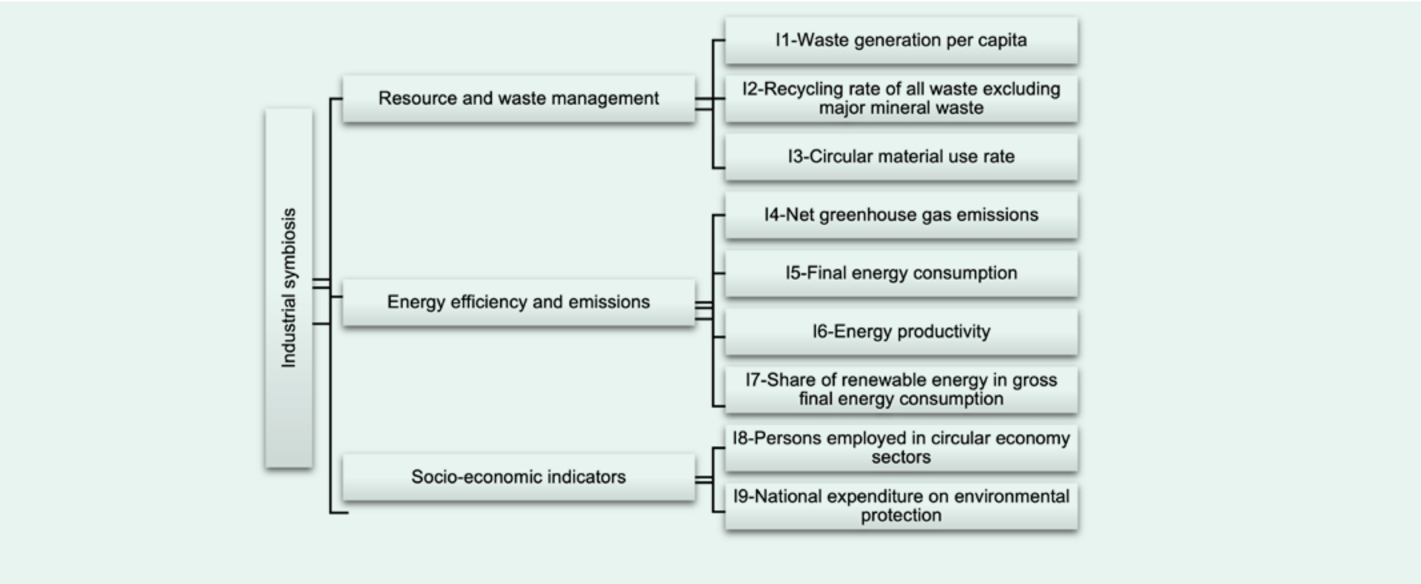


Figure 1 Industrial Symbiosis Indicators (Source: Eurostat)

Data collected from the Eurostat database are presented in Table 1, which summarizes key statistical information relevant to the research.

	I1	I2	I3	I4	I5	I6	I7	I8	I9
Bulgaria	- 14.603		- 3	- 7,7	- 9.856,902	- 2,55	- 19,044	- 94.319	- 1,8
Denmark	- 3.333	- 63	- 9,3	- 7,4	- 13.024,076	- 18,02	- 42,383	- 42.049	- 1,9
Greece	- 2.858		- 6,3	- 7,4	- 15.399,676	- 8,43	- 22,671	- 79.328	- 1,4
Croatia	- 1.838	- 60	- 6,8	- 5,5	- 6.719,174	- 6,72	- 28,088	- 66.553	- 1,8
Romania	- 8.410	- 37	- 1,5	- 3,3	- 23.923,243	- 6,03	- 24,229	- 200.489	- 2,7
Slovenia	- 5.397	- 80	- 8,3	- 7,3	- 4.763,827	- 7,21	- 25,002	- 27.241	- 2,5
Bosnia and Herzegovina	- 1.797				- 4.290,012	- 2,37			
Montenegro	- 2.050				- 752,609	- 3,87	- 41,064		
North Macedonia	- 1.038				- 1.804,859	- 3,31	- 19,213		
Albania	- 245				- 1.958,847		- 44,076		
Serbia	- 26.325				- 9.491,229	- 2,53	- 24,670		
Türkiye	- 1.284				- 108.196,107	- 6,71			

Table 1 Data (Source: Eurostat)
Note: Indicator units of measure. I1- Kilograms per capita; I2- Percentage; I3- Percentage; I4- Tonnes per capita; I5- Thousand tonnes of oil equivalent; I6- Euro per kilogram of oil equivalent; I7- Percentage; I8- Full-time equivalent; I9- Percentage of gross domestic product

RESULTS AND DISCUSSION

The absence of monitoring in non-EU countries is significantly holding back research in the areas of circular economy and industrial symbiosis in SEE. However, several conclusions can be drawn from the available results presented in Figures 2, 3, and 4.

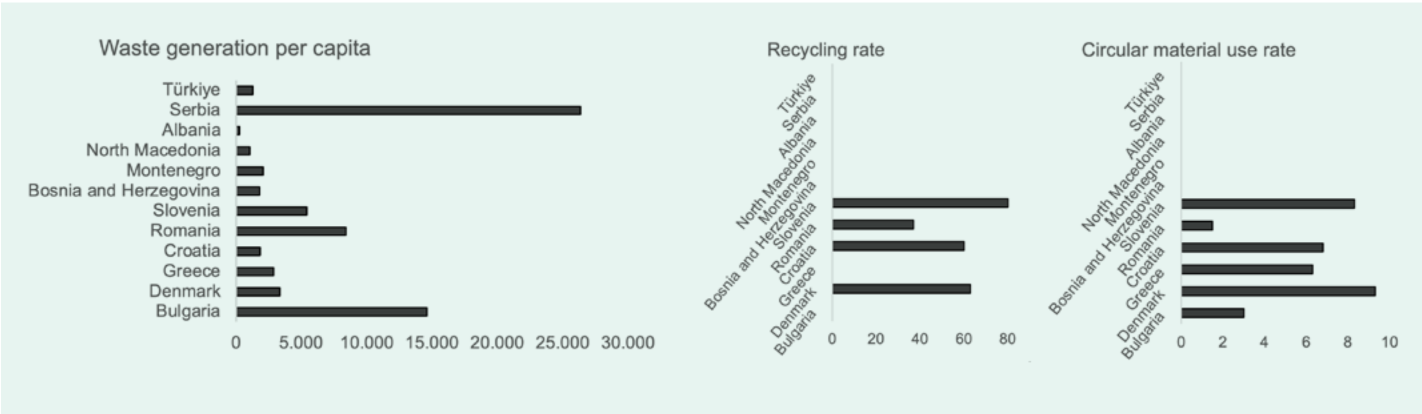


Figure 2 Indicators of resource and waste management

Analyses indicate a generally bad picture of waste management, especially in the Western Balkan countries (The Balkan Forum, 2021; Ndoka & Alimehmeti, 2024). It is noticeable on the graph that Serbia and Bulgaria have the highest level of waste generation per capita, while Albania and North Macedonia have the lowest. These results indicate the possible influence of the degree of urbanization on the amount of waste created and a better infrastructure for collecting and recording waste. When looking at the recycling rate, Slovenia stands out, with a result that is better than the benchmarking country of Denmark. Otherwise, the EU member states must adhere to high environmental standards that include increasing the degree of recycling, which conditions the development of the Waste Management System and the programs for reducing waste per capita. Therefore, recycling material use rates in new production cycles are pretty uniform.

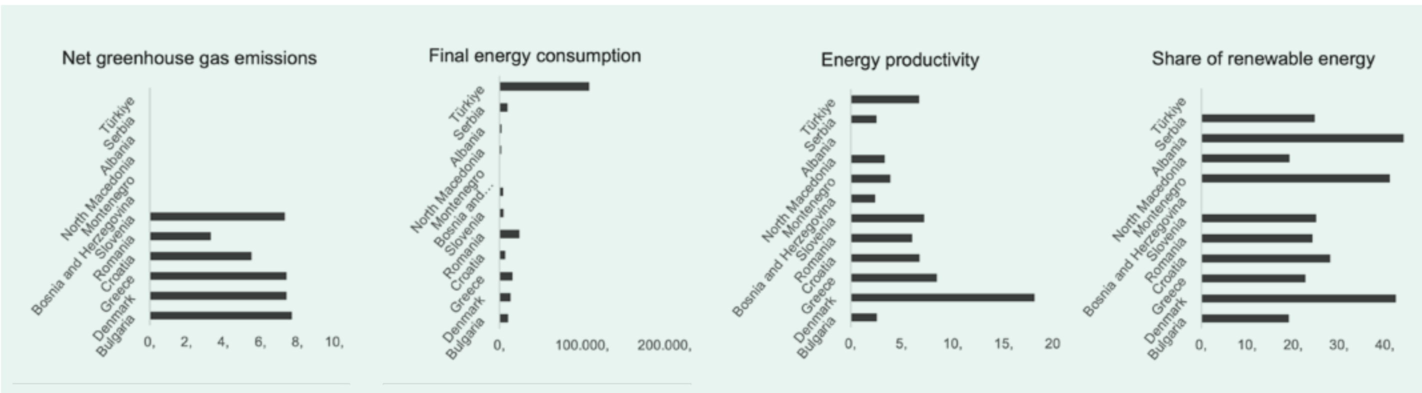


Figure 3 Indicators of energy efficiency and emissions

The EU institutions have set ambitious targets within the Green Deal for reducing carbon dioxide emissions by 2050 and for reducing energy consumption. Member countries have mandatory standards for reducing greenhouse gas emissions and improving energy efficiency, which creates similar amounts among them. Emission reduction targets have also been set for countries that are not members of the EU, but data collection in the Eurostat database has not yet been carried out. It is important to highlight the fact that the largest share of energy production in countries outside the EU is based on fossil fuels, which are less energy efficient than renewable sources and contribute to those countries being marked as the largest generators of air pollution in Europe (Frey, 2024). However, the results of research by Adamović et al. (2018) indicate the significant potential of municipal solid waste for energy production, which directly leads to a reduction in the use of fossil fuels and, consequently, can contribute to the reduction of greenhouse gas emissions. Energy productivity in South-Eastern Europe is improving, but significant challenges remain. Countries such as Slovenia, Greece, and Croatia have made progress thanks to EU initiatives and sector modernisation. In contrast, others, such as the Western Balkans, still need to invest more in technologies and infrastructure to enable higher energy yields per unit of energy consumption. The transition towards renewable energy sources and energy efficiency can be financially challenging in countries with lower economic standards. Southeastern European countries are gradually transitioning to renewable energy sources, but the level of integration of these sources is still lower than in Denmark, the benchmarking country.

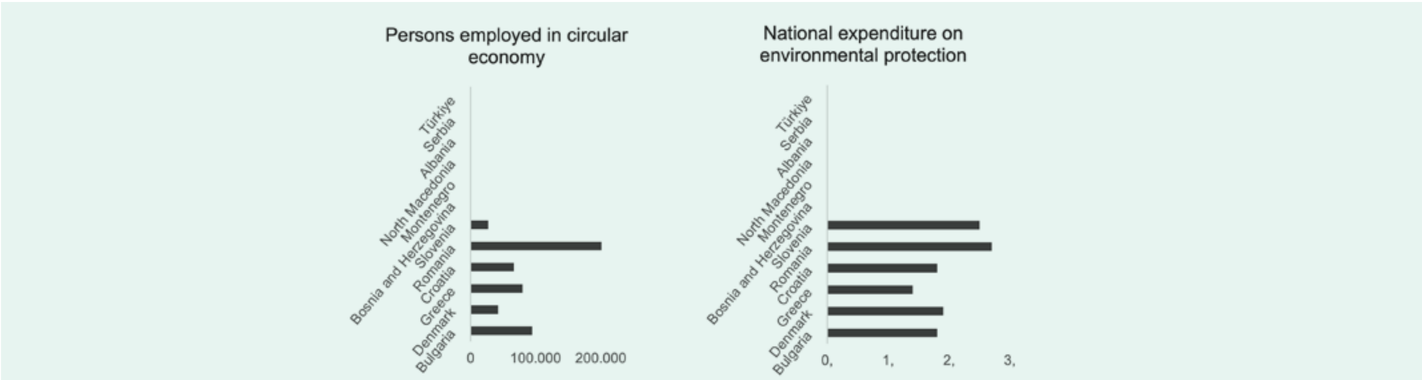
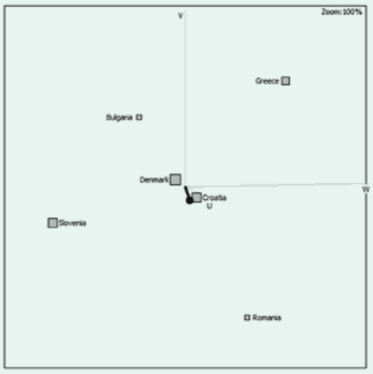


Figure 4 Socio-economic indicators

The lack of information on the circular economy and industrial symbiosis in non-EU countries indicates that they still face challenges in implementing circular models. The implementation of industrial symbiosis requires a specific set of general, sustainable, and circular skills (Straub et al., 2023). Tracking the number of employees in the circular economy can provide key information on the development of industrial symbiosis, which is a fundamental component of the circular economic model.

There are clear signals that employment in this sector could develop positively, especially with the support of political and economic initiatives. In particular, non-EU countries often face challenges in terms of financing environmental and sustainable initiatives. Therefore, national environmental expenditures show the spending on subsidizing research and innovation that enable better use of by-products or waste, thus creating competitiveness in industries based on circular principles. When compared to Denmark, which is considered the benchmarking country in terms of environmental performance, the SEE countries that are members of the European Union exhibit relatively comparable outcomes, as evidenced by the similarity in key indicator values.

To enable a more detailed assessment of SEE countries with respect to selected IS indicators, the PROMETHEE-GAIA multi-criteria analysis methodology, developed by Brans and De Smet (2016), is employed. The PROMETHEE-GAIA analysis further reveals that Romania most closely approximates Denmark's position, while Croatia shows the worst results (Figure 5).



Rank	Country	Phi value
1	Denmark	0,375
2	Romania	0,1
3	Slovenia	-0,05
4	Bulgaria	-0,075
4	Greece	-0,075
6	Croatia	-0,275

Figure 5 PROMETHEE-GAIA results

The PROMETHEE-GAIA results expectedly show that Denmark, as the benchmarking country, has the highest rank. Denmark is known for its ambitious environmental goals and carbon emissions reduction. It is also a leader in industrial symbiosis and the circular economy. The results indicate a solid position for the Southeastern European EU member state, but it may need to work on several aspects to reach the set targets.

CONCLUSIONS

The research provided insight into the performance of Southeast European countries in the context of industrial symbiosis, considering several key indicators. The results showed that although they have made significant progress, Southeast European countries still face challenges in terms of energy efficiency, recycling, and the implementation of circular principles.

In countries characterized by a lower level of economic development, there are still significant challenges in the implementation of advanced waste management systems (Boom Cárcamo & Peñabaena-Niebles, 2022; Ndoka & Alimehmeti, 2024). On one hand, the challenges they face relate to large amounts of waste generated as well as many resources that are not recycled or reused in industrial activities. On the other hand, these countries offer unique opportunities for investors seeking high returns and diversification benefits. SEE countries, especially those not members of the EU, are also burdened with less liquidity on the market and higher political and economic risks compared with leading EU economies. However, in recent years, there has been an increase in awareness of the importance of sustainability and changes in legislation that encourage higher recycling rates and a reduction in waste disposal. These changes represent an important step towards developing a green economy and better environmental protection in this region.

Investments in circular and green technologies and industrial symbiosis not only reduce the need for large environmental expenditures but can also reduce the ecological footprint, encourage the development of sustainable industrial practices, and create economic benefits through efficient use of resources and reduction of waste. The key role is played by the direction of sustainability policies that can be aimed at facilitating the implementation of industrial symbiosis, including legislative initiatives, sustainability strategies, financial mechanisms, regulatory infrastructure, and symbiotic utilization guidance (Wang et al., 2023).
SEE countries can perform better in terms of industrial symbiosis because they can more effectively benefit from the specific advantages that the transition and modernization of their economies bring, such as faster growth of the circular economy sector, lower operating costs, and more efficient use of EU funds.

ACKNOWLEDGEMENTS

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Sustainability assessment in an industrial symbiosis case study: olive mills and olive mill waste biorefineries

Anestis Vlysidis
School of Chemical Engineering, National Technical University of Athens, Athens, Greece
anestisvlysidis@chemeng.ntua.gr

Michael Stamatis
School of Chemical Engineering, National Technical University of Athens, Athens, Greece
mixahlstamatis@gmail.com

Konstantinos Bampalioutas
School of Chemical Engineering, National Technical University of Athens, Athens, Greece
babalioutas@yahoo.gr

Pantelis Manakas
School of Chemical Engineering, National Technical University of Athens, Athens, Greece
manakaspa@gmail.com

ABSTRACT

Industrial symbiosis (IS) facilitates the transition to a circular economy by promoting cross-sector collaborations where waste streams are transformed into valuable resources. This study explores an IS case within the olive oil sector, demonstrating how olive mill waste (OMW) can be converted into high-value products while minimizing environmental impact. The proposed biorefinery model integrates multiple valorization pathways, including the extraction of secondary oil and phenolic-rich bioactives, alongside the transformation of residual fractions into biofertilizers. To assess the feasibility and sustainability of this approach, a combination of techno-economic analysis (TEA) and life cycle assessment (LCA) was employed. The results indicate that the biorefinery concept enhances resource efficiency, reduces environmental burdens, and strengthens local value chains. These findings align with the LIAISE COST Action's objectives of supporting IS implementation through knowledge exchange, stakeholder engagement, and the development of practical tools for businesses and policymakers. This work directly contributes to several Key Performance Indicators (KPIs) outlined in CA22110, such as (i) Knowledge dissemination and capacity building, (ii) Industrial engagement and policy impact by addressing technical and non-technical barriers to IS adoption and (iii) Development of assessment frameworks as the integration of sustainability tools (TEA and LCA) aligns with the KPI of establishing key sustainability indicators for IS business models. By showcasing a practical IS implementation within the olive oil sector, this study bridges the gap between technical feasibility and real-world application. The findings contribute to the broader goals of the LIAISE COST Action by promoting interdisciplinary collaboration, fostering innovation, and supporting the shift toward a more circular and sustainable industrial landscape.

KEYWORDS
Industrial Symbiosis - Olive Mill Waste Valorization - Circular Economy
Sustainability Assessment - Knowledge Transfer - Business Models

INTRODUCTION

The global shift toward sustainability has prompted increased efforts to reduce dependence on fossil resources and mitigate environmental degradation caused by industrial emissions, resource depletion, and waste generation. A promising response to this challenge is the development of biorefineries that operate under circular economy principles, converting biomass and waste into value-added products while minimizing environmental impact. In particular, agro-industrial residues such as olive mill waste (OMW) represent abundant, low-cost, and underutilized feedstocks with considerable valorization potential. OMW, a by-product of the olive oil industry, is generated in significant volumes across Mediterranean countries and is typically characterized by high organic content, low pH, phytotoxic phenolic compounds, and elevated salinity (Niaounakis et al., 2006, Dermeche et al., 2013). Its uncontrolled disposal poses serious environmental risks to soil, groundwater, and aquatic ecosystems. Traditional management strategies, such as land application or direct discharge, are increasingly considered unsustainable due to their ecological footprint and regulatory constraints.

In this context, the integration of OMW into biorefinery systems emerges as a sustainable alternative, enabling the production of high-value products while simultaneously addressing waste management. Several studies have demonstrated the feasibility of converting OMW into bio-based outputs such as residual oil, phenolic-rich extracts with antioxidant and antimicrobial activity, and stabilized compost suitable for agricultural application (Roig et al., 2006, Ahmad-Qasem et al., 2013, Azbar et al., 2004). However, to guide decision-making and industrial implementation, such valorization pathways must be evaluated not only in terms of technical performance but also through a life cycle perspective that quantifies their environmental impacts. In line with the principles of industrial symbiosis (IS), the valorization of olive mill waste (OMW) offers a compelling opportunity to reduce environmental burdens while generating value-added products within the agri-food sector. By treating OMW not as waste but as a resource, cross-sector synergies can be created between olive oil producers, biorefineries, and agricultural stakeholders, supporting the transition toward more circular and sustainable production models.

To ensure the viability of such integrated systems, it is essential to assess both their environmental performance and economic feasibility. In this study, a combined Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) approach was adopted to evaluate an integrated biorefinery concept that simultaneously produces residual oil, phenolic-rich extracts, and compost. While LCA quantifies environmental impacts across multiple categories, TEA provides insights into cost structure, profitability, and scalability. Together, these tools offer a robust framework for evaluating circular bio-based systems and guiding decision-making in the early stages of technology development. Despite increasing interest in OMW valorization, few studies to date have provided a comprehensive cradle-to-gate LCA of integrated biorefineries that simultaneously produce oil, phenolic extracts, and compost. Existing literature often focuses on isolated conversion routes (e.g., anaerobic digestion, phenolic recovery) or reports only partial environmental indicators such as GHG emissions or energy use (Borja et al., 2006, Kalderis et al., 2010). This limits the capacity to compare valorization pathways and to assess the full potential of waste-based biorefineries in achieving environmental sustainability.

The present study aims to address this gap by conducting a comprehensive environmental life cycle assessment of an integrated biorefinery that utilizes olive mill waste (OMW) as feedstock to produce (i) residual olive oil through acid hydrolysis and separation, (ii) phenolic extracts via membrane filtration and adsorption, and (iii) compost. The overall process design, developed in Aspen Plus, is illustrated in Figure 1.1. A cradle-to-gate Life Cycle Assessment (LCA) was carried out using the ReCiPe 2016 midpoint methodology within SimaPro 10.1, covering 18 environmental impact categories. In parallel, a Techno-Economic Analysis (TEA) was conducted to evaluate the system's economic performance based on simulation outputs, process parameters, operational costs, and estimated market prices of the biorefinery products. By integrating both LCA and TEA, this study provides a holistic evaluation of the environmental and economic feasibility of OMW valorization and delivers valuable insights for guiding sustainable technology development and circular bioeconomy strategies.

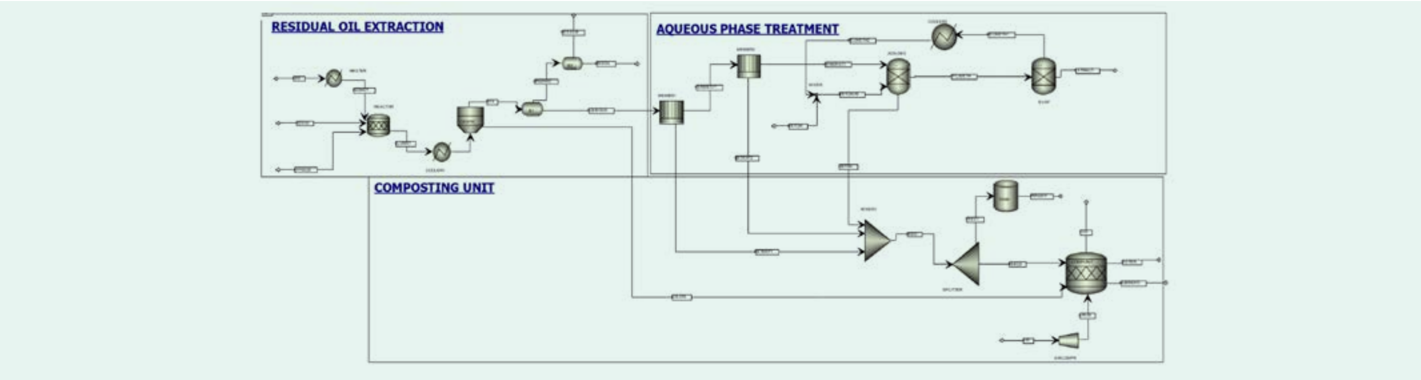

Figure 1.1 Process flow diagram of the integrated OMW biorefinery developed in Aspen Plus, including (i) residual oil extraction, (ii) aqueous phase treatment for phenolic recovery, and (iii) composting unit for solid residues.

METHODOLOGY

LCA methodology

Life Cycle Assessment (LCA) is a globally standardized approach used to evaluate the environmental impacts associated with a product, process, or service. By covering a broad spectrum of environmental impact categories, LCA helps prevent the risk of burden shifting—a situation where reducing one environmental impact (such as climate change) might inadvertently increase others (such as acidification of soil or water) (Bjørn et al., 2020). The present study follows the guidelines outlined in ISO standards 14040 and 14044 (ISO, 2006a; 2006b), which divide the LCA process into four main phases: (i) definition of goal and scope, (ii) compilation of the life cycle inventory (LCI), (iii) execution of the life cycle impact assessment (LCIA), and (iv) interpretation of the results.

Goal and scope definition

The goal of this study is to evaluate the environmental performance of an integrated biorefinery that valorizes olive mill waste (OMW) into three main outputs: residual olive oil, phenolic-rich extracts, and compost. A comparative cradle-to-gate Life Cycle Assessment (LCA) was performed at a laboratory scale to identify environmental hotspots, quantify potential burdens, and assess the viability of OMW valorization within a circular economy framework. The functional unit (FU) is defined as the treatment of 10- tons of two-phase OMW, capturing the system's primary function of converting agricultural waste into value-added products.

The system boundaries cover all upstream and on-site processes, including the extraction and transport of input materials (e.g., chemicals and energy), production of processing agents such as sulfuric acid and solvents, electricity and heat supply, OMW pretreatment (acid hydrolysis and phase separation), recovery of oil and phenolic compounds through membrane filtration and adsorption, composting of solid residues, and treatment of resulting wastewater. These processes are included up to the point where the final products are ready for distribution.

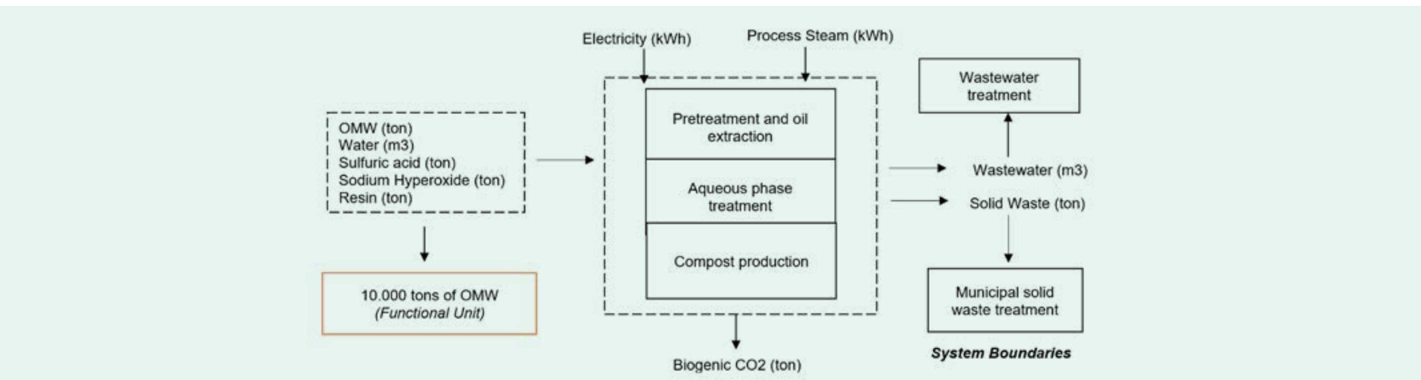

Fig. 1.2 System boundaries for OMW biorefinery

Life cycle inventory

The life cycle inventory (LCI) for this study is based on the Aspen Plus simulation described in the Introduction. The simulation models the conversion of 10,000 tons of two-phase olive mill waste (OMW) into residual olive oil, phenolic-rich extracts, and compost within an integrated biorefinery system. Foreground data were extracted directly from the simulation outputs and included all process-specific flows of materials, energy, chemical reagents, water, and emissions. Electricity consumption was calculated using the installed power of processing equipment and estimated operating time per unit process. Background data for upstream activities—such as the production of sulfuric acid, ethanol, NaOH, electricity, and water—were sourced from the Ecoinvent 3.10 database (Ecoinvent, 2024). Due to the co-location of all process units in the biorefinery, there is no need to model transport between unit operations. All data are reported per the functional unit of 10,000 tons of OMW processed, as defined in Section 2.2.

Life cycle impact assessment

The Life Cycle Impact Assessment (LCIA) was conducted using the ReCiPe 2016 midpoint method (Huijbregts et al., 2017), within the SimaPro 10.1 software (Pré-Sustainability). The analysis covered 18 environmental impact categories, including global warming (GW, 100 years), fossil and mineral resource scarcity (FRS, MRS), freshwater and marine eutrophication (FWEU, MAEU), stratospheric ozone depletion (SOD), ionizing radiation (IR), land use (LU), water consumption (WC), terrestrial acidification (TEAC), ozone formation (OFHH, OFTE), fine particulate matter formation (FPMF), and toxicity indicators (HCT, HNCT, TEEC, FWEC, MAEC).

A process contribution analysis was performed, following the approach of Clavreul et al. (2012), to identify the main contributors to environmental impacts across the biorefinery system. Subsystems analyzed included electricity consumption, production of chemical reagents, wastewater, and municipal solid waste treatment. An elementary flow contribution analysis (Table 3.1) was also conducted to trace environmental impacts to specific emissions and resource flows. In all scenarios, electricity consumption was identified as the primary environmental hotspot, contributing significantly to categories such as global warming, ionizing radiation, ozone formation, and freshwater ecotoxicity. This is mainly due to the energy-intensive nature of processes such as hydrolysis, filtration, and thermal operations.

A sensitivity analysis was carried out to assess the influence of the electricity supply mix on the overall environmental performance. The results revealed that switching to a cleaner, renewable-based electricity grid could significantly reduce impacts across multiple categories, underlining the importance of energy sourcing in the implementation of sustainable biorefinery systems.

Techno-economic assessment

In parallel with the environmental analysis, a techno-economic assessment (TEA) was performed to evaluate the economic viability of the proposed integrated biorefinery for olive mill waste (OMW) valorization. The system processes 10,000 tons of OMW per year, yielding three primary products: residual olive oil, phenolic-rich extracts, and compost. The analysis aimed to quantify the capital and operational costs, identify economic bottlenecks, and determine the financial feasibility of implementing such a process under circular economy principles.

RESULTS

Environmental performance of the omw biorefinery

This study adopted a no-allocation approach, meaning that the impacts of co-produced residual olive oil, phenolic-rich extracts, and compost were not divided among outputs. Instead, the results reflect the overall environmental footprint of treating 10,000 tons of OMW within a single integrated process. While these limits direct attribution of impacts to individual products, it aligns with the concept of waste valorization in a circular economy, where the primary objective is to transform a problematic waste stream into a suite of useful bio-based products. Notably, the biorefinery operates as a closed-loop, co-located system, reflecting principles of industrial symbiosis—whereby outputs, residues, and utilities are internally circulated or valorized, minimizing waste and reducing dependency on external inputs. Composting of solid residues and recovery of valuable compounds (oil, phenolics) within the same facility reduces the need for additional infrastructure, intermediate transport, or waste treatment operations. This integration not only streamlines the process flow but also enhances the system's overall sustainability.

Among the impact categories assessed, electricity consumption emerged as the dominant hotspot, significantly contributing to impacts such as global warming, ionizing radiation, and freshwater ecotoxicity. These results highlight the strategic role of energy sourcing in environmental performance and underscore the potential benefits of integrating renewable energy systems into future OMW valorization schemes.

Impact category	Reference unit	SI
FPMF	- kg PM2.5	- 3,6
FRS	- kg oil-eq	- 1,05E3
FWEC	- kg 1,4-DCB	- 106
FWEU	- kg P	- 2,26
GW	- kg CO2	- 2,52E3
HCT	- kg 1,4-DCB	- 1,49E4
HNCT	- kg 1,4-DCB	- 3,06E3
IR	- kBq Co-60	- 80,4
LU	- m2 annual crop	- 23,1
MAEC	- kg 1,4-DCB	- 155
MAEU	- kg N	- 0,196
MRS	- kg Cu	- 3,01
OFHH	- kg NOx	- 3,36
OFTE	- kg NOx	- 3,67
SOD	- kg CFC11	- 0,0115
TEAC	- kg SO2	- 7,59
TEEC	- kg 1,4-DCB	- 106
WC	- m3	- 26,5

Table 3.1 Environmental impact of life cycle of 10.000 tons of OMW, using ReCiPe 2016 Midpoint (H) methodology.

Hotspot analysis

A comprehensive process contribution analysis was undertaken to systematically identify and evaluate the critical environmental hotspots associated with the proposed olive mill waste (OMW) biorefinery system. While no product-level allocation was applied, the cumulative impacts of the entire process were assessed across a broad range of environmental indicators. This analysis forms the basis for the identification of the most environmentally burdensome process stages and provides a foundation for targeted sensitivity analyses and potential system improvements.

In Figure 3.1, the life cycle impact assessment reveals that electricity consumption is the dominant contributor across most environmental categories. This is attributed to the energy-intensive nature of unit operations such as acid hydrolysis, membrane filtration, and drying, which are core components of the integrated biorefinery.

Electricity use accounted for substantial shares of impacts in global warming (2,520 kg CO_2 eq), fossil resource scarcity (1,050 kg oil-eq), ionizing radiation (80.4 kBq Co-60 eq), and fine particulate matter formation, among others. These results highlight the dependency of the system on conventional grid electricity, indicating strong potential for environmental improvement through renewable energy integration. Chemical reagent use, including sulfuric acid, sodium hydroxide, and methanol, emerged as the second most significant hotspot, particularly influencing categories such as stratospheric ozone depletion, ecotoxicity, and human toxicity. The replacement or optimization of these reagents could yield substantial reductions in environmental burden. In contrast, water production, wastewater, and solid waste treatment contributed minimally to most impact categories. An exception is observed in the Water Consumption (WC) category, where the return of treated water to the environment results in a net benefit, leading to a negative contribution from wastewater treatment.

The impact of land use (23.1 $m^2 \cdot a$ crop-eq) and mineral resource scarcity (3.01 kg Cu-eq) was relatively low, largely due to the reliance on agro-industrial residues rather than dedicated agricultural inputs.

In summary, the primary environmental hotspots of the OMW biorefinery are linked to electricity consumption and chemical input usage, emphasizing the importance of energy efficiency and sustainable chemical sourcing in future optimization and scale-up of such systems.

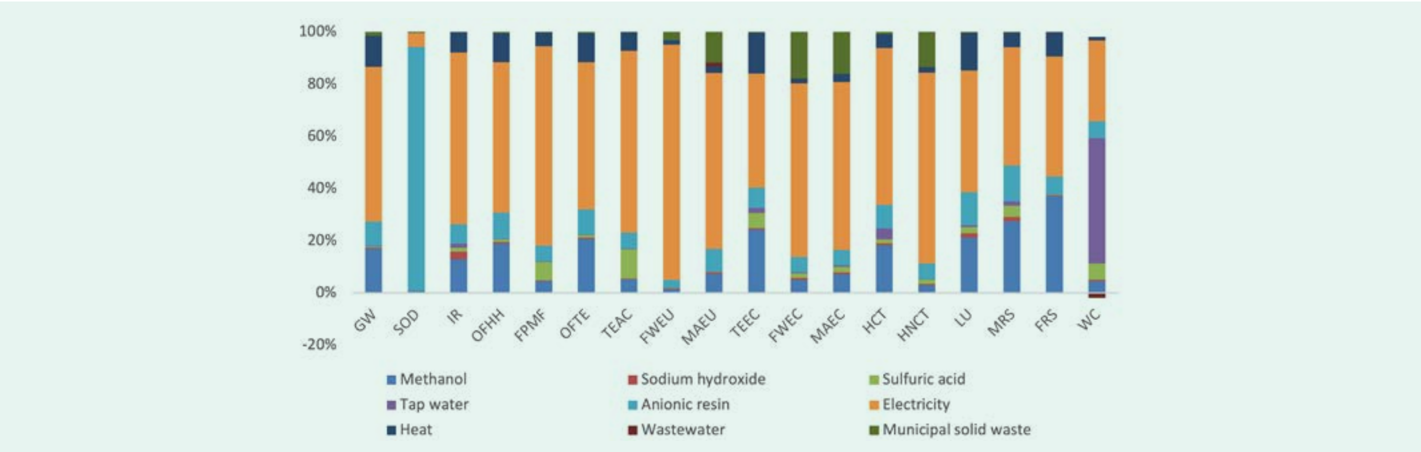

Fig. 3.Process contribution analysis for OMW biorefinery.

Sensitivity analysis

As demonstrated in the hotspot analysis (Section 3.2), electricity consumption is the dominant contributor to environmental burdens in the OMW biorefinery system. Given this dependency, a sensitivity analysis was conducted to evaluate the influence of different electricity grid mixes on the system's overall environmental performance, using the ReCiPe 2016 Midpoint (H) methodology.

The base case in this study reflects the Greek national electricity mix, sourced from the Ecoinvent 3.10 database. Greece's energy profile is characterized by approximately 30–35% renewable energy, with the remainder supplied mainly by natural gas, lignite, and imports (Hellenic Statistical Authority, 2022). Although the share of lignite has declined, fossil fuels still play a significant role in the energy mix.

To assess the influence of electricity sourcing, two alternative scenarios were compared:

A high-renewables scenario based on Norway (~99% renewable, mostly hydropower),

A low-renewables scenario based on Cyprus (~15% renewable, largely fossil-fuel based).

Figure 3.2 illustrates the comparative impact of these three electricity mixes across 18 midpoint categories. The results clearly show that the Norwegian electricity mix leads to a substantial reduction in environmental impacts across nearly all categories. The most pronounced improvements occur in Global Warming (GW), where emissions decrease by up to 70–80%, as well as in Fossil Resource Scarcity (FRS), Ozone Formation (OFHH, OFTE), Terrestrial Acidification (TEAC), and various toxicity and ecotoxicity indicators.

Notably, the only category where the Norwegian scenario performs worse than the Greek baseline is Water Consumption (WC). This is primarily due to the high-water footprint associated with hydropower generation, which dominates Norway's energy system. Despite being low in emissions, hydropower is associated with substantial water use, especially when accounting for water evaporation from reservoirs. In contrast, the Cypriot electricity mix, with its strong fossil fuel reliance, consistently exhibits the highest environmental impacts across all categories, further emphasizing the advantage of transitioning toward cleaner energy sources.

Overall, this sensitivity analysis confirms that electricity mix is a critical parameter in determining the environmental performance of biorefinery systems. Transitioning to renewable-dominant grids can significantly mitigate climate-related and resource depletion impacts—though trade-offs such as water use must also be considered within a comprehensive, multi-indicator LCA framework.

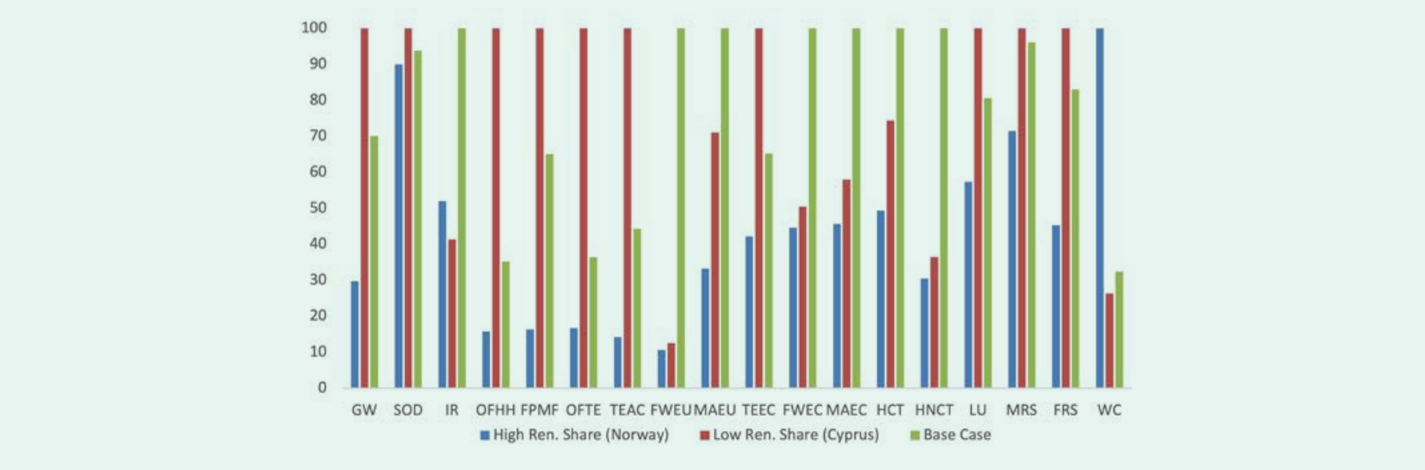

Figure 3.2 Sensitivity analysis of electricity mix (Norway, Cyprus, Base Case) on midpoint impact categories.

Methodological framework tea

The TEA was based on a process flow simulation developed in Aspen Plus, from which equipment sizing and material balances were extracted. Equipment costs were estimated using empirical cost correlations, and prices were adjusted to 2022 values using the Chemical Engineering Plant Cost Index (CEPCI). Installation costs were calculated using standard installation factors, and the fixed capital investment (FCI) was determined to be 5.82 million euros for the 10,000 t/y plant.

Operating costs were divided into raw materials, utilities, labor and overhead, and waste treatment. Specifically, the annual costs were estimated as follows: 1.67 M€ for raw materials, 0.41 M€ for utilities, 0.34 M€ for operational labor and overhead, and 0.09 M€ for waste treatment. These values were used to calculate the total production cost (TPC) according to the following equation:

$$TPC_{woD} = 0.18FCI + 2.73C_{OL} + 1.23(C_{RM} + C_{UT} + C_{WT})$$

The resulting TPC was 4.64 million euros per year, which corresponds to a unit production cost of 2.11 €/kg OMW (dry basis).

Profitability insights

A sensitivity analysis across different production capacities revealed that unit production costs decrease significantly with scale, confirming the presence of strong economies of scale. A power-law regression showed the relationship between TPC and capacity with a high correlation ($R^2 = 0.94$), as illustrated in Figure 3.3.

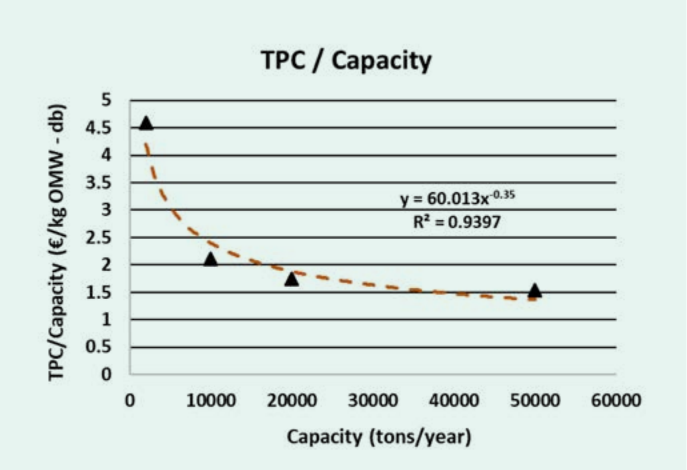

Figure 3.3 Effect of capacity on total production cost per kg OMW (dry basis)

While the 10,000 t/y scenario reflects a relatively high unit cost, the analysis indicates that larger facilities—e.g., 20,000 or 50,000 t/y—can achieve significantly lower costs per unit of input.

A net present value (NPV) analysis, assuming a 10-year project lifetime, 40% tax rate, and 7-year MACRS depreciation, further highlighted the impact of scale. As shown in Figure 3.4, the 10,000 t/y plant yields a negative NPV, suggesting limited profitability under current assumptions. In contrast, larger capacities exhibit positive NPV values and reduced payback periods, indicating economic feasibility when economies of scale are leveraged.

The sensitivity analysis also demonstrated that profitability is strongly dependent on the market value of phenolic compounds. As illustrated in Figure 3.5, profitability improves substantially when the selling price of phenolic extract exceeds ~28.3 €/kg, with the 20,000 t/y plants considered a threshold for positive returns.

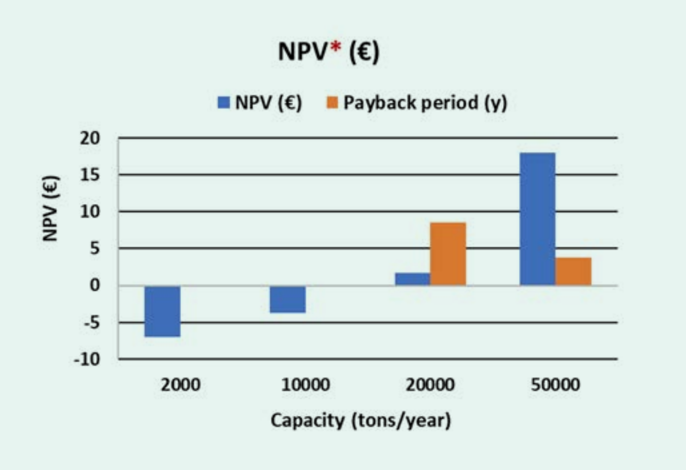

Figure 3.4 Net Present Value and Payback Period at varying plant capacities.

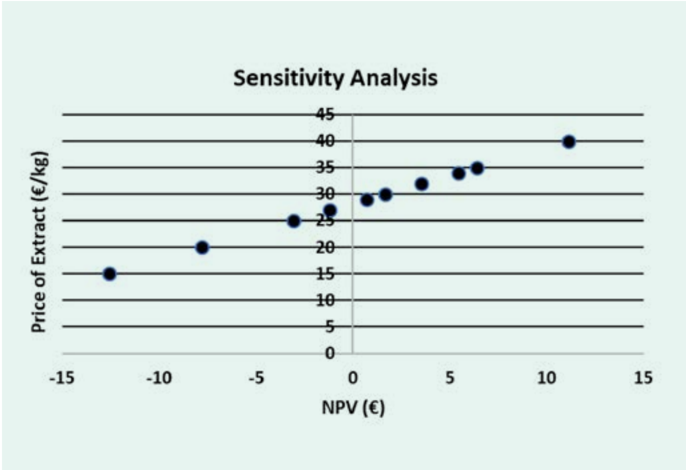

Figure 3.5 NPV sensitivity to selling price of phenolic extracts.

CONCLUSION

This study presented a comprehensive sustainability assessment of an integrated biorefinery designed to valorize olive mill waste (OMW) into three valuable outputs: residual olive oil, phenolic-rich extracts, and compost. By applying a combined Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) approach, we evaluated both the environmental performance and economic feasibility of the proposed system at a 10,000 tons/year capacity.

The LCA, conducted using the ReCiPe 2016 midpoint method, revealed that electricity consumption is the dominant contributor to most environmental impact categories, including global warming, resource depletion, and human toxicity. Nonetheless, the system demonstrated clear environmental benefits by transforming problematic agro-industrial waste into value-added bio-products. Substituting conventional feedstocks with waste-derived inputs and optimizing resource flows through a closed-loop process architecture reflected strong alignment with circular economy principles. Additionally, scenario and sensitivity analyses indicated that integrating renewable energy sources could significantly reduce the system's environmental footprint, particularly in carbon-intensive categories.

On the economic side, the TEA showed that although the biorefinery is technically feasible, its economic viability at the 10,000 t/y scale remains limited under current market assumptions. A total production cost of 2.11 €/kg OMW (dry basis) was estimated, with profitability highly dependent on the selling price of phenolic extracts. Sensitivity and NPV analyses indicated that larger-scale implementation (e.g., ≥20,000 t/year) would significantly improve financial performance due to economies of scale and more favorable payback periods.

Together, the integrated LCA-TEA framework highlights both the environmental merits and economic challenges of implementing circular bioeconomy solutions in the olive oil sector. To realize its full potential, future efforts should focus on process optimization, decarbonizing energy inputs, and strengthening downstream value chains. The findings of this study provide decision-relevant insights for stakeholders aiming to scale up sustainable waste valorization pathways within the Mediterranean agri-food industry.

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8

Challenging fossil feedstocks through industrial symbiosis: a waste-to-product case study

Maddalena Eloisa Logrieco
MNEXT, Avans University of Applied Sciences, Breda, Netherlands
me.logrieco@avans.nl

Philippa Roots
MNEXT, Avans University of Applied Sciences, Breda, Netherlands
pm.roots@avans.nl

Willem van Liemt
MNEXT, Avans University of Applied Sciences, Breda, Netherlands
wbs.vanliemt@avans.nl

Martijn Zieverink
MNEXT, Avans University of Applied Sciences, Breda, Netherlands
mmp.zieverink@avans.nl

ABSTRACT

The biobased transition is currently in its early stages, where the key foundations, major players, and operational dynamics are still being established. This is an emerging field, and we find ourselves at the beginning of a complex race, with limited data and a few past examples to guide decision-making. There is no definitive "right" product to replace or universally ideal business model to adopt, and technology is often not the primary limiting factor. Once the appropriate Technology Readiness Level (TRL) has been achieved and the "valley of death" has been crossed, biobased pioneers encounter a new set of challenges. These include issues related to feedstock availability, regulatory hurdles, shareholder commitment, cultural factors, and the need for effective value chain collaboration. Industrial symbiosis (IS) presents a promising solution to many of these challenges, as it can deliver environmental and economic benefits when implemented correctly. IS can foster collaboration across industries, optimize resource use, and reduce waste, making it a valuable strategy for biobased startups seeking sustainability and profitability. This case study provides a comprehensive overview of a Dutch IS journey within the biobased sector, from initial concept to commercialization. It adopts a dual lens, focusing on both technical innovation and business strategy through the Business Model Canvas framework. Data is gathered through desk research and interviews. The qualitative study evaluates the case from an entrepreneurial perspective, identifying key challenges and strategic decisions. Insights from this analysis will help generalize strengths, weaknesses, and lessons learned. The goal is to refine the business model and establish KPIs for assessing IS in the biomaterial industry.

KEYWORDS
Biobased Transitions - Biobased Entrepreneur - Business Model - ndustrial Symbiosis - Waste Valorization

LIST OF ACRONYMS

5HM: Quintuple innovation helix framework
BMC: Business Model Canvas
CP: Citrus peels
IS: Industrial Symbiosis
SDGs: Sustainable Development Goals
SMEs: Small and medium-sized enterprises
UN: United Nations

INTRODUCTION

Citrus peels (CP) pose significant waste management challenges due to their high volume and perishable nature. With about 80% water content, CP decomposes rapidly, attracting microbes, flies, and mold, and can also produce mycotoxins. Proper disposal of citrus waste demands considerable investment, as improper disposal can lead to soil and water contamination, further harming aquatic ecosystems (Suri et al., 2022).

However, CP is also a valuable bioresource. The peel waste, along with seeds and pomace, accounts for 50–60% of the fresh fruit's weight. These byproducts hold potential for high-value applications, ranging from food ingredients to biomaterials and biofuels (Sharma et al., 2022). The recycling of food waste and its value addition has become an important area of research in sustainability. The United Nations (UN) supports food waste management as a strategy to achieve several Sustainable Development Goals (SDGs), including ending hunger (SDG 2), promoting health and well-being (SDG 3), ensuring clean water and sanitation (SDG 6), advancing sustainable energy (SDG 7), and encouraging responsible consumption and production (SDG 12) (Kumar et al., 2025).

Industrial symbiosis (IS) could help integrate these waste streams into circular systems. However, challenges exist, such as food safety regulations, consumer acceptance, and the strict timing of the food supply chain (Rao et al., 2024). Large-scale industrial valorization of food waste remains limited, with most initiatives originating from academic projects or a few companies specializing in waste resource management (Müller & Laibach, 2022, p. 5).

This case study focuses on a success story of food waste valorization within European food systems, particularly in the Netherlands, including strategies to successfully scale up industrial symbiosis. Each year, around 250 million kilograms of orange peels are produced in the Netherlands, primarily originating from supermarkets and the food service industry after fresh orange juice production (Renewi, n.d.). The scale-up company PeelPioneers B.V. (hereafter PeelPioneers), is a multi-output upcycling production company that operates with a "waste-based" upcycling-driven business model bringing innovation using mutual industrial symbiosis.

METHODOLOGY – CASE STUDY PROTOCOL

The purpose of this study is to analyze the successful implementation of IS practices and strategic decisions in both the business and technological development of a "sustainable entrepreneurship" case. This single qualitative case study focuses on a success story in the circular bioeconomy model and industrial symbiosis at a commercial scale.

Research questions:

- How can IS practices be successfully implemented and scaled up?
- How is the business model structured?
- What are the key success factors?
- What lessons can be learned?

Selection criteria include, but are not limited to:

- Successfully scaling up a circular business model.
- Bio-based activities as the core of the business.
- Fewer than 250 employees, in line with the EU's definition of SMEs (European Commission, n.d.).
- Implementation of IS practices.

Data collection was conducted through multiple sources of evidence to ensure construct validity. This included data gathered from academic papers, publicly available news and videos, and interviews with a former employee. The study's data collection procedure is repeatable and supported by a reliable chain of evidence.

The unit of analysis for this case study is a technology-based scale-up. To evaluate the business aspect, the Business Model Canvas (BMC) tool was used to visualize the core elements of the business model. Assumptions were made where necessary to fill gaps in information. IS practices were analyzed using the quintuple innovation helix framework (5HM).

The study is limited to the Netherlands and focuses exclusively on one specific type of waste stream and value chain.

RESULTS

Company overview

PeelPioneers was founded in 2016 by Sytze van Stempvoort, Bas van Wieringen, and Lindy Hensen, with the mission to create value from CP that was previously discarded as waste. The idea stemmed from van Stempvoort's studies in the UK, where he participated in a project for the valorization of CP. The company began by testing processing techniques in Amsterdam and soon formed a key partnership with waste processor Renewi, which collects CP waste from supermarkets, restaurants, and catering establishments.

With financial backing from BOM Brabant Ventures and Stichting DOEN amongst others, PeelPioneers established its first factory in Son, North Brabant, which officially opened in 2018. A major breakthrough came when the Dutch government approved the use of processed CP in food and animal feed, removing regulatory barriers (PeelPioneers, n.d.). The company expanded further and relocated, announcing in 2020 the construction of Europe's largest citrus peel processing plant in Den Bosch, a €10 million investment with a capacity to process 120,000 kilograms of peels per day (Eiwittrends, 2020).

PeelPioneers currently processes 70% of all available CP in the Netherlands and employs approximately 50 people across the region. Building on this success and leveraging its visibility for fundraising efforts, PeelPioneers plans to expand its operations by constructing a CP processing facility in Spain's Murcia region, valorizing the CP waste of major juice producers (Vakblad Voedingsindustrie, 2024).

Business model

<table>
<tr>
<td rowspan="2">Key Partnerships
• Supplier network already in place - waste processor collaboration
• Supermarket chain
• Continuously looking for orange peel producers
• Business developer
• Patent advisor
• Technology supplier
• Offtake agreements</td>
<td>Key Activities
• 72 h process to guarantee quality
• lean startup method
• tracking and tracing the food streams (digitalization)</td>
<td rowspan="2">Value Proposition
• Upcycling orange peels waste using 100% of the peel as a new, circular ingredient
• All ingredients are plant-based, natural, vegetarian, hypoallergenic, gluten-free, and non-GMO
• Price-competitive products to have a bigger impact (and market)</td>
<td>Customer Relationship
• B2B business</td>
<td rowspan="2">Customer Segment
• food, food ingredient, cosmetics, and cleaning products producing companies</td>
</tr>
<tr>
<td>Key Resources
• Access to inputs of sufficient quality and quantity
• Certifications
• Patents
• Awards</td>
<td>Channels
• Free sample pack
• Updated website
• Youtube videos
• Social media</td>
</tr>
<tr>
<td colspan="3">Cost Structure
• Operational expenses: labor costs, service costs, general and administrative expenses
• Pilot in Amsterdam
• Commercial plant</td>
<td colspan="2">Revenue Streams
• diced orange peel
• Cold Pressed Orange Oil (CPO)
• D-limonene
• Finix citrus fiber
• Fivefold oil
• Orange peels</td>
</tr>
</table>

Table 1 Peel Pioneers business model canvas - create value from waste archetype

PeelPioneers has developed a robust business model focused on CP valorization. Instead of managing the collection process and owning trucks, the company partnered with an existing waste collector already handling logistics. This collaboration ensures a consistent supply of orange peels and creates additional revenue streams. Key activities, such as a 72-hour processing method and digital tracking, support both quality control and operational efficiency. The most labor-intensive task is the initial hand-picking to remove physical contaminants like plastic bags and gloves from the waste stream. The value chain and key players are shown simplified in Figure 1.

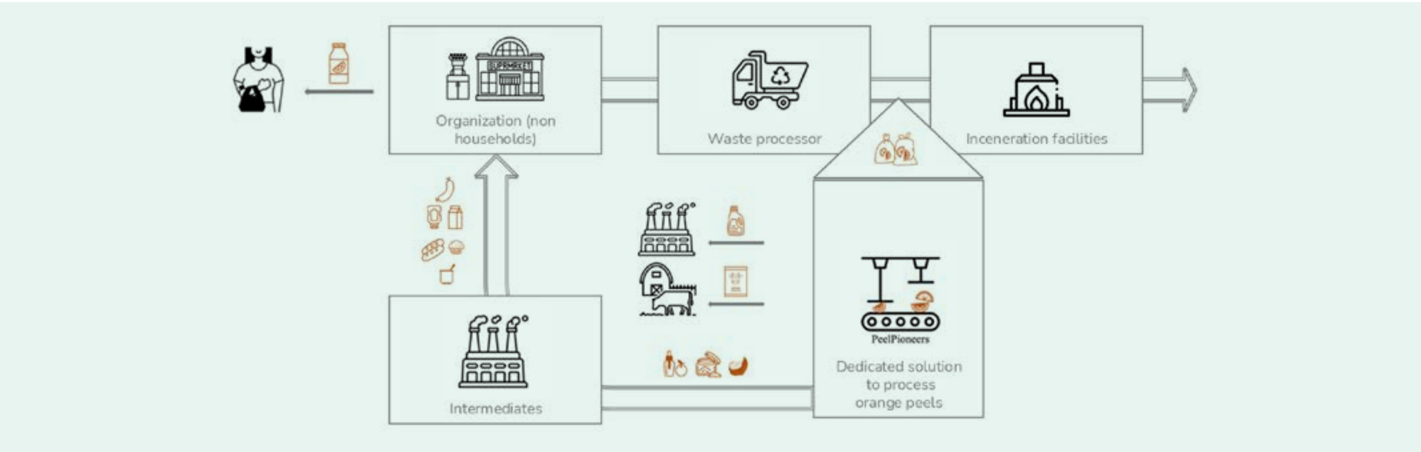

Figure 1 Adapted from (Rao et al., 2024): from linear to circular

The company's value proposition centers on upcycling 100% of orange peel waste into plant-based, natural ingredients. An off-take agreement for the high-margin oil product was secured early on. PeelPioneers invests in patents and certifications and maintains an active presence on social media.

INDUSTRIAL SYMBIOSIS IN PRACTICE

The PeelPioneers case exemplifies how industrial symbiosis operates through the Quintuple Helix model, which involves the collaboration of government, industry, academia, and the environment. Each sector plays a key role in driving sustainable innovation (see Figure 2).

- Government: provides essential subsidies, regulations, and patent support, ensuring a favorable environment for innovation and the company's freedom to operate (PeelPioneers, 2022).
- Industry: contributes investment, infrastructure, offtake agreements, and market credibility, enabling the scaling of innovative processes and the practical application of research into business solutions.
- Academia: supplies the ideas, conducts hi-gh-risk research, and provides skilled inter-ns who bring academic expertise and low-cost labor into the company's operations.
- Environment: acts as both a motivator and a beneficiary, as the focus on reducing waste and improving resource efficiency directly benefits the environment through sustainable practices.
- Civil society: creating jobs and bringing visibility to a less prominent area.

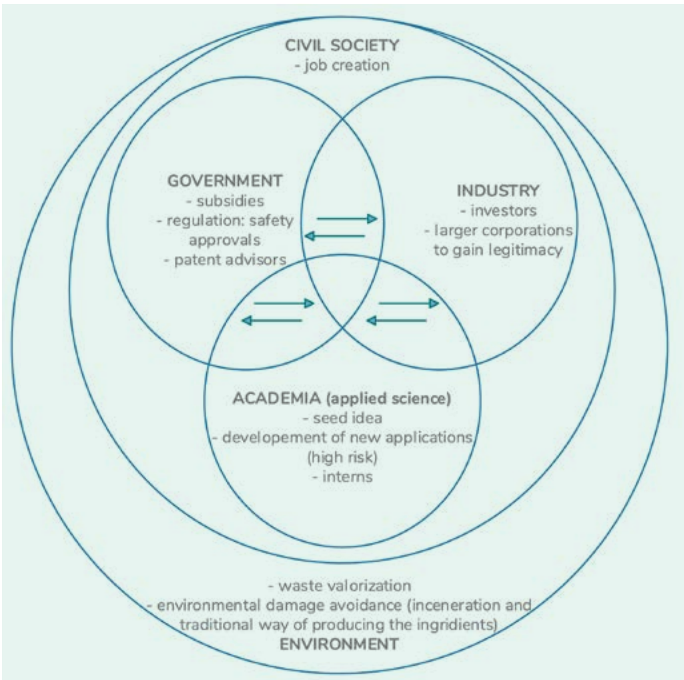

Figure 2 PeelPioneers through the Quintuple Helix model

This model supports waste valorization and minimizes environmental damage. By transforming by-products into raw materials, PeelPioneers reduces waste and enhances resource efficiency, demonstrating the business potential of a circular economy.

CONCLUSIONS

The PeelPioneers case demonstrates how industrial symbiosis can create value from waste streams while highlighting the complexities of scaling such a model. The company successfully integrated key players in the value chain—waste collectors, processing facilities, and end-users—turning citrus peel waste into valuable products. However, these connections also introduce dependencies that can be both beneficial and risky, especially when dealing with regulatory changes or shifts in supply and demand.

Upscaling requires securing stable input streams, regulatory compliance, and building strong industry partnerships. PeelPioneers benefited from an early off-take agreement for citrus oil, ensuring revenue stability, and from regulatory shifts that allowed orange peels to be processed into food ingredients. The Dutch ecosystem, with its structured waste collection and strong sustainability incentives, played a role in the company's success. However, replicating the model in other regions such as Spain, where juicing facilities often dispose of waste differently, would require adaptations in logistics, automation, and regulatory alignment.

Compared to traditional startups, circular ventures face additional hurdles. Consumer perception of upcycled products can affect market acceptance, requiring investment in branding and certification. The labor-intensive nature of waste valorization such as manual quality checks to remove contaminants, adds costs, though automation could reduce this in some markets. Additionally, securing intellectual property rights is crucial when introducing new processes and requires significant investment in both time and budget.

Several factors contributed to PeelPioneers' early success:

- Strategic integration into the value chain, leveraging partnerships instead of building logistics infrastructure.
- Secured customer base through offtake agreements and major distributors committed to selling products made with PeelPioneers' ingredients.
- Complementary founding team, combining business and technical expertise.
- Flexibility in plant location, ensuring proximity to key suppliers.
- Regulatory timing, aligning product development with policy shifts in food waste regulation.

The economic viability of the model lies in extracting high-margin ingredients while adding value through initial processing steps, such as contaminant removal. However, green premiums may not be long-lasting, requiring businesses to compete on cost and functionality rather than just sustainability credentials.

PeelPioneers' journey highlights the importance of early industry buy-in, with corporations like IFF (Brabant is Bright, 2023) playing a role in de-risking operations through long-term agreements. Regulatory navigation, supported by consultants working on a results-based payment model, was also a critical factor. However, challenges remain, including the potential decline in juice consumption, shifts in waste availability, and the transition from an agile startup culture to a structured production business.

This case study offers a blueprint for industrial symbiosis in the circular economy, but its success is tied to market dynamics, regulatory frameworks, and value chain collaboration. Future expansion will depend on how well these factors align in new ecosystems.

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9

Industrial symbiosis opportunities in the livestock sector – a cross-sectoral analysis of resource recovery and circular value chains

Dogan Turkyilmaz
Atatürk University, Faculty of Agriculture, Erzurum, Türkiye
dogan.turkyilmaz@atauni.edu.tr

Ulku Dagdelen
Atatürk University, Faculty of Agriculture, Erzurum, Türkiye
ulku@atauni.edu.tr

ABSTRACT

This systematic review examines the opportunities for industrial symbiosis in the livestock sector, focusing on circular value chains and cross-sectoral resource recovery potential. The study analysed academic literature published between 2000 and 2024 using Web of Science, Scopus, and Google Scholar databases. Keywords used in the search included 'industrial symbiosis', 'livestock sector', 'resource recovery', 'circular economy', and 'waste management'. From an initial pool of 450 studies, 20 livestock symbiosis studies were selected for detailed analysis based on pre-defined inclusion and exclusion criteria. The analysis identifies three primary dimensions of symbiotic relationships in livestock value chains: resource transformation, cross-sector integration, and value networks. The findings reveal significant opportunities for industrial symbiosis, particularly in manure management systems that facilitate biogas production and organic fertiliser production. Integration with rendering plants demonstrates effective value chain optimisation, where slaughterhouse by-products are converted into valuable animal feed components, while secondary products such as leather and wool form symbiotic links with the textile industry. The study under scrutiny here highlights strong circular value chain relationships between the livestock sector and adjacent industries, including agriculture, food processing, and energy production. Agricultural residues are used as animal feed, while livestock waste contributes to bioenergy generation. Food industry by-products provide supplementary feed resources, creating circular resource flows. The research presents exemplary cases of integrated biogas facilities that demonstrate effective closed-loop systems, where animal waste is used for energy production while digestate is converted into agricultural fertiliser. The findings indicate that industrial symbiosis practices significantly enhance resource efficiency, reduce operational costs, and improve environmental sustainability in livestock sector value chains. The study concludes that regional industrial symbiosis networks present considerable opportunities for sustainable sector development, recommending further research on implementation frameworks and supportive policy mechanisms to facilitate cross-sectoral circular value chain integration.

KEYWORDS
Industrial Symbiosis - Livestock Sector - Resource Recovery - Circular Economy - Cross-sectoral Integration

INTRODUCTION

This systematic review explores the substantial opportunities for industrial symbiosis within the livestock sector, with particular emphasis on circular value chains and the potential for cross-sectoral resource recovery. Industrial symbiosis, a key concept within the broader framework of circular economy, involves collaborative exchanges where waste, by-products, and resources from one industrial process become valuable inputs for another (Chertow, 2000). The livestock sector, facing increasing scrutiny regarding its environmental footprint, presents numerous opportunities for such symbiotic relationships that can transform waste streams into valuable resources (Boons et al., 2017).

The research methodology employed a comprehensive analysis of academic literature published between 2000 and 2024, utilizing leading academic databases including Web of Science, Scopus, and Google Scholar. The search strategy incorporated key terms such as 'industrial symbiosis', 'livestock sector', 'resource recovery', 'circular economy', and 'waste management', reflecting the interdisciplinary nature of the subject matter (Geissdoerfer et al., 2017). Through rigorous application of pre-defined inclusion and exclusion criteria focusing on empirical evidence and practical applications, the initial pool of 450 studies was refined to 20 high-quality livestock symbiosis studies for detailed analysis and synthesis.

The analytical framework revealed three primary dimensions characterizing symbiotic relationships within livestock value chains: resource transformation, cross-sector integration, and value networks. These dimensions provide a structured approach to understanding the complex interactions that facilitate circular material flows across different industrial sectors (Jacobsen, 2006). The findings demonstrate particularly significant opportunities for industrial symbiosis in manure management systems, which serve as a cornerstone for both biogas production and organic fertilizer generation, creating valuable energy and agricultural inputs from what was traditionally considered waste (Holm-Nielsen et al., 2009).

Further examination revealed effective value chain optimization through integration with rendering plants, where slaughterhouse by-products—including inedible offal, bones, and tissue—undergo transformation into high-value animal feed components, protein meals, and tallow (Sanchez-Vazquez et al., 2021). Additionally, secondary products from livestock production, such as leather and wool, establish important symbiotic links with the textile industry, extending the value chain beyond food production (Ramirez, 2019).

The study highlights robust circular value chain relationships connecting the livestock sector with adjacent industries. In particular, the agricultural sector provides crop residues and by-products as animal feed inputs, while receiving organic fertilizers derived from livestock waste in return (Ellen MacArthur Foundation, 2019). Similarly, the food processing industry supplies valuable by-products that serve as supplementary feed resources, creating efficient circular resource flows that minimize waste and maximize resource utilization across sectors (Mirabella et al., 2014).

Exemplary cases of integrated biogas facilities demonstrate particularly effective closed-loop systems, where animal waste generates renewable energy while the resulting digestate is converted into high-quality agricultural fertilizer, simultaneously addressing waste management challenges, energy needs, and soil fertility requirements (Winquist et al., 2021). These integrated approaches represent the practical application of industrial ecology principles in agricultural contexts.

The findings consistently indicate that industrial symbiosis practices deliver multiple benefits across the triple bottom line: they significantly enhance resource efficiency, reduce operational costs through shared infrastructure and logistics, and improve environmental sustainability metrics throughout livestock sector value chains (Domenech et al., 2019). These benefits align with global sustainability goals and offer pathways for the livestock industry to address environmental challenges while maintaining economic viability.

The study concludes that regional industrial symbiosis networks present considerable opportunities for sustainable development within the livestock sector, particularly when supported by appropriate governance structures and stakeholder engagement processes (Walls and Paquin, 2015). The research recommends further investigation into implementation frameworks that can overcome existing barriers, along with supportive policy mechanisms designed to facilitate cross-sectoral circular value chain integration. Such policies should address regulatory barriers, provide economic incentives, and promote knowledge-sharing platforms that catalyze industrial symbiosis initiatives in diverse geographical and regulatory contexts (Mulrow et al., 2017).

METHODOLOGY

This study employed a systematic review approach to investigate industrial symbiosis opportunities within the livestock sector, with particular emphasis on circular value chains and cross-sectoral resource recovery potential. The methodological framework was designed to ensure comprehensive coverage of the existing literature while maintaining analytical rigor throughout the review process.

Search Strategy and Data Collection

A structured literature search was conducted utilizing three prominent academic databases: Web of Science, Scopus, and Google Scholar. The temporal scope encompassed publications from January 2000 through December 2023, representing a comprehensive 24-year period of scholarly development in this domain. The search query incorporated primary keywords including 'industrial symbiosis', 'livestock sector', 'resource recovery', 'circular economy', and 'waste management', which were combined using Boolean operators to optimize retrieval precision. Supplementary search terms such as 'by-product valorization', 'cross-sectoral integration', and 'bio-based value chains' were employed to enhance the search sensitivity.

Selection Criteria and Screening Process

The initial database queries yielded an aggregate of 450 potentially relevant studies. These were subsequently subjected to a systematic screening process employing predefined inclusion and exclusion criteria to ensure methodological consistency and relevance to the research objectives. The inclusion criteria encompassed: (i) empirical investigations of industrial symbiosis in livestock production systems; (ii) studies examining cross-sectoral material flows involving the livestock sector; (iii) research analyzing circular economy applications specific to animal production; (iv) peer-reviewed publications; and (v) studies presenting quantifiable outcomes or robust case analyses.

Conversely, exclusion criteria comprised: (i) purely theoretical works lacking empirical application; (ii) studies with methodological inadequacies; (iii) non-English publications; and (iv) research focused exclusively on crop production without livestock integration. The screening procedure was implemented in two consecutive phases: an initial title/abstract review followed by a comprehensive full-text assessment. This rigorous selection process culminated in the identification of 20 high-quality studies meeting all criteria for inclusion in the final analysis.

Analytical Framework and Data Extraction

The analytical procedure employed a systematic content analysis methodology utilizing a bespoke three-dimensional framework developed specifically for this investigation. This analytical structure categorized symbiotic relationships according to: (1) resource transformation pathways; (2) cross-sector integration mechanisms; and (3) value network configurations. For each included study, data extraction was performed using a standardized protocol that captured methodological characteristics, geographical context, livestock subsector, symbiotic relationship typology, and documented outcomes.

The analysis focused particularly on the symbiosis relationship areas identified in Table 1, namely: Waste-to-Resource Conversion, Inter-sectoral Integration, Closed Cycle Systems, and Economic Impacts. Within each category, specific opportunities and their corresponding benefits were systematically catalogued and analyzed. A standardized coding scheme was applied to facilitate cross-study comparison and synthesis.

Data Synthesis and Quality Assessment

The extracted data underwent a mixed-methods synthesis incorporating both narrative integration and quantitative aggregation where applicable. The synthesis process entailed: (1) systematic mapping of industrial symbiosis opportunities against their corresponding benefits; (2) classification of symbiotic relationships according to the established analytical dimensions; (3) critical evaluation of the methodological rigor and evidence quality for each identified opportunity; and (4) assessment of the transferability potential across diverse geographical and regulatory contexts.

The methodological quality of the included studies was evaluated using adapted criteria from the Critical Appraisal Skills Programme (CASP), with particular attention to research design appropriateness, methodological rigor, data quality, and analytical validity. This quality assessment informed the interpretation of findings and the confidence assigned to specific conclusions.

Methodological Limitations

Several methodological limitations warrant acknowledgment. First, despite comprehensive database searching, relevant publications in non-English languages may have been inadvertently excluded. Second, the heterogeneity of livestock production systems across geographical contexts introduces challenges for comparative analysis and generalizability of findings. Third, the emphasis on peer-reviewed literature potentially excluded valuable insights from gray literature sources, including industry reports and governmental documents. These limitations were addressed through careful contextualization and appropriate qualification of conclusions in the discussion section.

RESULTS

The analysis identified several significant waste-to-resource conversion opportunities within livestock operations. Biogas production through advanced manure management systems emerged as a prominent example of resource recovery, with multiple studies highlighting its effectiveness (Dong et al., 2019; Martin & Eklund, 2011). These systems facilitate the transformation of animal waste into renewable energy, simultaneously addressing waste management challenges and energy needs. As noted by Martin and Eklund (2011), such conversions can reduce energy costs by 30-45% in intensive livestock operations while significantly mitigating methane emissions.

Organic fertilizer production represents another valuable waste conversion pathway, creating agricultural inputs from livestock waste streams. This practice establishes crucial nutrient cycling mechanisms that support sustainable agriculture (Harris et al., 2020). Harris et al. (2020) demonstrated that fertilizer derived from processed livestock waste can contain up to 85% of the original nutrient content, providing a cost-effective alternative to synthetic fertilizers while reducing waste management expenditures.

Additionally, the conversion of slaughterhouse by-products into animal feed components demonstrates effective value chain optimization (Neves et al., 2020). This process involves rendering facilities that transform otherwise discarded materials into protein-rich feed supplements, enhancing resource efficiency while providing economic benefits through reduced feed costs (Gottumukkala et al., 2016).

Inter-sectoral Integration

The review identified several productive inter-sectoral integration pathways involving the livestock sector. The utilization of agricultural by-products as animal feed creates synergistic relationships between crop production and livestock systems (Kirchherr et al., 2017). These exchanges increase overall resource efficiency by redirecting materials that would otherwise be considered waste into valuable inputs for animal nutrition.

Cooperation with leather and wool processing industries represents another significant inter-sectoral integration opportunity (Sendra et al., 2007). This symbiotic relationship extends the value chain beyond food production, creating additional revenue streams and enhancing the overall economic viability of livestock operations. Sendra et al. (2007) documented cases where such integration increased total value recovery from livestock production by 15-20%.

The utilization of food industry wastes for animal nutrition further demonstrates inter-sectoral synergies (Aydın-Şişman, 2021). By-products from food processing that are unsuitable for human consumption can often serve as nutritional inputs for livestock, creating circular resource flows while reducing feed costs. Aydın-Şişman (2021) reported operational cost reductions of 10-18% in livestock facilities implementing such practices.

Closed Cycle Systems

Integrated biogas plants emerged as exemplary closed-cycle systems within the livestock sector (Sun et al., 2017). These facilities create interconnected resource flows where animal waste generates energy, while the resulting digestate returns to agricultural land as fertilizer. Such systems demonstrate the practical implementation of circular economy principles, creating self-sustaining resource cycles with minimal external inputs.

The conversion of digested waste into fertilizer completes these circular systems, returning nutrients to agricultural production (Valentine, 2016). Valentine (2016) documented environmental sustainability improvements including 30-40% reductions in carbon footprint compared to conventional waste management approaches, along with significant improvements in soil health indicators.

Rendering facility integration further reinforces closed-cycle systems by ensuring comprehensive resource recovery from animal production (Wang et al., 2017). These integrated approaches enhance resource independence and operational resilience by minimizing reliance on external inputs while maximizing value recovery from all components of the livestock value chain.

Economic Impacts

The development of regional industrial symbiosis networks demonstrates significant economic potential for the livestock sector (Chertow & Park, 2016). These collaborative networks enable resource sharing, infrastructure optimization, and waste valorization across multiple facilities and sectors. Chertow and Park (2016) reported increases in operating profitability ranging from 8-25% for livestock facilities participating in well-established industrial symbiosis networks.

Value chain optimization through systematic implementation of circular principles creates competitive advantages for participating operations (Yazan et al., 2016). The enhanced resource efficiency and reduced waste management costs translate directly to improved economic performance, particularly in regions with stringent environmental regulations or high resource costs.

The transition toward circular economy models within the livestock sector contributes to local economic development through job creation, enhanced competitiveness, and improved environmental performance (Zhang et al., 2015). Zhang et al. (2015) documented cases where industrial symbiosis implementation in livestock-dominant regions created secondary industries and enhanced local economic resilience.

Table 1 synthesizes the identified opportunities and corresponding benefits across the four symbiotic relationship areas, providing a comprehensive framework for understanding industrial symbiosis potential in the livestock sector. This structured approach reveals that beyond environmental benefits, industrial symbiosis practices deliver tangible economic advantages, creating compelling incentives for sector-wide adoption.

Symbiosis Relationship Area	Identified Opportunities	Potential Benefits
Waste-to-Resource Conversion	• Biogas production with manure management systems • Organic fertiliser production • Conversion of slaughterhouse by-products into animal feeding	• Reduction in energy costs • Reduction in waste management costs • Reduction in feed costs
Inter-sectoral Integration	• Use of agricultural by-products as feed • Co-operation with leather and wool processing plants • Utilisation of food industry wastes	• Increased resource efficiency • New sources of income • Operational cost reduction
Closed Cycle Systems	• Integrated biogas plants • Conversion of digested waste into fertiliser • Rendering facility integration	• Environmental sustainability • Reduction in carbon footprint • Resource independence
Economic Impacts	• Regional industrial symbiosis networks • Value chain optimisation • Circular economy model	• Increase in operating profitability • Competitive advantage • Local economic development

Table 3.1 Environmental impact of life cycle of 10.000 tons of OMW, using ReCiPe 2016 Midpoint (H) methodology.

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Business models fostering industrial symbiosis and a circular economy: a bibliometrics approach

Ina Keçi
University of Seville, Seville, Spain & European University of Tirana, Tirana, Albania
inakec@alum.us.esi
ina.keci@uet.edu.al

Besa Shahini
University of Tirana, Tirana, Albania
besashahini@feut.edu.al; besa.shahini@unitir.edu.al

Ani Mbrica
Tirana Business University, Tirana, Albania
ani.mbrica@tbu.edu.al

ABSTRACT

Business model concepts incorporate many pioneering insights within the transformative context of industrial symbiosis philosophy and the circular economy perspective. The transition to industrial symbiosis and circular economy practices demands fundamental changes in how businesses create and capture value, yet existing business models remain deeply established in linear economic thinking. Current models fail in three critical ways: they lack mechanisms for coordinating complex multi-stakeholder networks, struggle to distribute value among ecosystem partners equitably, and cannot effectively manage the bidirectional resource flows essential for industrial symbiosis. While scholarly literature has extensively documented these limitations, a crucial knowledge gap exists in understanding how business models must evolve to overcome these challenges and successfully enable industrial symbiotic relationships. This research addresses this gap by systematically analysing how business model innovations can catalyse the transition to industrial symbiosis and circular economic practices.

Within this dynamic framework, scholarly research and studies methodically differentiate between innovative circular business model strategies and the persuasive value logic approach, clarifying how these strategies can significantly influence and redefine the core components of business models. Moreover, integrating ecosystem partnerships into this discourse introduces the essential aspect of coordination, emphasises the crucial importance of stakeholder considerations, and highlights the indispensable necessity of networks in fostering robust synergies. Concurrently, the value chain framework aims to revolutionise traditional linear business models by transforming them into innovative circular paradigms, examining two transformative dimensions: shifting from an intra-organizational perspective to a broader organisational environment and transitioning from an individual business unit to a comprehensive corporate vision. This research is carefully constructed to critically analyse the existing theoretical framework and discover emerging business models that advance industrial symbiosis and a prosperous circular economy. By employing comprehensive scientific databases, this study utilises a bibliometric approach to examine the evolution of business model concepts in response to the urgent demands for more sustainable value creation. It investigates how pioneering innovations and transformations within existing business models can act as catalysts for industrial symbiosis and the circular economy while identifying the key factors that facilitate the development of novel, emergent business models. Ultimately, an innovative research agenda is formulated, grounded in rigorous quantitative analysis of the current body of knowledge.

KEYWORDS
Sustainable Business Models - Circular Economy - Industrial Symbiosis Network - Business Model Innovation - Bibliometrics

INTRODUCTION

In recent years, a shift toward more sustainable production and consumption systems has gained notable momentum, with circular economy (CE) principles being increasingly seen as a solution to resource scarcity and environmental degradation (Korhonen et al., 2018). Under the CE framework, industrial symbiosis (IS) has become a pivotal strategy that allows industries to exchange materials, energy, water, and by-products to achieve mutual economic and environmental advantages (Chertow, 2000). Although interest in IS is rising, its adoption is still limited and often confined to eco-industrial parks or specific industrial clusters (Domenech et al., 2019). For IS to be successfully implemented, the development of suitable business models that enable resource exchanges and add value for participating entities is crucial (Fraccascia et al., 2019). These models must overcome several challenges, such as transaction costs, regulatory obstacles, and technological hurdles. Over the past decade, the academic literature on business models supporting IS and CE has grown significantly, indicating heightened interest among researchers, practitioners, and policymakers. Nevertheless, this literature is dispersed across various fields, including industrial ecology, business management, environmental science, and engineering. Consequently, an integrated understanding of the field's structure, evolution, and significant contributions is vital to steer future research and practice.

This paper intends to systematically review the literature on business models that promote IS and CE through bibliometric analysis. By analysing publication trends, citation networks, and thematic clusters within the Scopus database, we aim to address the following research questions:

- R.Q.1 How has the literature on business models for IS and CE progressed?
- R.Q. 2 Which countries, institutions, and authors have impacted this sector most?
- R.Q. 3 What are the literature's primary thematic clusters and research directions?
- R.Q. 4 What key conceptual frameworks and implementation methods have been proposed for IS business models?

The paper is organized as follows: Section 2 outlines the methodology of the bibliometric analysis; Section 3 details the analysis results, including publication trends, geographical distribution, and thematic clusters; Section 4 discusses the implications of the findings for theory and practice; and Section 5 concludes with a summary of contributions and future research recommendations.

METHODOLOGICAL APPROACH

Analysis of Bibliometric Data

Bibliometric analysis is a quantitative approach that applies statistical methods to publications to identify patterns in scientific literature (Donthu et al., 2021). It allows researchers to map the knowledge structure, evolution, and relationships within a research field based on publication metadata such as authors, citations, keywords, and abstracts (Zupic & Čater, 2015). Bibliometric methods are widely employed to provide objective overviews of research domains and to identify influential works, authors, and emerging trends. We employed performance analysis and science mapping techniques (van Eck & Waltman, 2014). Performance analysis focused on publication metrics, such as publication counts, citation analysis, and geographical distribution. Science mapping sought to visualize the intellectual structure of the field through keyword co-occurrence.

Data Collection

We systematically searched the Scopus database, recognized for its comprehensive coverage of peer-reviewed literature across disciplines. The search strategy aimed to capture publications related to business models within the context of IS and CE. The following search query was used: TITLE-ABS-KEY ((“business model*” OR “value creation” OR “value proposition”) AND (“industrial symbiosis” OR “industrial ecology” OR “circular economy” OR “industrial metabolism” OR “eco-industrial” OR “resource exchange” OR “by-product exchange” OR “waste valorisation”))

The search focused on English-language documents published from 2010 to 2024. The initial search produced 3,044 documents, to which exclusion and inclusion criteria were applied. The documents were then screened for relevance based on titles, abstracts, and missing information. After excluding documents that did not directly address business models in the context of IS or CE, the final dataset included 437 documents.

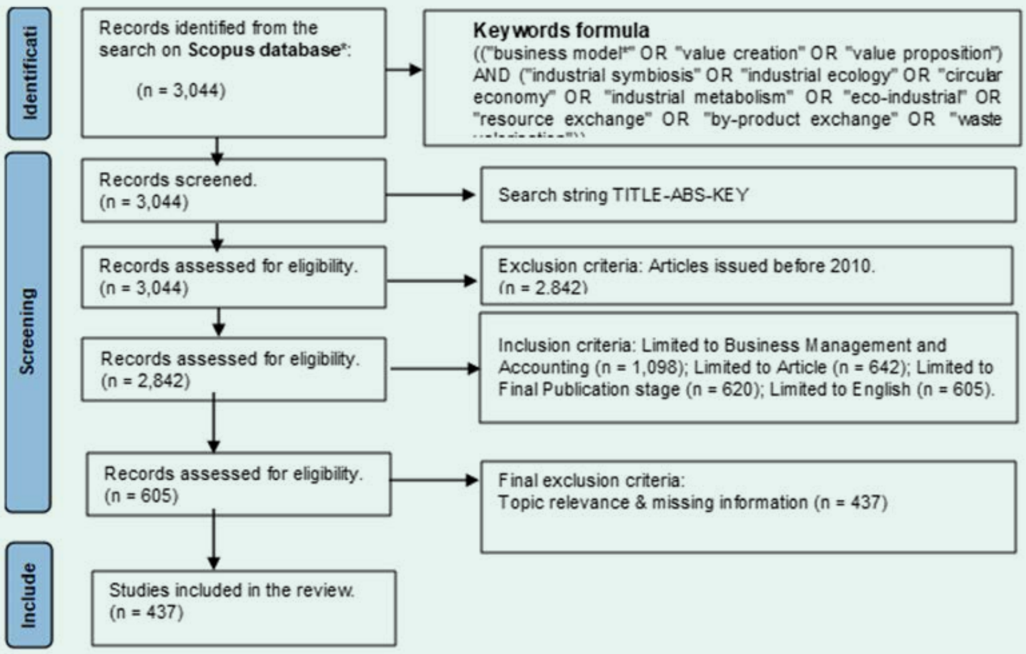

Figure 1 Adapted from (Rao et al., 2024): from linear to circular

Data Analysis

The bibliometric analysis was conducted using VOS viewer (version 1.6.18), a software tool for creating, visualizing, and exploring bibliometric maps (van Eck & Waltman, 2010). The following analyses were performed: (1) Performance analysis: Examination of publication trends over time, top-contributing countries, institutions, authors, and highly cited publications; (2) Co-citation analysis: Identification of intellectual foundations by analysing frequently cited references; (3) Keyword co-occurrence analysis: Mapping research themes based on the co-occurrence of author keywords. Additionally, we used R software (bibliometrics package) for supplementary analyses, including calculating collaboration indexes and creating country collaboration networks (Aria & Cuccurullo, 2017).

RESULTS

Publication Trends and Distribution

Figure 2 illustrates the annual number of publications on business models for IS and CE from 2010 to 2024. The graph indicates minimal publication activity from 2010 to 2016 (fewer than 10 articles per year), followed by a sharp increase from 2016 to 2017, with continued growth to over 100 publications annually by 2024. The field has seen substantial growth, with a noticeable acceleration since 2016. This growth coincides with heightened global focus on CE principles, as indicated by policy initiatives such as the European Union's CE Action Plan launched in 2015.

Figure 3 demonstrates the country's production over time. The geographical distribution of publications reveals that European countries dominate research in this field. As illustrated in Figure 2, the United Kingdom shows the steepest growth trajectory, reaching approximately 220 publications by 2024, followed closely by Italy with around 230 publications. The Netherlands and Sweden also demonstrate significant research output, with approximately 150 and 120 publications by 2024. Brazil has made notable contributions among non-European countries with about

110 publications by 2024. All countries show minimal publication activity before 2016, followed by accelerated growth, with Italy and the UK displaying particularly sharp increases after 2020. This European dominance reflects the region's strong policy focus on circular economy and industrial symbiosis.

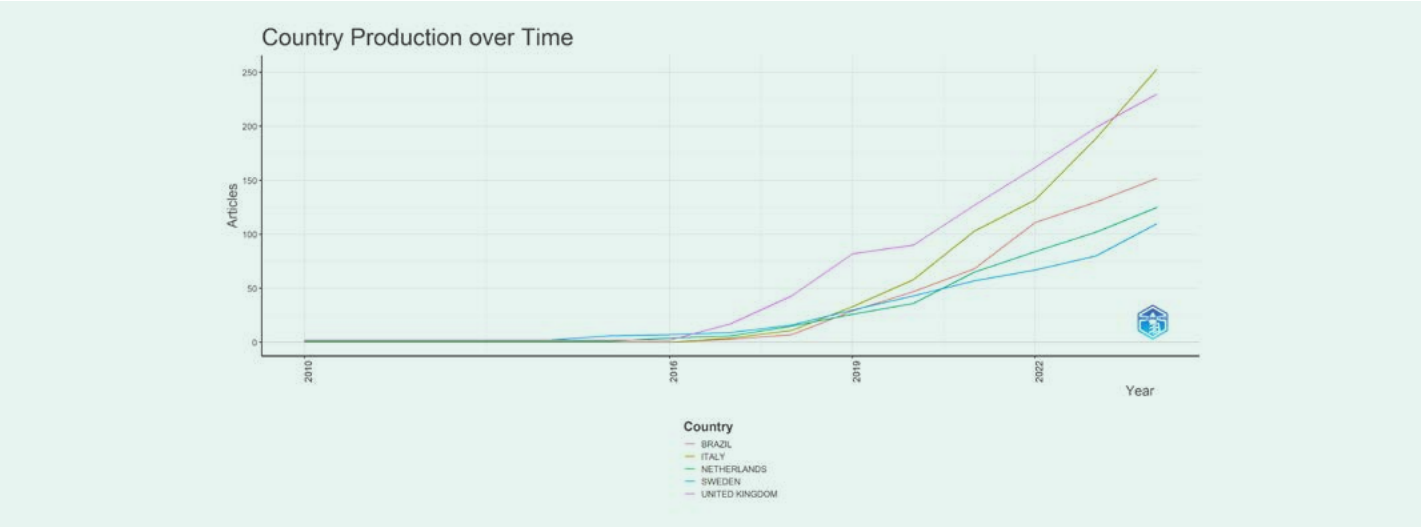

Figure 3 Country Production over Time

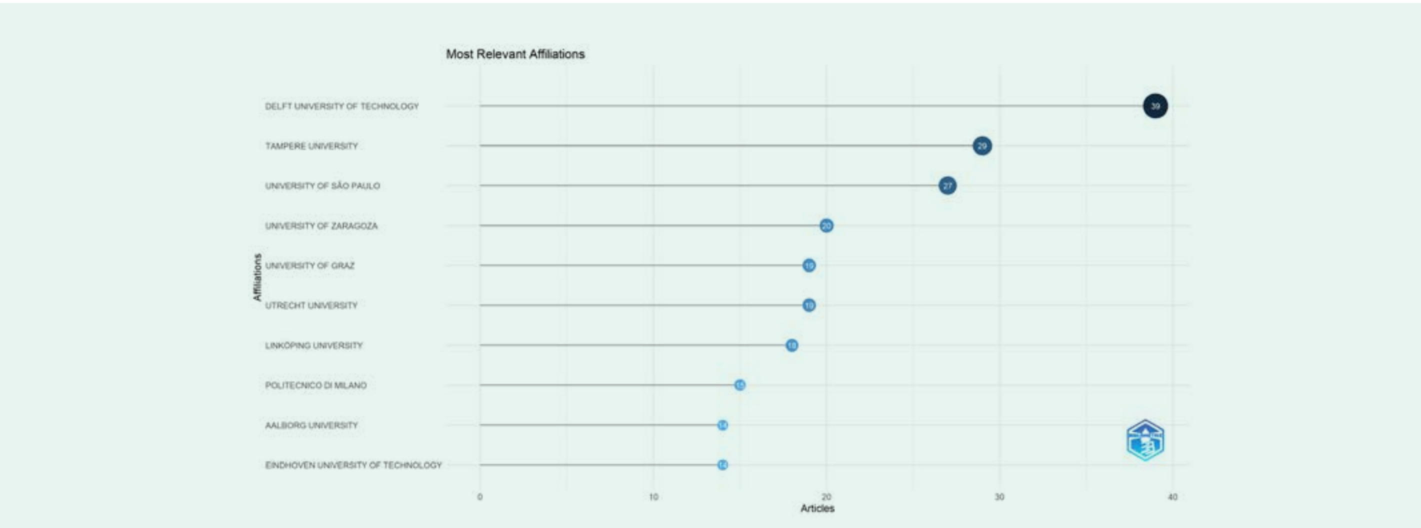

Figure 4 Most relevant affiliations

Delft University of Technology (Netherlands) leads with 39 publications at the institutional level, significantly ahead of other institutions. Tampere University (Finland) holds second place with 23 publications. The University of São Paulo (Brazil) follows in third position with 21 publications, representing the highest contribution from a non-European institution. The University of Zaragoza (Spain) has 20 publications. The University of Graz (Austria) and Utrecht University (Netherlands) have contributed 19 publications each. Linköping University (Sweden) has produced 18 publications. Politecnico di Milano (Italy) has 15 publications. Aalborg University (Denmark) and Eindhoven University of Technology (Netherlands) have 14 publications. The graph reveals that European institutions dominate the research landscape in this field, with 8 out of the 10 top contributors being European. The Netherlands is well-represented, with three universities in the top 10 (Delft, Utrecht, and Eindhoven). Additionally, including the University of São Paulo indicates Brazil's significant contribution to this research domain, supporting the previous graph showing Brazil as a significant non-European contributor. This institutional data complements the country-level analysis and confirms the strong European leadership in research on circular economy and industrial symbiosis business models.

Citation Analysis

The citation analysis output, presented in Figure 5, identified the most influential publications in the field. Murray A. (2017) published in "Business Ethics" has received the highest number of citations at approximately 1,950 global citations, making it the most influential document in this field by a significant margin. Geissdoerfer M. (2016) published in "Journal of Cleaner Production" is the second most cited with around 825 citations. Two documents tied for third place with approximately 725 citations each: Lieder M. (2017) published in "Business Strategy and Environment" and Urbinati A. (2017) published in "Journal of Cleaner Production". The remaining six documents have between 350-500 citations each: Tura N. (2019) in "Journal of Cleaner Production" (~500 citations); De Angelis R. (2018) in "Production Planning & Control" (~480 citations); Centobelli P. (2020) in "Business Strategy and Environment" (~450 citations); Bressanelli G. (2019) in "International Journal of Production Research" (~420 citations); Despeisse M. (2017) in "Technological Forecasting and Social Change" (~400 citations); Chauhan C. (2022) in "Technological Forecasting and Social Change" (~380 citations). Several patterns emerge from this data: Most influential papers were published between 2016-2020, with the most recent highly-cited paper from 2022; Journal of Cleaner Production appears multiple times, indicating its importance as a venue for this research; Business Strategy and Environment and Technological Forecasting and Social Change each appear twice; The top paper has more than twice as many citations as the second-most cited work, suggesting it is a seminal work in the field. The graph shows the importance of both business and environmental journals in this interdisciplinary research area.

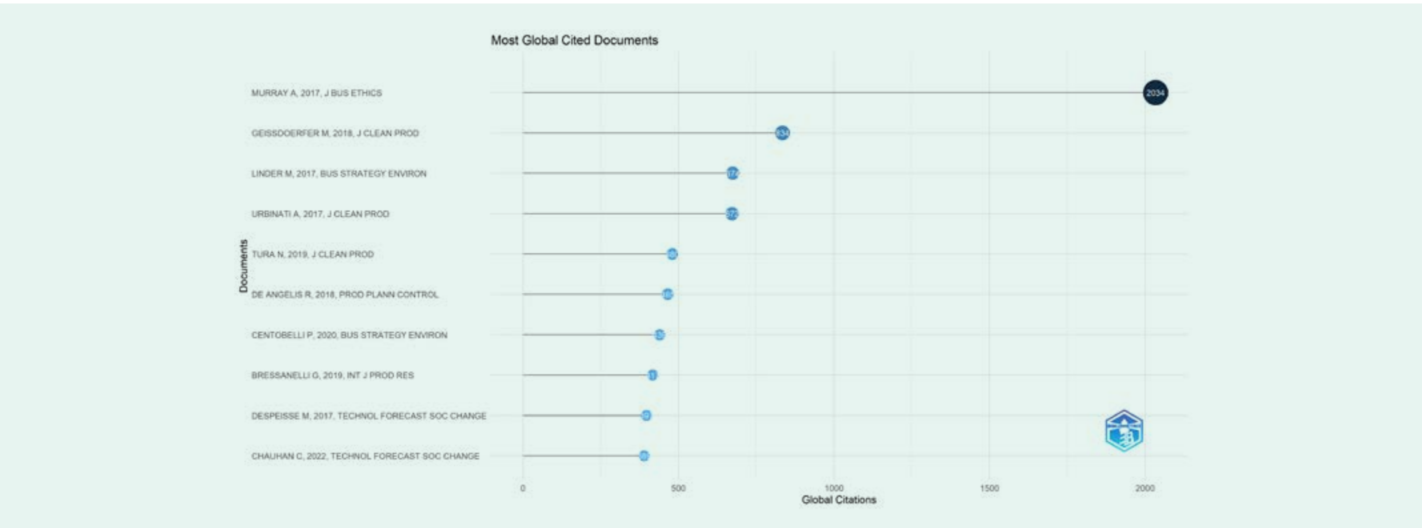

Figure 5 Most Global Cited Documents

Thematic Analysis

The keyword co-occurrence analysis revealed the intellectual structure of the field. Figure 5 presents a network visualization of the most frequent keywords, with node size indicating frequency and links representing co-occurrence relationships. The visualization shows CE as the dominant central node, with sustainable development, circular business models, and business model innovation as other prominent nodes. Five main thematic clusters can be identified: (1) Business and Strategic Approaches (the green cluster): This cluster focuses on strategic implementation aspects with keywords including business, corporate strategy, industrial technology, stakeholder, eco-innovation, and industrial performance. (2) Product Design and Engineering (the red cluster): This cluster addresses the technical aspects of circular implementation with keywords like product design, industrial engineering, production engineering, eco-design, circular strategies, and electronics industry. (3) Circular Business Models (the blue cluster): This central cluster connects business models with circular economy principles, featuring keywords such as circular business models, business model innovation, commerce, and social aspects. (4) Service-Oriented Approaches (the orange cluster): This cluster highlights service-based solutions with keywords including product-service system, reuse, repair, and Internet of Things. (5) Implementation Frameworks and Barriers (the purple/cyan clusters): These interconnected clusters explore implementation challenges with keywords like supply chain, barriers, energy efficiency, planning, and environmental protection. The visualization demonstrates how CE is the conceptual core connecting various research domains from business models to technical implementation approaches.

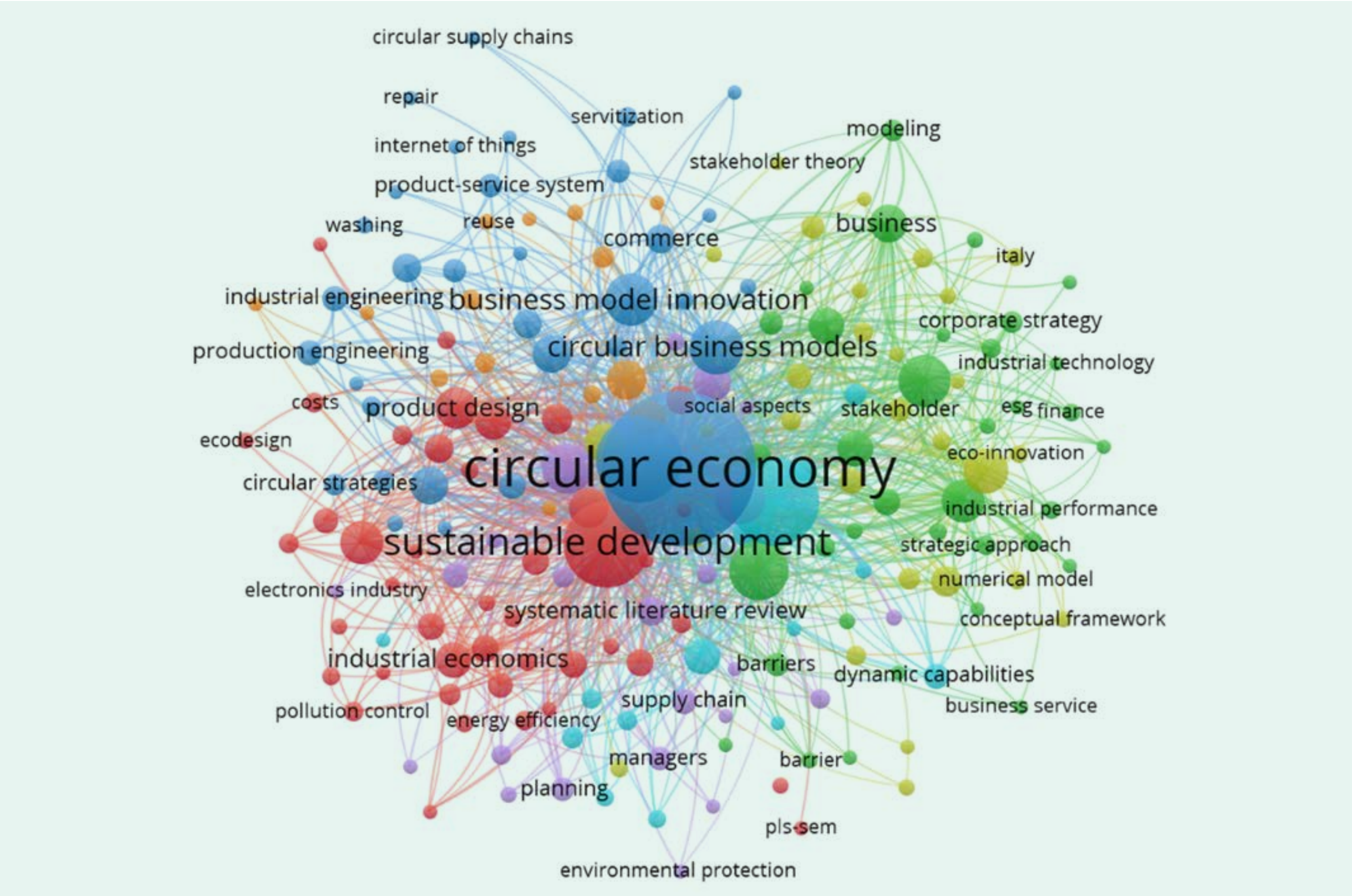

Figure 6 Co-occurrence analysis

Conceptual Frameworks and Implementation Approaches

The in-depth analysis of the literature unveiled a host of pivotal conceptual frameworks and dynamic implementation approaches for business models in IS: Facilitated IS: This groundbreaking approach underscores the vital role of intermediary organizations or platforms in both identifying and unleashing opportunities for resource exchange (Paquin & Howard-Grenville, 2012). Notable examples include the UK's highly successful National Industrial Symbiosis Programme (NISP) and various eco-industrial park initiatives emerging across the globe. Digital Platforms for Resource Exchange: Numerous studies assert that innovative digital platforms are revolutionizing industrial symbiosis by significantly reducing transaction costs and alleviating information asymmetries (Fraccascia & Yazan, 2018). These platforms exert transformative influence at local, regional, and national levels, seamlessly connecting waste generators with potential users. Product-Service Systems (PSS): This revolutionary concept focuses on the transition from mere product sales to the provision of services, compelling manufacturers to prioritize durability, repairability, and recyclability (Tukker, 2015). PSS models are particularly beneficial for capital-intensive equipment and consumer electronics. Waste-as-a-Resource Business Models: These visionary models dedicate themselves to extracting value from waste streams through various recovery and valorisation processes (Schroeder et al., 2019). They typically encourage collaborations among waste generators, processors, and end-users, fostering a mutually beneficial relationship. Collaborative Value Creation Networks: This pioneering approach emphasizes the crucial importance of collaborative networks and ecosystems in advancing circular business models (Brown et al., 2021). It recognizes that individual organizations often lack the necessary capabilities and resources to implement circular solutions independently.

DISCUSSION

Evolution of Research Focus

Our comprehensive bibliometric analysis reveals a striking evolution in research trends over the past decade. In the early period from 2010 to 2015, scholarly works predominantly focused on establishing conceptual foundations and elaborating on theoretical frameworks, with a strong emphasis on the intricate relationships within industrial ecology and the fundamental principles of cleaner production. However, since 2016, there has been a pronounced shift towards addressing the complex challenges of practical implementation, pioneering business model innovations, and leveraging digital technologies to advance IS. This transformation underscores the field's maturation, marking a change where researchers are progressively transitioning from the critical task of establishing theoretical underpinnings to tackling significant practical barriers that hinder implementation. Now, more than ever, recent publications emphasize a critical understanding that technological solutions, when considered in isolation, fall short, and that developing robust business models and governance mechanisms is essential for scaling IS initiatives beyond the limits of pilot projects and traditional eco-industrial parks.

Integration of Industrial Symbiosis and Circular Economy Concepts

The analysis uncovers a robust and evolving synergy between the foundational concepts of IS and CE within academic discourse. Historically, IS has been deeply rooted in industrial ecology; however, contemporary scholarly works are increasingly reframing it as a forward-thinking strategy to embody circular economy ideals on an inter-organizational scale. This dynamic convergence is brilliantly showcased by the emergence of innovative terms such as "circular industrial systems" and "circular supply chains," which ingeniously blend and harmonize the essence of both ideologies. Nevertheless, our detailed investigation highlights a noticeable trend. While the narrative surrounding business models in the literature predominantly champions the overarching reach of the CE, it tends to sideline IS, signalling a substantial opportunity for targeted research endeavours. Such investigations could drive the development of business model frameworks specifically tailored to enhance resource exchange processes among organizations, elevating both efficiency and sustainability.

Barriers and Enablers

The literature consistently highlights a range of significant barriers to implementing business models designed for industrial symbiosis, covering various economic challenges, such as dauntingly high transaction costs, unpredictable returns on investment, and a notable lack of robust financing mechanisms essential for advancing circular initiatives. At the same time, entrenched regulatory hurdles remain, with waste regulations that significantly hinder the transformative reclassification of by-products into valuable resources, exacerbated by conflicting policy objectives across different governance levels. Moreover, informational barriers are particularly evident, characterized by a severe lack of awareness about lucrative resource exchange opportunities, insufficient information regarding material compositions, and widespread confidentiality concerns. The technological arena is also challenged, dealing with technological incompatibilities and ongoing quality issues related to secondary materials, intensified by an evident lack of standardization. Social and organizational dynamics are similarly burdened with obstacles, including a lack of trust among potential symbiotic partners, deep-seated organizational resistance to change, and limited inter-organizational collaboration capabilities. Concurrently, the literature identifies a set of enablers that are crucial for the successful development of business models: (1) Intermediary organizations that skilfully facilitate connections and build trust among potential symbiosis partners; (2) Innovative digital platforms that effectively reduce transaction costs and address information asymmetries; (3) Supportive policy frameworks that strongly incentivize resource efficiency while removing regulatory barriers to by- product exchange; (4) Advanced collaborative governance arrangements that actively engage a wide range of stakeholders in developing and implementing symbiotic relationships; (5) Forward- thinking financing mechanisms, utilizing circular economy funds, green bonds, and public- private partnerships as vehicles for transformation growth.

Research Gaps and Future Directions

The present analysis clarifies several research gaps and suggests promising avenues for future investigations in IS. Performance measurement: There is a lack of research on evaluating business models regarding their economic, environmental, and social performance in IS. Future research efforts should prioritize the development of comprehensive performance metrics and assessment frameworks. Scaling strategies: Numerous successful initiatives in IS are geographically confined to specific industrial parks or regions. Therefore, research is essential to devising strategies that expand these initiatives in larger industrial systems and supply chains. Digital enablers: Despite frequently citing digital technologies as facilitators, there is a limited body of empirical research examining the effectiveness of specific digital solutions, such as blockchain, AI, and IoT, in advancing IS. Future studies are encouraged to assess these technologies within real-world contexts empirically. Business model innovation processes: The existing literature predominantly addresses the outcomes (business model types) rather than the methodologies through which organizations develop and implement new business models for IS. Research focused on these processes could yield significant insights for practitioners. Cross-sectoral symbiosis: Current research mainly addresses symbiosis within manufacturing industries, with little attention to interactions between disparate sectors, such as agriculture, energy, manufacturing, and services. Future inquiries should investigate business models that facilitate cross-sectoral symbiosis.

CONCLUSION

This bibliometric analysis offers a comprehensive overview of the growing body of literature focused on revolutionary business models that drive the advancement of industrial symbiosis and the circular economy. Since 2016, this field has experienced significant growth, with European nations and renowned institutions leading the increase in research output. Five groundbreaking research clusters have emerged: innovative business and strategic approaches, cutting-edge product design and engineering, transformative circular business models, innovative service-oriented paradigms, robust implementation frameworks, and crucial barrier analysis. The analysis reveals a dynamic integration of IS and CE paradigms, with a heightened focus on the practical implementation challenges and the vital role business models play in facilitating effective resource exchanges. Pioneering conceptual frameworks and implementation methodologies have been developed, featuring facilitated IS, advanced digital platforms for resource exchange, product-service systems, innovative waste-as-a-resource business models, and collaborative value creation networks. Despite the growing body of literature, significant challenges remain in expanding IS practices beyond eco-industrial parks and preliminary pilot projects. Future research is essential to bridge gaps in performance measurement, scalability strategies, digital enablers, business model innovation processes, and cross-sectoral symbiosis enhancement. This study deepens the understanding of how visionary business models can underpin the monumental transition to sustainable industrial systems by highlighting emerging research trends, influential works, and novel research trajectories. The insights gained here serve as an invaluable guide for researchers, practitioners, and policymakers, directing the development and successful implementation of effective business models for IS and CE.

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Circular economy strategies for animal waste valorization in the livestock industry

Ulku Dagdelen
Atatürk University, Faculty of Agriculture, Department of Animal Science, Erzurum, Türkiye
ulku@atauni.edu.tr

Dogan Turkyilmaz
Atatürk University, Faculty of Agriculture, Department of Animal Science, Erzurum, Türkiye
dogan.turkyilmaz@atauni.edu.tr

ABSTRACT

The livestock sector holds significant potential for sustainable resource management through effective waste valorization and cross-sectoral integration. While waste generated by this sector is often perceived as an environmental burden, proper valorization strategies can transform it into valuable resources. Through the implementation of appropriate cross-sectoral integration strategies and business models, animal waste can be transformed into high-value products such as biogas, organic fertilizers, and feed additives. This study explores waste valorization opportunities through industrial symbiosis processes, focusing on establishing cross-sectoral relationships between livestock production and other industries to enable efficient waste utilization in diverse production systems. The research highlights the environmental, economic, and social benefits of innovative business models based on waste valorization approaches and cross-sectoral integration. Strategies that facilitate comprehensive waste valorization across different sectors and promote agricultural and industrial symbiosis are evaluated. Additionally, the study addresses policy and managerial approaches that support the adoption of these practices while proposing financial and technical solutions to enhance feasibility, particularly for small and medium-sized livestock enterprises. The findings demonstrate that systematic waste valorization through cross-sectoral integration can significantly enhance resource efficiency and reduce environmental impacts in the livestock sector. This study offers concrete recommendations for innovative industrial symbiosis applications aimed at enhancing the sustainability of agricultural production and underscores the importance of cross-sectoral collaboration in advancing circular economy initiatives.

KEYWORDS
Circular Economy - Industrial Symbiosis - Livestock Sector - Animal Waste Valorization
Sustainable Resource Management - Cross-sectoral Integration - Waste Management

INTRODUCTION

The livestock sector constitutes a vital component of global food systems, experiencing substantial growth driven by population expansion, urbanization, and rising incomes in developing economies (Herrero et al., 2020). Global meat production has more than quadrupled in the past fifty years, reaching approximately 340 million tonnes annually, while milk production has surpassed 850 million tonnes (FAO, 2022). This growth trajectory is expected to continue, with projections indicating a further 70% increase in demand for animal-derived protein by 2050 (Godfray et al., 2018). Despite its economic importance and contribution to food security, the livestock sector faces mounting scrutiny regarding its environmental footprint, particularly concerning resource utilization, biodiversity impact, and waste management challenges (Steinfeld et al., 2019).

A significant environmental concern emerging from intensified livestock production is the management of substantial quantities of animal waste. Globally, livestock operations generate approximately 13-15 billion tonnes of manure annually, alongside millions of tonnes of slaughterhouse by-products, processing residues, and mortalities (Bradford et al., 2020). Traditional waste management approaches—including direct land application, stockpiling, and disposal in landfills—have proven increasingly problematic as production intensifies and concentrates geographically (Loyon, 2018). These conventional practices contribute to a cascade of environmental impacts, including soil degradation, water eutrophication, atmospheric pollution, and public health risks through pathogen transmission (Hou et al., 2021).

The environmental implications of inadequate animal waste management are particularly concerning in the context of climate change. Livestock waste contributes significantly to greenhouse gas emissions through the release of methane (CH_4) during anaerobic decomposition and nitrous oxide (N_2O) from nitrogen transformation processes (Grossi et al., 2019). Recent research indicates that emissions from manure management account for approximately 10% of total livestock-related greenhouse gas emissions, with substantial variation across production systems and geographical regions (IPCC, 2022). Beyond climate impacts, ammonia volatilization from animal waste contributes to air quality degradation and acid deposition, while nutrient leaching and runoff lead to water quality impairment and ecosystem disruption (Bouwman et al., 2021).

In response to these challenges, policy frameworks advocating for sustainable waste management have emerged at international, national, and regional levels. The European Union's Circular Economy Action Plan, integrated within the European Green Deal, explicitly identifies agricultural waste, including livestock residues, as a priority area for intervention (European Commission, 2020). Similarly, China's 14th Five-Year Plan (2021-2025) emphasizes "zero-waste" agriculture with specific targets for livestock waste recycling (Chen et al., 2022). These policy frameworks reflect a paradigm shift from viewing animal waste as an environmental liability toward recognizing it as a valuable resource within circular bioeconomy systems (Stegmann et al., 2020).

The circular economy concept represents a transformative approach that challenges the traditional linear "take-make-dispose" economic model. As articulated by the Ellen MacArthur Foundation (2021), circular economy principles emphasize designing out waste and pollution, keeping materials in use, and regenerating natural systems. When applied to livestock production, these principles manifest through innovative approaches to waste valorization—the process of converting waste materials into products of higher value through biological, chemical, or physical transformations (Makkar, 2023). Rather than managing waste as a disposal problem, valorization creates regenerative cycles where outputs from one process become valuable inputs for another, mirroring natural ecosystems' functioning.

Applications of circular economy principles in the livestock sector encompass diverse valorization pathways. Anaerobic digestion technologies convert organic waste into biogas for renewable energy production and nutrient-rich digestate for soil amendment (Vasco-Correa et al., 2022). Composting systems transform solid manure into stable organic fertilizers that enhance soil health and carbon sequestration (Bernal et al., 2021). Innovative approaches include insect farming on organic waste to produce protein for feed applications (Chia et al., 2022), extraction of high-value compounds for pharmaceutical and nutraceutical applications (Zhang et al., 2021), and development of biomaterials from waste streams (Matthews et al., 2019). These approaches not only address waste management challenges but also generate economic benefits through cost savings, new revenue streams, and reduced dependency on external inputs (Zabaniotou, 2018).

Beyond technological innovations, circular approaches to animal waste management require fundamental shifts in governance structures, economic incentives, and social perceptions. Research indicates that successful implementation depends on integrated policy frameworks that align environmental regulations, agricultural support mechanisms, and renewable energy incentives (Termeer & Metze, 2019). Economic viability remains a central concern, with profitability varying significantly based on technology choice, scale of operation, local market conditions, and supporting policies (Pannell et al., 2020). Furthermore, social factors—including cultural attitudes toward waste utilization, knowledge transfer mechanisms, and stakeholder engagement processes—influence adoption rates and implementation outcomes (Burton & Paragahawewa, 2021).

Despite growing recognition of circular economy opportunities in livestock waste management, significant barriers to widespread implementation persist. Technical challenges include variability in waste composition, process control difficulties, and quality assurance concerns for derived products (Pardo et al., 2021). Economic barriers encompass high initial investment requirements, uncertain returns on investment, and competition with subsidized conventional alternatives (Yang et al., 2022). Institutional constraints include fragmented regulatory frameworks, insufficient technical support services, and inadequate market infrastructure for bio-based products (Lombardi & Laybourn, 2022). Addressing these challenges requires coordinated interventions across technical, economic, social, and policy dimensions.

This study explores the evaluation of animal waste within the context of the circular economy in the livestock sector through a multidisciplinary lens. It examines biotechnological and mechanical methods available for waste valorization, analyzing their technical performance, resource efficiency, and scalability across different production contexts. The economic, environmental, and social impacts of various valorization strategies are systematically assessed, employing life cycle thinking to identify synergies and trade-offs between sustainability dimensions. Additionally, the study investigates current policy frameworks across major livestock-producing regions, identifying regulatory enablers and barriers to circular transitions.

By integrating insights from waste management science, agricultural systems analysis, environmental assessment, and policy studies, this research provides a comprehensive framework for understanding how circular economy principles can transform livestock waste management practices. The findings will contribute to the growing body of knowledge on sustainable livestock production while offering practical guidance for producers, technology developers, policymakers, and other stakeholders seeking to implement circular approaches. Ultimately, the study contends that strategic management of animal waste as a valuable resource represents a critical leverage point for enhancing environmental sustainability, economic resilience, and social acceptability of livestock production systems in an increasingly resource-constrained world.

METHODOLOGY

This study employs a multidisciplinary approach to assess the valorisation of animal waste within the framework of circular economy principles. The methodology integrates three complementary components: a comprehensive literature review, stakeholder analysis, and sustainability assessment, each contributing to a holistic understanding of livestock waste management and utilization strategies.

Literature Review

A systematic literature review was conducted to evaluate existing technologies, processes, and strategies for animal waste valorization. The review encompassed peer-reviewed journal articles, industry reports, and policy documents published between 2018 and 2023, with particular emphasis on recent advancements in waste management technologies. The search strategy utilized multiple academic databases including Web of Science, Scopus, and ScienceDirect, employing relevant keywords and Boolean operators to identify pertinent literature.

The review focused on four primary categories of waste valorization approaches. First, biological treatment methods were examined, including anaerobic digestion, composting, hydrothermal processing, and enzymatic hydrolysis techniques that harness microbial activity to transform organic matter into valuable products. Second, thermochemical processes were evaluated, with emphasis on pyrolysis, gasification, and hydrothermal carbonization methods that utilize heat and pressure to convert waste into energy carriers and carbonaceous materials. Third, nutrient recovery techniques were analyzed, including biofertilizer production methodologies and nutrient extraction protocols designed for sustainable soil management. Fourth, innovative applications of waste-derived materials were investigated, such as insect farming for alternative protein production and bioplastics manufacturing from waste substrates.

Furthermore, a comprehensive analysis of case studies from diverse geographical regions was conducted to identify best practices, implementation challenges, and contextual factors influencing success. These case studies were systematically categorized according to geographical location, scale of implementation, technological approach, and documented outcomes. This facilitated cross-case comparison and identification of transferable insights across contexts. The literature review provided a foundational understanding of the technological, economic, and environmental aspects associated with animal waste valorisation, while identifying knowledge gaps warranting further investigation.

Stakeholder Analysis

To gain insights into the practical feasibility and adoption challenges of circular economy strategies in livestock waste management, a multi-dimensional stakeholder analysis was conducted. This analysis integrated qualitative and quantitative methods to capture the perspectives, interests, and constraints of various actors within the waste management ecosystem.

In-depth interviews were conducted with 28 key stakeholders, including livestock farmers (n=12), waste management professionals (n=6), policymakers (n=5), and academic researchers specializing in agricultural sustainability (n=5). The interviews followed a semi-structured protocol designed to elicit detailed perspectives on technological adoption barriers, economic feasibility, regulatory compliance challenges, and potential incentives for implementing circular economy practices. These interviews were recorded, transcribed, and analyzed using thematic content analysis to identify recurring patterns and divergent viewpoints.

Complementing the interviews, a structured survey was administered to a broader sample of 145 stakeholders across the agricultural waste management sector. The survey employed both Likert-scale items and open-ended questions to quantify stakeholder attitudes toward various valorization technologies, perceived implementation barriers, and potential facilitating factors. Statistical analysis of survey data provided quantitative insights that complemented the qualitative interview findings.

Three regional workshops and four focused group discussions were organized, bringing together diverse stakeholders to facilitate dialogue on industry challenges, regulatory constraints, and potential incentives for adopting waste valorization techniques. These sessions were facilitated using participatory methods designed to encourage collaborative problem-solving and knowledge exchange. Discussions were documented through detailed notes and visual mapping of key themes and relationships.

Additionally, a comparative analysis of existing waste management policies and incentive programs in five different regions was conducted to assess their effectiveness in promoting circular economy practices. This analysis involved document review, consultation with policy experts, and examination of implementation outcomes where available. The integration of qualitative and quantitative data from these multiple sources yielded a comprehensive stakeholder analysis that provided valuable insights into economic viability, regulatory compliance mechanisms, and practical implementation challenges faced by different actors in the livestock industry.

Sustainability Assessment

To evaluate the environmental, economic, and social impacts of different valorization strategies, a tripartite sustainability assessment was conducted using complementary methodological approaches. This integrated assessment framework enabled comprehensive evaluation of sustainability dimensions across various waste management scenarios.

Life Cycle Assessment (LCA) was employed to quantify the environmental footprint of various animal waste processing technologies. The assessment followed ISO 14040/14044 standards and utilized a functional unit based on the management of one metric ton of animal waste. System boundaries encompassed all processes from waste collection to final product utilization, including transportation, processing, and application phases. Key environmental impact categories analyzed included greenhouse gas emissions, acidification potential, eutrophication potential, water usage, and energy consumption. The LCA was conducted using SimaPro software with the Ecoinvent database, supplemented by primary data collected from operational facilities where available.

Cost-Benefit Analysis (CBA) was utilized to examine the financial feasibility of each valorization strategy. The analysis incorporated initial investment costs, operational expenses, maintenance requirements, and potential revenue generation from valorized products. Net Present Value (NPV), Internal Rate of Return (IRR), and payback period were calculated for each technology scenario, with sensitivity analysis performed to account for market price fluctuations and technology performance variations. The CBA employed a 15-year time horizon with appropriate discount rates to reflect the long-term nature of infrastructure investments.

Social Impact Assessment (SIA) was conducted to evaluate the implications of different waste valorization approaches on rural livelihoods, job creation, community well-being, and social acceptance. The assessment employed a mixed-methods approach combining quantitative indicators of employment generation and income effects with qualitative analysis of community perceptions and quality of life impacts. Data collection included structured interviews with community members, employment records analysis, and assessment of skills development requirements for various technologies.

The results from these three assessment methods were synthesized using a multi-criteria decision analysis framework that enabled integrated evaluation of trade-offs between environmental, economic, and social dimensions. This approach facilitated the identification of valorization strategies that offered optimal sustainability performance across multiple criteria, while accounting for contextual factors and implementation constraints.

The integration of these three methodological components—literature review, stakeholder analysis, and sustainability assessment—constitutes a comprehensive framework for understanding how circular economy strategies can enhance sustainability in the livestock sector. This methodological approach acknowledges the complex, multidimensional nature of waste management challenges and provides a robust foundation for identifying evidence-based, contextually appropriate solutions for animal waste valorization within circular economy frameworks.

RESULTS

The findings of this study demonstrate that circular economy strategies for the valorisation of animal waste offer substantial environmental and economic benefits while promoting resource efficiency in the livestock sector. A notable environmental advantage is the mitigation of greenhouse gas emissions, particularly methane and nitrous oxide, which are recognised as significant contributors to climate change. The utilisation of anaerobic digestion and composting has been demonstrated to mitigate these emissions by converting organic waste into bioenergy and nutrient-rich fertilisers. Furthermore, the utilisation of biofertilisers derived from manure and slaughterhouse by-products has been shown to enhance soil health by increasing organic matter content and reducing dependency on synthetic fertilisers. This, in turn, has the effect of minimising nutrient runoff, a key factor in water pollution, thus improving overall water quality.

From an economic perspective, the adoption of circular economy strategies has been demonstrated to generate new revenue opportunities for livestock farmers while concurrently reducing waste management costs. The production of biogas, biofertilizers, and alternative animal feed ingredients allows farmers to generate additional income, making waste management not only a sustainability effort but also a financially viable practice. Case studies indicate that the return on investment for small-scale biogas plants can be recouped within five to seven years, contingent on the availability of subsidies and prevailing market conditions. Furthermore, the cost savings associated with waste valorisation, such as reduced landfill fees and lower fertilizer expenses, contribute to long-term financial benefits for livestock operations. Furthermore, the increasing demand for sustainable agricultural inputs, such as bio-based fertilisers and organic feed, represents a growing market opportunity for products derived from livestock waste.

Beyond the economic and environmental advantages, strategies for a circular economy have been shown to enhance resource efficiency and drive innovation in the field of agricultural waste management. The conversion of manure and slaughterhouse residues into feedstock for insect farming, particularly black soldier fly larvae, has emerged as a promising solution to address the increasing demand for protein in animal feed while reducing reliance on conventional soy-based feed sources. Furthermore, the production of biogas not only provides a renewable energy source but also generates digestate, a nutrient-rich by-product that can be used as an organic soil amendment. When integrated with precision agriculture techniques, these bio-based fertilisers contribute to more efficient nutrient management, optimising soil fertility and reducing environmental footprints.

However, the widespread adoption of circular economy strategies in animal waste management is limited by several barriers. Regulatory and policy constraints, including inconsistent waste management regulations and complex permitting processes, create obstacles for farmers and industry stakeholders seeking to implement sustainable waste valorisation techniques. Financial constraints, particularly for small and medium-sized livestock farms, are also a significant barrier to adoption, as the high initial costs of technologies such as biogas plants, composting systems and insect farming facilities are challenging to invest in. A further complicating factor is the lack of awareness and technical knowledge among farmers, which hinders the adoption of these practices. This emphasises the need for capacity-building initiatives and knowledge-sharing platforms. The issue is further complicated by the uncertainty of market demand for bio-based fertilisers and alternative feed ingredients, coupled with inadequate infrastructure for waste collection and processing.

The results of the study indicate that strategies for the circular economy in the field of animal waste valorisation offer considerable potential to enhance sustainability in the livestock sector. This is achieved by reducing environmental impact, generating economic benefits and promoting resource efficiency. Nevertheless, it is imperative to acknowledge the necessity of surmounting regulatory, financial, and informational impediments to ensure the efficacious implementation of these strategies. The successful implementation of these strategies will be facilitated by policy incentives, financial support mechanisms, and targeted educational programmes.

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12

Antibiotic use in poultry production: agent based industrial symbiosis with dependencies and dynamics of a patron-client relationship

Muhammad Asaduzzaman
Institute of Health and Society, University of Oslo, Oslo, Norway
zamansohag08@gmail.com

ABSTRACT

The use of antibiotics in animal food production poses a significant risk of antimicrobial resistance transmission through the food chain. In low- and middle-income countries like Bangladesh, the commercial poultry sector primarily consists of small-scale producers who depend on credit from poultry dealers to purchase day-old chicks and feed. These dealers, who also supply and promote antibiotics, are key actors in a system characterized by informal, reciprocal relationships—a hallmark of Industrial Symbiosis. This interconnected network of actors, driven by mutual dependencies and the flow of resources such as credit, feed, and antibiotics, underpins poultry production in unregulated systems. This study explores these interdependencies within the Industrial Symbiosis framework to uncover the social and contextual determinants of antibiotic use in resource-limited settings.

KEYWORDS
Patron-Client Relationship - Antibiotic Use - Poultry Value Chain - Industrial Symbiosis Business Model - Dependencies and Dynamics

INTRODUCTION

Demand for animal sourced protein for human consumption has increased from 7 grams to 25 grams per capita per day between 1960 and 2013 (Van Boeckel et al., 2015) due to increased access to information on meeting nutritional requirements and higher purchasing ability in low and middle-income countries (LMICs) (Tilman et al., 2011).

In Bangladesh, approximately 37% of all animal protein meat consumption originates from poultry (Hamid et al., 2017). Small-scale commercial broiler poultry farms, defined as those having less than 5,000 birds in each batch (Begum et al., 2013), comprise 81% of the commercial poultry sector (Hamid et al., 2017) providing about 78% of the total poultry meat supply in Bangladesh (Bangladesh Bureau of Statistics, 2017). The small-scale broiler farming usually conducted around farmer's homestead with a close system rudimentary structure using available low cost materials, where farmers use family labor and utilize own backyard land (Islam, Takashi & Chhabi, 2010).

Small-scale commercial poultry farmers have limited working capital, poor access to formal credit and also have limited information on market opportunities or new technologies. For example, small-scale commercial poultry farms cannot afford to buy day-old chicks and poultry feed directly from the hatcheries or feed manufacturing companies and thus depend on dealers or agents who provide a credit system (Shah et al., 2006). This credit system in turn provides social networks and relationships, described in social capital theory, through which information can flow. For example these networks can convey useful information about opportunities and choices and information about market needs (Liñán and Santos, 2007; Lin, 2017)(Lin, 1999).

'Social networks' can also affect decision making, influenced through the credit system (Liñán and Santos, 2007). In the entire process of the food value chain, there are multilevel relationships among different actors which can be defined as social capital captured in the form of social relationships with expected returns, either formal or informal, generated by individuals in their interaction with other individuals trying to obtain an expected reward in the market (Lin, 2002). Besides, social capital can facilitate access to information, allowing the coordination of activities, and ultmiately influencing decision-making (Grootaert and Van Bastelaer, 2001).

There is increasing concern around the use of antibiotics in animal food production and the risk that poses for antimicrobial resistance transmission in the food chain (Laxminarayan et al., 2013; Van Boeckel., et al. 2015)). In small-scale commercial poultry farms antibiotics are more likely to be used without veterinary supervision, particularly for therapeutic purposes. Antibiotics are also used in sub-therapeutic doses by adding to feed and water for prophylaxis, growth promotion and as a risk-management strategy (Begum et al., 2013). In Bangladesh, the Animal Feed Act prohibits the use of antibiotics in feed (Bangladesh. Ministry of Fisheries and Livestock, 2010). However, anecdotally poultry farmers circumvent the law by including antibiotics in drinking water provided to broilers. Moreover, governance and monitoring of small-scale producers is weak.

The scientific community assigns both social context and entrepreneurs' behavior a central role in the growth and development of the global economy. However, the relationships between these two factors have not been sufficiently studied in business and economics (Liñán and Santos, 2007). Few studies have examined the social and economic drivers of antibiotic use in unregulated food production systems. As part of a study to determine drivers of antibiotic use in poultry production, this paper aims to describe the nature of dependencies and reciprocal relationships between different actors in small-scale broiler poultry production (social networks) and how the dependent relationships influence farmers' decisions to use antibiotics to raise broilers.

METHODOLOGY

Study Area, Study Participants, and Sample Size

We used a cross-sectional qualitative design including face-to-face in-depth interviews among purposefully selected farm workers from small-scale commercial poultry farms (<5000 birds) (n=10) and sales representatives of three leading livestock pharmaceutical companies (n=3). We conducted in-depth interviews with poultry dealers (n=5) representing each of the top five poultry feed brands in the country. Poultry dealers supply day-old chicks, poultry feed, and medicines. They also purchase mature market-ready birds from the poultry farmers. Additionally, the local sub-district

(Upazila) government livestock officer was interviewed as a key-informant (n=1).

Data Collection

Data collection was carried out in Bengali language. In-depth and key-informant interview guidelines were developed based on the research objectives and relevant literature. A checklist was developed for use in spot observations to record medicines, supplements, additives used together with poultry feed products found at commercial poultry farms. Interviews with participants were audio-recorded and field notes used for additional information. Medicines used by farmers were captured using a camera to help complete the checklist. During analysis, a veterinary physician categorized all the items into antibiotic and non-antibiotic medicines.

Data Analysis

We described findings under key components of social capital theory; information flow and decision making. Additionally, a conceptual framework for the patron-client relationship between farmers and poultry dealers was developed. We reached data saturation within the sample size.

RESULTS

Role of Farmers and Poultry Dealers/ Credit Based Marketing

Poultry farmers reported that while starting up their farm, they usually consulted with other farmers and poultry dealers to determine the estimated cost required for installation of poultry sheds and equipment. Most interviewed farmers started poultry production with only a poultry shed/pen and some basic equipment such as; water feeders, feeding tray and brooders (heating equipment). They usually bought day-old chicks, poultry feed, medicines and additives from a poultry dealer based on their personal relationship and a credit facility. Poultry dealers reported that they also informed new farmers about the support that they can provide (e.g. credit purchase, selling poultry). “Few years back, I have shown my interest to start farming and consulted with a dealer. He said, if I feel encouraged enough, then he will give full support to start a poultry farm. Then I started my farm and purchased everything on credit from dealer.” [Commercial poultry farmer, age-35]

The key-informant reported that dealers often impose some preconditions to the credit receivers such that the farmers are bound to buy all feeds and medicines from that respective dealer for the entire period of poultry nurturing and that the farmers sell all mature, market-ready poultry to that respective dealer. “If you receive any favor from any person, you will naturally have a good impression about that person and take his advice.” [Livestock officer of sub-district].

Poultry dealers reported that when they started their business, they sold a range of poultry feed brands. Based on the comparisons among different brands and feedback from poultry farmers, dealers decided on the most popular and profitable brands to market; feed companies also provided dealers with reasonable credit facilities for their business. “First, I started my business with some different brands. Finally, I tied up with a particular brand, when they assured me that they will provide products with highest credit facilities, because we sell most of the products on credit.” [Poultry dealer, age-40]. Poultry dealers reported that they have direct interactions with poultry hatcheries, poultry feed and pharmaceutical manufacturing companies. Feed companies give credit purchase facilities by fixing a sales target for one poultry dealer, who acts as the sole distributor of that feed brand in one upazila. For example, one dealer reported that 50 tons (1000 bags) of poultry feed was the sales target for one month. If a dealer achieves the sales target, they receive Taka 20 to 25 (US$0.23 to 0.29) per bag of feed sold. This amounts to commission of around US$ 250 to 300 per month for 50 tons of feed. Poultry dealers also reported that for renowned and popular medicine brands, they usually pay cash, but a credit facility is also available for up to 30 days. When dealers pay cash for medicines including antibiotics, they get different percentages of commission for different products. “As we sell everything on credit to the commercial poultry farmers, we therefore prefer credit purchase from the medicine company.” [Poultry dealer, age-40]

Both dealers and farmers reported that credit facilities, both for sales and purchase, depend on “a good relationship” which they consider a bilateral requirement that stands upon ‘trust worthiness’ and previous ‘healthy’ financial transactions. The key-informant reported that over the last 10 years there has been an increasing trend of credit-based business established through the entire supply chain to sustain a competitive market.

Feed and pharmaceutical manufacturers often provide credit facilities to the dealers so that they can expand their business.

Role of Pharmaceutical Company Sales Representatives

Sales representatives are a further group participating in the broiler production social network. They reported that they are set sales targets by the pharmaceutical company. The target varied by season, but the average sales target was Taka 600,000 – 800,000 (approximately US$ 7,000-10,000) per month. There were peaks in demand for antibiotics by season for poultry and other farm animals. “We are often given some targets. In the case of poultry, the target is higher during winter when disease occurrence is higher than other months. We are bound to achieve the target” [Pharmaceutical sales representative, age-31].

Sales representatives reported that feed companies, pharmaceutical companies and hatcheries provide farmers with veterinary treatment service for their broilers free of cost. Sales representatives facilitate these services to the farmers through the poultry dealers. Sales representatives reported that “a good relationship” with dealers and veterinarians often helps them achieve sales targets.

Information Flow- Farmers’ Knowledge on Antibiotic Application for Poultry Raising

Some poultry dealers reported that they learn how to treat common diseases by following veterinarians’ prescriptions. Others learned through feedback from other farmers after applying antibiotics for a specific disease. Dealers apply this combined knowledge whenever any farmer reports concern over poultry disease to them. If the antibiotic does not work or the disease spreads rapidly, then they ask veterinarians from the feed or pharmaceutical company for possible solutions. “About 80% of poultry farmers maintain their poultry by gathering experience from dealers and sales representatives. Only 20% of farmers consult with the veterinarians when they are unable to control disease and death of poultry.”[Pharmaceuticals sales representative, age-30]

The key-informant reported that in most instances, sales representatives also provide treatment advice directly to the farmers. Sales representatives reported that pharmaceutical companies provide product manuals for distribution among poultry dealers, which list symptoms of the disease and the appropriate treatment. Small-scale commercial poultry farmers were able to identify very few items as antibiotics among the medications that they apply every day to poultry; instead they explained the purpose of using medicines. “We describe the symptoms of the disease to the dealers or sales representative and they suggest medicine accordingly.”[Commercial poultry farmer, age-28]

Decision Making- Antibiotic Application for Broiler Production

Spot observations and interviews showed that all commercial poultry farmers used antibiotics throughout the poultry production cycle (Table 1). The most common antibiotics observed at the time of interview were ciprofloxacin and doxycycline (7/10 farms), followed by tylosin and doxycycline (combination), oxytetracycline, enrofloxacin and erythromycin (6/10 farms). Colistin sulphate was used by 5 of the 10 surveyed farms. Multiple antibiotics were used on the same farm.

Generic name	Number of farms using antibiotics
Ciprofloxacin	7
Doxycycline	7
Tylosin + Doxycycline	6
Oxytetracycline	6
Enrofloxacin	6
Erythromycin	6
Amoxicillin	5
Colistin sulfate	5
Levofloxacin	4
Erythromycin + Trimethoprim + Sulphadiazine	4
Gentamicin + Enrofloxacin	4
Telcomycin	4
Sulphamethoxazole + Trimethoprim	3

Table 1 Antibiotics used in small-scale commercial poultry farms during spot-checks.

Administration of antibiotics started from day one and continued until sale of mature live birds, based on recommendation by dealers. "I use medicine routinely for the entire period from day one to the last day to prevent my poultry from disease and for better growth."[Commercial poultry farmer, age-45]. Some antibiotic use was therefore for disease prevention. Poultry dealers and farmers reported that some diseases occur seasonally; hence different antibiotics were applied in each season. For example, Gumboro (highly contagious acute viral infectious disease in chickens) occurs at the end of the rainy season (August/September). Dealers reported that, during winter (December to February), farmers fear 'bird' (avian) flu and therefore apply antibiotics for prevention. This was confirmed by the poultry farmers who reported that they apply antibiotics more during winter compared to other seasons, because winter is the bird flu season. Farmers reported that they fear epidemics and said once a disease breaks out; it is difficult to save the flock. If any poultry appear unwell, farmers apply antibiotics to all birds. During spot observations we found a wide spectrum of antibiotics that farmers had used for disease prevention in all farms.

Pharmaceutical sales representatives reported that the reliance on antibiotic use is higher among small poultry farmers who have limited capital, small investment and receive substantial credit from the dealer. "Small and medium-scale poultry farmers use more antibiotics because they have small capital and huge credit, therefore they do not want to take any risk." [Pharmaceuticals sales representative, age-31].

Patron-Client Relationship

The roles of farmers, dealers and pharmaceutical company sales representatives in poultry rearing were intimately linked; these data were used to develop a conceptual framework of the patron-client relationship (Figure 1). Dealers invest in the poultry farms from start up through credit purchase with preconditions that the farmers buy all feed and medicines from them for the entire production cycle. Farmers are also obligated to sell the mature, market-ready poultry back to the same dealer. The credit arrangement therefore provides an unwritten contractual agreement between the credit receivers (poultry farmers) and a specific dealer. The dealers control information flow from pharmaceutical companies regarding disease prevention and growth promotion in addition to information on the retail market and how to maximize the farmer's return on investment which then impacts on decision making.

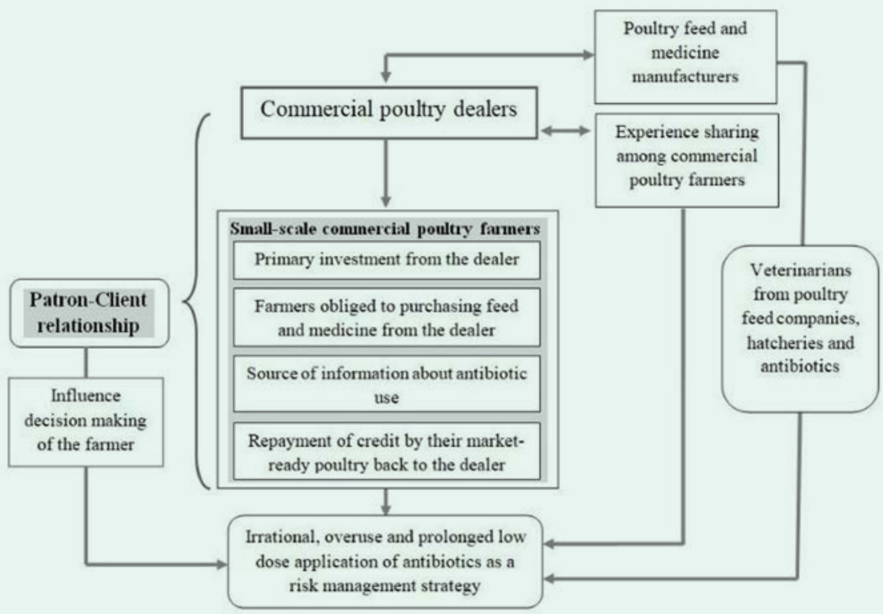

Figure 1 Factors that influence farmers' decisions on antibiotic use in broiler production

The key informant defined this relationship between dealers and poultry farmers as a "gentleman's agreement", where both parties protect their own benefit "The relationship among poultry dealers and poultry farmers seems very harmless. That's why I say it is a 'gentleman's agreement', where both dealers and farmers look for their own benefits and never complain about each other. The relationship stands on a gentleman's agreement so the government and any authority can't get access to this relationship." [Livestock officer of sub-district]

We asked poultry dealers about how they recover money from farmers if they face losses. Poultry dealers said that they often extend the credit facility to farmer so that they can purchase necessary commodities for another batch of broilers to overcome the previous loss. "All batches are not equally profitable for a farmer. Sometimes they face loss. In that situation we sometime give another credit to overcome the losses. Because, we also depend on the farmer, if farmers live then we live." [Poultry dealer, age 40]. Farmers reported that when they sell mature, market-ready poultry to the dealer, the amount in credit is deducted and they receive the remaining amount.

The key informant compared this dealer-farmer relationship to a micro financing institute and credit receiver relationship, whereby dealers have a long-term business plan similar to that used by micro-financing institutes but in a different format. If a farmer gets a profit from the first broiler batch, then he will take a larger amount in credit from dealers for a second batch to expand the farm and maximize profit. On the other hand, if farmers make a loss, they make all the next purchases on credit to recover from the loss. This credit system is an integral part of the poultry food value chain, where dealers also get support from the poultry hatchery; poultry feed manufacturer and pharmaceutical companies.

Generic name	Number of farms using antibiotics
Ciprofloxacin	7
Doxycycline	7
Tylosin + Doxycycline	6
Oxytetracycline	6
Enrofloxacin	6
Erythromycin	6
Amoxicillin	5
Colistin sulfate	5
Levofloxacin	4
Erythromycin + Trimethoprim + Sulphadiazine	4
Gentamicin + Enrofloxacin	4
Telcomycin	4
Sulphamethoxazole + Trimethoprim	3

Table 1 Antibiotics used in small-scale commercial poultry farms during spot-checks.

CONCLUSIONS

This study revealed a critical key relationship between poultry dealers and farmers in the provision of credit to farmers that is essential for their livelihoods and a critical driver for antibiotic use during poultry rearing. Poultry dealers act as the sole supplier of a single poultry feed brand, receive credit and commission from poultry feed suppliers and manufacturers, and obtain antibiotics on credit from pharmaceutical company representatives. Dealers create functional connections between the input producers and the small-scale farmers by sourcing the production inputs from the large companies through their networks and self-credibility. They purchased production inputs in credit and distribute it in farms and buy back product from the marginal farmers through the post harvesting channel (forward linkage channel) to generate the cash revenue, and thus keep the production cycle in motion (Mandal & Khan, 2017). Pharmaceutical representatives are always focused to achieve the sales target and maintain a continuous liaison with dealers. Pharmaceutical companies provide their own veterinarian's support through dealers to the small farmers. There is a substantial penetration and promotion of animal drug use by pharmaceutical companies and their agents (Roess et al. 2013).

This study found that farmers routinely used antibiotics, including those banned for use in animals such as colistin. Multiple antibiotics were applied from day one of the production cycle until the point of sale. Farmers use antibiotics ubiquitously for growth promotion and prophylaxis as a risk-management measure (Begum et al., 2013). In the supply chain of antibiotics has been distributing antimicrobial products to the wholesalers, retail pharmacies and feed dealers and even to commercial poultry farmers. Most commercial poultry farmers use antibiotics themselves directly from feed dealers or even directly from companies (Antibiotic use and resistance in Bangladesh, report 2018). Most of the farmers (>60%) used antibiotics without the prescription of the veterinarians (Islam, Shiraj-Um-Mahmuda, & Hazzaz-Bin-Kabir, 2016). Hence, it is challenging to monitor whether the poultry products are being sold maintaining withdrawal period. Another study conducted in Bangladesh among the small-scale layer farms of Mymensingh district revealed that about 94.16% of farmers are using antibiotics without maintaining the minimum withdrawal period before marketing (Ferdous, Sachi, Zakaria Al Noman, Hussani, & Sikder, 2019). The residue of ampicillin, ciprofloxacin and enrofloxacin in liver and meat of broilers were evaluated by using thin layer chromatography (Khan, Ferdous, Ferdous, Islam, Rafiq & Rima, 2018). Irrational and injudicious uses of antibiotics make poultry meat unsafe for human consumption due to the presence of residues, if withdrawal period is not maintained properly (Lee et al., 2001). Similar to our findings, antibiotics were considered an essential element for disease prevention and treatment in Cambodia, where farmers focused on the benefits to their food production system rather than concerns about the consequences of antibiotic use (Om and McLaws, 2016). Among the broiler farmers in Indonesia, Vietnam, and Thailand, the routine use of antibiotics in broiler production systems were found and farm profitability, disease prevention, and mortality rate reduction were identified as drivers toward antimicrobial use (Coyne et al. (2019). Based on the consideration of economic factors and profitability, poultry farmers decide to use antibiotic as a growth-promoter and perceive the cost of antibiotic is relatively beneficial by taking into consideration the improvements in body weight and growth rates (Sirdar, Picard, Bisschop & Gummow, 2012). Farmers belief that using more or different types of antibiotics will keep their farm more secure and productive (Islam, Shiraj-Um-Mahmuda, & Hazzaz-Bin-Kabir, 2016).

Our study found that the major poultry production inputs are purchased from dealers on credit. Dealers control the information flow to farmers and, in the absence of any other sources of information; farmers follow these recommendations without question. In contrast, poultry farmers from central Uganda were found to make decisions about antimicrobial use themselves; either based on previous experience, with guidance from dealers or from previous veterinary advice (Kigozi and Higenyi, 2017). Despite concerns around antibiotic use in food production, the growing poultry sector in Bangladesh is highly valuable to the economy through the creation of direct and indirect employment opportunities, improved food security and increased access to animal-source protein (Hamid et al., 2017).

As described in social capital theory, social networks include a range of relationships that can offer access to production resources that include information, credit purchase facilities, physical or human capital. This in turn affects decision-making processes and collective action through reciprocity and mutual trust (Liñán and Santos, 2007). Due to limited capital and market information channels, we found that small-scale farmers are highly dependent on dealers for the entire process of poultry production and marketing in a credit based reciprocal relationship. Dealers, who obtain income through sales commission, forcedly push so-called nutrient-ready feed and antibiotics through credit facilities and farmers are economically tied to buy chicks and feed from same dealers (Shah et al., 2006). These farmers face the challenges of limited access to institutional credit, inadequate knowledge of poultry rearing practices, loss of profit due to death or disease outbreaks among flocks. They have no access to production and marketing information or poultry marketing channels (Ali and Hossain, 2012). In many developing countries, a large proportion of the broiler poultry farms benefited from contract farming (Islam, M.S., Takashi, S., and Chhabi, 2010) which provides day old chicks, feeds, veterinary services and technical supports on credit and ensures purchase of the output (Sheel, S.K., and Sen, B.K.J.J.o.B. (2013). Vertically integrated poultry contract farming was introduced in Bangladesh in 1994 by a single company as an experimental extension program and later, some limited number of companies initiated contract farming. However, contract broiler farming is developed only in a few places by some limited companies and still under experiment and the growth of contract farming has been very slow. While self-regulated small-scale broiler farming is dominant and performed for the development of the broiler industry (Islam, M.S., Takashi, S., and Chhabi, 2010). A disorganized marketing system prevails in Bangladesh that further disadvantages small farmers. A multi-country systematic review highlights that most small-scale commercial poultry farms in LMICs rely on an informal marketing system based on verbal contracts to sale-purchase agreements. In this verbal agreement, farmers are less likely have the choice of technology, input supplies or any service support (Ahuja and Sen, 2007). The influence of social capital on the decision making for the small and medium entrepreneur is reasonably important because for the access to production resources and market information. Therefore, the decision is mostly carried through the social networks (De Carolis et al., 2009; Heavey et al., 2009).

In Bangladesh, according to the fish feed and animal feed act 2010, under article 14, the use of antimicrobials for sub-therapeutic purpose (growth promotion) has been completely prohibited to avoid the development of antibiotic resistance (Fish Feed and Animal Feed Act 2010). However, research has revealed antibiotic residues are still present in poultry meat and eggs (Samad et, al., 2010). This may happen due to injudicious use of antibiotic during treatment or a preventive procedure or the addition of antibiotic to feed as growth promoter vested interest, low veterinary regulation and low enforcement of the Act may be the root cause of this situation (Antibiotic use and resistance in Bangladesh, report 2018). Food safety administration and inspection does not include the monitoring of the entire chain of production and transaction (Rahman & Kabir, 2012). Multi-country studies suggest that poor state governance is associated with less effective controls of antibiotic use in the human and animal sectors (Collignon et al., 2015). In most instances, the absence of a clear legislative framework on the use of antimicrobials in livestock production in LMICs may result in increased irrational consumption (Van Boeckel et al., 2015). Other factors that adversely impact the capacity to control antibiotic use in food animals include limited technical staff in agriculture departments to monitor farming practices as well as over-the-counter availability of antibiotics (Om and McLaws, 2016). In a setting where governance is weak, relying on law enforcement is inadequate. Investigating ways to exploit the patron-client relationship for improved antibiotic stewardship is a logical next step in developing a sustainable poultry value chain (Begum et al., 2013). Regulation, monitoring and control programs for the prudent use of antibiotics in food-producing animals must begin with feed manufacturers and small/medium-scale poultry industries and must address or exploit the strong bonds within the patron-client relationship.

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A catalyst for industrial symbiosis: a brief guide to the EU's framework for setting ecodesign requirements for sustainable products

Ilke Göçmen
Department of European Union Law, Ankara University Law Faculty, Ankara, Türkiye
ilkegocmen81@yahoo.com

ABSTRACT

Ecodesign requirements can support industrial symbiosis (IS) by encouraging the design of products with sustainability in mind. By embedding sustainability into product design, the European Union (EU) facilitates IS practices, reduces environmental impact, and accelerates the transition to circular business models. Recently, the EU adopted Regulation 2024/1781 as part of the European Green Deal, introducing a comprehensive legal framework for ecodesign requirements applicable to nearly all products. Entering into force on 18 July 2024, this Regulation is binding in its entirety and directly applicable in all EU Member States. Given its complexity –comprising 122 recitals, 80 articles, and 8 annexes– summarizing its objectives, scope, and content may also be beneficial for those working on IS more broadly. This research provides a concise introduction to the Regulation, analysing its legal implications and relevance to IS. Using a doctrinal legal research methodology, it systematizes the Regulation's provisions, examines their legal implications, identifies underlying principles, and explores their interconnections with other sources of law. The analysis draws upon the Regulation itself, relevant case law, legislative history, and scholarly commentary. Regulation 2024/1781 aims to improve the environmental sustainability of products while ensuring their free movement within the EU's internal market. It applies to nearly all physical goods, allowing only compliant products with a digital product passport to be placed on the market. These harmonized ecodesign requirements will foster the development of circular business models across the internal market. The Regulation empowers the European Commission to set product-specific and horizontal ecodesign requirements via delegated acts. These requirements cover durability, reusability, repairability, recyclability, energy and water efficiency, environmental impact, and waste reduction. It imposes obligations on economic operators, ensuring compliance through designated authorities. Additionally, it introduces measures to curb the destruction of unsold products and promotes green public procurement, directing public funds toward sustainable practices. By supporting the transition to a circular economy, the Regulation fosters practices that promote resource efficiency, material recovery, and cross-sector collaboration. Ultimately, it is expected to play a key role in advancing IS practices across the EU.

KEYWORDS
Internal Market of the European Union - Regulation 2024/1781 - Environmental Sustainability
Ecodesign Requirements - Digital Product Passport - Green Public Procurement

INTRODUCTION

Ecodesign requirements, recently regulated by Regulation 2024/1781 in the European Union (EU), are linked to industrial symbiosis (IS). On the one hand, both ecodesign requirements and IS serve the same end: circular economy. While IS "is considered a key strategy supporting the transition towards the circular economy" (Fraccascia & Giannoccaro, 2020, p. 1), ecodesign requirements are seen as an enabler of "the development, deployment and scaling-up of new circular economy business models throughout the [EU] internal market" (Preamble (3) of Regulation 2024/1781). On the other hand, ecodesign requirements can and should be set with IS in mind. In this respect, IS "engages traditionally separate entities in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products" (Chertow, 2000, p. 314). The LIAISE Cost Action defines IS as "where one industry's waste becomes another's raw material" (liaise-action.eu/). The establishment of new ecodesign requirements includes considerations for "recyclability", "the possibility of recovery of strategic and critical raw materials" and "remanufacturing", which is defined as "actions through which a new product is produced from objects that are waste" (Preamble (3) and Article 2(16) of Regulation 2024/1781). Overall, not only do ecodesign requirements and IS both serve a circular economy as an end, but ecodesign requirements may also become the legal framework under which IS operates.

Thus, providing a concise introduction to Regulation 2024/1781, analysing its legal implications and relevance to IS, becomes necessary. This Regulation is a recent EU act adopted as part of the European Green Deal (Preamble (1) of Regulation 2024/1781), introducing a comprehensive legal framework for ecodesign requirements applicable to nearly all products (Article 1(2) of Regulation 2024/1781). Its primary aim is to enhance the environmental sustainability of products while ensuring their free movement within the EU's internal market (Article 1(1) of Regulation 2024/1781). Entering into force on 18 July 2024, Regulation 2024/1781 is binding in its entirety and directly applicable in all EU Member States. Given its complexity –comprising 122 recitals, 80 articles, and 8 annexes– summarizing its objectives, scope, and content may also be beneficial for those working on IS more broadly.

METHODOLOGY

This paper uses a doctrinal legal research methodology. Thus, it systematizes the Regulation's provisions, examines their legal implications, identifies underlying principles, and explores their interconnections with other sources of law. The analysis draws upon the Regulation itself, relevant case law, legislative history, and scholarly commentary.

A CONCISE INTRODUCTION TO REGULATION 2024/1781: RESULTS

The following results serve as a concise introduction to Regulation 2024/1781.

Directive 2009/125 as a Pioneer to Regulation 2024/1781

Firstly, Regulation 2024/1781 is a follow-up to Directive 2009/125, the first legal act to set ecodesign requirements in the EU, which was later repealed by the former (Article 79 of Regulation 2024/1781). Regulation 2024/1781 establishes a "regulatory framework to progressively introduce ecodesign requirements for products" "by making the ecodesign approach initially set out in [Directive 2009/125] applicable to the broadest possible range of products" (Preamble (5) of Regulation 2024/1781). Thus, although the Directive 2009/125 is repealed, the ecodesign approach based on this Directive will likely guide the interpretation and application of the Regulation (see Article 79(3) and Annex VIII of Regulation 2024/1781 and (Barkhausen et al., 2022, pp. 1–26)).

Secondly, Regulation 2024/1781 is an extended version of Directive 2009/125. In terms of scope, while the Directive establishes a framework for the setting of ecodesign requirements for energy-related products (Article 1(1) of Directive 2009/125), the Regulation extends this framework to nearly all products (Article 1(2) of Regulation 2024/1781). In terms of content, while the Directive focuses solely on establishing a framework for setting ecodesign requirements (Article 1 of Directive 2009/125), the Regulation also covers additional aspects such as the digital product passport, the non-destruction of unsold consumer products, and mandatory green public procurement (Article 1 of Regulation 2024/1781). In terms of legal consequences, while a Directive is binding as to the result to be achieved but needs to be transposed into national law by Member States, a Regulation is binding in its entirety and directly applicable in all Member States (Article 288 of the Treaty on the Functioning of the EU (TFEU)). Therefore, by shifting from a Directive to a Regulation as the type of legal act, and in addition to broadening its scope and content, Regulation 2024/1781 clearly aims to establish binding rules across all 27 Member States with the broadest possible coverage.

Objectives and Scope of Regulation 2024/1781

Firstly, the objective of Regulation 2024/1781 is twofold: on one hand, to improve the environmental sustainability of products, and on the other hand, to ensure the free movement of sustainable products within the internal market (Article 1(1) of Regulation 2024/1781). In this regard, the internal market is defined as "an area without internal frontiers in which the free movement of goods, persons, services and capital is ensured (Article 26(2) of the TFEU). Additionally, Article 114 of the TFEU serves as the legal basis for Regulation 2024/1781, providing for the adoption of measures to approximate the national laws of Member States for the establishment and functioning of the internal market (see (Wyatt, 2009, pp. 93–136). This Article requires, among other things, "a high level of protection" in relation to "health, safety, environmental protection and consumer protection" (Article 114(3) of the TFEU). Thus, the Regulation sets twin objectives of environmental protection and freedom of movement, which may influence the interpretation of its provisions. This is particularly relevant since teleological interpretation, alongside textual, contextual, and historical interpretation, is a common method employed by the Court of Justice of the European Union (CJEU) (Lenaerts & Gutiérrez-Fons, 2013; Srl CILFIT and Lanificio di Gavardo SpA v Ministry of Health, 1982, paras. 16–20).

Secondly, the scope of Regulation 2024/1781 is quite broad. It "applies to any physical goods that are placed on the market or put into service, including components and intermediate products" (Article 1(2) of Regulation 2024/1781). However, it does not apply to the following categories, some of which are governed by separate EU acts: (i) food, (ii) feed, (iii) medicinal products, (iv) veterinary medicinal products, (v) living plants, animals and micro-organisms, (vi) products of human origin, (vii) products of plants and animals relating directly to their future reproduction, (viii) vehicles (Article 1(2) of Regulation 2024/1781). Therefore, since Regulation 2024/1781 generally applies to any physical goods, it has significant potential in terms of its scope of application.

Content of Regulation 2024/1781

In terms of content, Regulation 2024/1781 primarily establishes a framework for setting ecodesign requirements, while also complementing it with provisions on digital product passports, the non-destruction of unsold consumer products, and mandatory green public procurement (Article 1(1) of Regulation 2024/1781).

The Framework for the Setting of Ecodesign Requirements

Regulation 2024/1781 primarily establishes a framework for setting ecodesign requirements. The Commission is empowered to adopt delegated acts to establish these requirements (Article 4(1) of Regulation 2024/1781, on delegated acts see Article 290 of the TFEU and (Türk, 2020, pp. 415–428)). Once set, products can only be placed on the market or put into service if they comply with these requirements (Article 3(1) of Regulation 2024/1781). Therefore, in general, the set ecodesign requirements function as maximum harmonisation, regulating the area exhaustively and preventing Member States from taking action (see (Criminal proceedings against Tullio Ratti, 1979, paras. 25–28) and (Barnard, 2016, pp. 580–600)).

In this context, key concepts can be defined as follows (Article 2(7-9) of Regulation 2024/1781): "Ecodesign requirement" refers to "a performance requirement or an information requirement aimed at making a product […] more environmentally sustainable". A "performance requirement" is defined as "a quantitative or non-quantitative requirement for or in relation to a product to achieve a certain performance level in relation to a product parameter". An "information requirement" refers to "an obligation for a product to be accompanied by information".

Regarding the substantive aspects of the delegated acts that will establish ecodesign requirements, the following observations can be made. These requirements will focus on improving the following product aspects: "(a) durability; (b) reliability; (c) reusability; (d) upgradability; (e) repairability; (f) the possibility of maintenance and refurbishment; (g) the presence of substances of concern; (h) energy use and energy efficiency; (i) water use and water efficiency; (j) resource use and resource efficiency; (k) recycled content; (l) the possibility of remanufacturing; (m) recyclability; (n) the possibility of the recovery of materials; (o) environmental impacts, including carbon footprint and environmental footprint; (p) expected generation of waste" (Article 5(1) of Regulation 2024/1781). However, the Commission is not obligated to regulate all product parameters, but only specific ones (Article 4(2) of Regulation 2024/1781). Additionally, ecodesign requirements will, as a rule, be set for specific product groups, and exceptionally, horizontally for more than one product group (Article 5(4 and 7) of Regulation 2024/1781). These requirements may consist of either or both performance requirements and information requirements (Articles 5(9), 6-8 of Regulation 2024/1781).

Regarding the procedural aspects of these delegated acts, the following observations can be made. The Commission will adopt a working plan, making it publicly available, which will set out a list of product groups to be prioritised for the establishment of ecodesign requirements (Article 18(3) of Regulation 2024/1781). The first product groups to be prioritised are as follows: "(a) iron and steel; (b) aluminium; (c) textiles [...]; (d) furniture [...]; (e) tyres; (f) detergents; (g) paints; (h) lubricants; (i) chemicals; (j) energy related products [...]; (k) information and communication technology products and other electronics" (Article 18(5) of Regulation 2024/1781). Moreover, the Commission will provide economic operators with sufficient time to comply with the ecodesign requirements, as a rule, no earlier than 18 months from the entry into force of the relevant delegated act (Article 4(4) of Regulation 2024/1781). The first delegated act will not enter into force before 19 July 2025 (Article 4(8) of Regulation 2024/1781). The power of the Commission to adopt delegated acts is subject to certain conditions, such as the possibility of being revoked at any time by the European Parliament or the Council (Article 72 of Regulation 2024/1781).

Regarding the institutional aspects of these delegated acts, the following observations can be made. Firstly, the delegated acts will "undergo a dedicated impact assessment and stakeholder consultation" (Preamble (22) of Regulation 2024/1781). Additionally, the Commission will set up an "Ecodesign Forum" as an expert group, ensuring balanced participation from Member States' experts and relevant stakeholders (Article 19 of Regulation 2024/1781). The Commission will create a "Member States Expert Group" as a subgroup of the Ecodesign Forum, consisting of experts appointed by the Member States (Article 20 of Regulation 2024/1781). This Forum and Group will assist the Commission, among other things, in preparing ecodesign requirements. Furthermore, economic operators may submit a self-regulation measure to the Commission that sets ecodesign requirements. If certain criteria are met, this measure may be assessed and approved (Article 21 of Regulation 2024/1781).

Regarding the implementation and/or enforcement of these delegated acts, the following observations can be made. Firstly, although certain obligations are imposed on economic operators, the primary responsibility rests with the manufacturer, who must ensure that the product is designed and manufactured in accordance with the performance requirements, accompanied by the necessary information requirements and DPP (Article 27(1) of Regulation 2024/1781).

Secondly, the operation of product conformity with the ecodesign requirements is designed as follows: The Commission is responsible for setting the applicable conformity assessment procedure in its delegated act (Articles 4(5) and 43 of Regulation 2024/1781). Manufacturers may either carry out this procedure themselves or have it carried out by a third party on their behalf (Article 27(2) of Regulation 2024/1781). Member States must appoint a notifying authority responsible for assessing and notifying third-party conformity assessment bodies, as well as monitoring notified bodies (Article 49(1) of Regulation 2024/1781). Requirements related to both the notifying authorities and notified bodies, as well as the notification procedure, are outlined in detail (Articles 50, 52 and 56 of Regulation 2024/1781). Additionally, Member States must include a section in their national market surveillance strategy outlining the planned activities to ensure that appropriate checks are conducted in line with this Regulation (Article 66(1) of Regulation 2024/1781).

Thirdly, there are civil, administrative, and/or criminal enforcement mechanisms. On the one hand, in the event of non-compliance with ecodesign requirements, and without prejudice to other remedies, the relevant economic operators (mainly the manufacturer) will be liable for any damage suffered by the consumer (Article 76 of Regulation 2024/1781). On the other hand, Member States must also establish rules for penalties related to violations of this Regulation, ensuring that they are effective, proportionate, and dissuasive, and take necessary measures to ensure their implementation (Article 74(1) of Regulation 2024/1781). These penalties should include at least: "(a) fines; (b) time-limited exclusion from public procurement procedures" (Article 74(3) of Regulation 2024/1781).

Digital Product Passport

Regarding the Digital Product Passport (DPP), the following rules are established. With the DPP, the EU aims to "enhance end-to-end traceability of a product throughout its value chain", thereby helping "customers make informed choices by improving their access to relevant information" (Preamble (32) of Regulation 2024/1781). The term "DPP" refers to "a set of data specific to a product that includes the [specified information] and that is accessible via electronic means through a data carrier" (Article 2(28) of Regulation 2024/1781). When ecodesign requirements include information requirements, products can generally only be placed on the market or put into service if a DPP with accurate, complete, and up-to-date data is available (Articles 7(2/a) and 9(1 and 4) of Regulation 2024/1781). The general framework for the essential requirements of the DPP, including its technical design and operation, is set out in the Regulation. Additionally, the Commission is empowered to adopt delegated acts to supplement or amend these provisions (Articles 10-15 of Regulation 2024/1781). Consequently, the DPP is regulated under a maximum harmonisation approach (see (Criminal proceedings against Tullio Ratti, 1979, paras. 25–28) and (Barnard, 2016, pp. 580–600)).

The Framework to Prevent Unsold Consumer Products from Being Destroyed

On the destruction of unsold consumer products, the following rules are established. The term "unsold consumer product" refers to "any consumer product that has not been sold […] and products returned by a consumer on the basis of their right of withdrawal" (Article 2(37) of Regulation 2024/1781). Firstly, there is the "general principle of prevention of destruction": Economic operators are required to take reasonable steps to avoid the destruction of unsold consumer products (Article 23 of Regulation 2024/1781). Secondly, there is the "disclosure of information on unsold consumer products": Economic operators must disclose certain information, including the number, weight, reasons, proportion, and the measures taken and planned for the unsold consumer products that are discarded (Article 24 of Regulation 2024/1781). Thirdly, there is the "prohibition on destruction of unsold consumer products": The destruction of unsold consumer products listed in Annex VII under "apparel and clothing accessories" and "footwear" is prohibited as of 19 July 2026 (Article 25(1) of Regulation 2024/1781). The Commission may adopt delegated acts either "to add new products" or to "update the entries within product groups" to this list (Article 25(2-5) of Regulation 2024/1781). Consequently, the destruction of unsold consumer products is regulated under a maximum harmonisation approach (see (Criminal proceedings against Tullio Ratti, 1979, paras. 25–28) and (Barnard, 2016, pp. 580–600)).

Setting of Mandatory Green Public Procurement Requirements

On the setting of mandatory green public procurement requirements, the following rules are established. As a preliminary remark, "public procurement amounts to 14 % of the Union's GDP" (Preamble (100) of Regulation 2024/1781). Hence, mandatory green public procurement requirements will enhance the impact of public spending on environmentally sustainable products compared to a voluntary approach (Preamble (100) of Regulation 2024/1781). This system will work as follows: The Commission is empowered to set the minimum requirements through implementing acts for products whose ecodesign requirements have been established by delegated acts (Article 65(2-3) of Regulation 2024/1781 and on implementing acts see Article 291 of the TFEU and (Türk, 2020, pp. 415–428)). Member States' contracting authorities and contracting entities will award public contracts in compliance with these minimum requirements (Article 65(1) of Regulation 2024/1781). However, Member States may also adopt or maintain stricter national requirements for green public procurement (Preamble (101) of Regulation 2024/1781), reflecting a minimum harmonization approach in this area (see (Criminal proceedings against André Ambry, 1998, paras. 23–24) and (Dougan, 2000, pp. 853–885)).

CONCLUSIONS

Regulation 2024/1781 is poised to support the transition to a circular economy by promoting resource efficiency, material recovery, and cross-sector collaboration. It is expected to play a pivotal role in advancing IS practices throughout the EU. From a legal perspective, with IS in mind, the IS community may seek to influence ecodesign requirements during the preparation and/or monitoring process, either through stakeholder consultations or as part of the Ecodesign Forum.

Additionally, cases before the courts, particularly the CJEU, may arise, either to seek the interpretation of the rules of Regulation 2024/1781 and its delegated and implementing acts, or to challenge the validity of the latter in light of the former (cf. (Bromine Science Environnemental Forum (BSEF) v European Commission, 2022)). In such instances, the IS community may seek to influence the interpretation and application of the law.

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Bioboosters model: driving innovation in circular economy and industrial symbiosis

Lina Stanionytė
Sunrise Tech Park, Vilnius, Lithuania
lina@ssmtp.lt

Anna Aalto
Institute of Bioeconomy, Jamk University of Applied Sciences, Jyväskylä, Finland
anna.aalto@jamk.fi

ABSTRACT

Industrial symbiosis (IS) and the valorization of side streams are becoming key business models, driving sustainability and creating additional value. However practical implementation of circular economy and IS models presents many challenges. Innovative solutions are needed to effectively match side streams with suitable applications and convert them into valuable components or entirely new products. JAMK University of Applied Sciences (Jamk) in Central Finland has developed the Bioboosters model – a bioeconomy business accelerator designed to unlock the innovation potential to deliver solutions to circular economy and to foster IS relations. The Bioboosters model is a business-driven approach that fosters innovative solutions in the bioeconomy through open calls, addressing real industry challenges. The model provides a well-structured path and clear guidelines for all participants of the process, including organisers, mentors, companies and solution providers. Rooted in circular economy principles, it promotes resource sharing, waste minimization, and process optimization by engaging participants in solving practical company problems. The Bioboosters model has been tested across nine regions of the Baltic Sea Region, driving a circular transition within the bioeconomy. By attracting international expertise and innovative solutions from across the EU, the Bioboosters initiative empowered companies to leverage open innovation, helping them find cooperation partners and discover solutions to enhance circularity, sustainability, and additional value. The article explores the journeys of nine regions, innovative solutions discovered and case studies with potential impact for IS. The first Bioboosters impact assessment1 and case studies examined highlight a high satisfaction rate among participants due to opportunities for collaboration, learning, about real-world circular economy applications, expanding their networks, and contributing to innovation. Innovative solutions discovered and new partnerships created highlight the value of open innovation and inter-regional collaboration. By effectively matching cross-sectoral and international knowledge expertise with business needs and leveraging on open innovation excellence, BioBoosters model advances innovative solutions in entering the market. By providing innovative solutions for waste valorization, BioBoosters promotes more efficient resource use and supports the adoption of circular economy and IS principles. Insights from the international innovation community showcase the transformative impact of this model. The BioBoosters model is driving a real change and also helping regions create the conditions for industrial symbiosis and a successful circular transition.

KEYWORDS

BioBoosters Model - Industrial Symbiosis - Circular Economy - Bioeconomy - Open Innovation - Business Accelerator - Hackathon - Baltic Sea Region

INTRODUCTION

Industrial symbiosis (IS) and the valorization of side stream are becoming key business models, driving sustainability and creating additional value. IS enhances value by fostering knowledge creation and exchange among industries and companies. Through collaborative networks, it drives innovation, improves business and technical processes, and enables mutually beneficial transactions. IS is a collaborative approach where different sectors share and reuse resources to create greater value and promote sustainability. (Mirata, 2018)

Despite the benefits of collaboration in IS model litterature mentions a number of challenges which can be economic, technical, financial or knowledge, management and strategy related (Kosmol & Otto, 2020). The article examines the role of international networks in alleviating some of the barriers in particular those related with information and knowledge contrains, mathching side streams, finding appropriate partners and innovators or research partner to find solutions and adapt their technologies to IS requirements.

The article highlights the BioBoosters cooperation, initiated by the EU BSR Interreg programme and led by Jamk in Central Finland, which was designed to pilot the BioBoosters hackathon model – one of the tools demonstrating the potential of the open innovation approach to advance the circular transition in the bioeconomy sector. It analyzes the results of the first piloting round, focusing on the valorisation of side streams and solutions for IS. The article also examines whether the open innovation model developed by BioBoosters can be instrumental in fostering IS across the Baltic Sea region. The study is focused around BioBoosters Impact Review 2024 (Aalto & Manerus, 2024) and 5 case studies with focus on valorisation of side streams and having potential for IS. These cases are analyzed in terms of waste stream valorisation and opportunities for cross-sectoral collaboration with IS prospects. The article concludes by emphasizing the benefits of transnational collaboration in enhancing innovative potential and fostering new opportunities for sustainable development.

Challenges and barriers to industrial symbiosis

Implementing IS can be a powerful strategy for improving sustainability and resource efficiency, but several barriers often limit its success. The important challenge is the lack of awareness about the potential of waste streams and lack of knowledge of IS opportunities (Kosmol & Otto, 2020). Many companies fail to recognize the value that their waste products or by-products could offer to other industries.

Another significant barrier is the difficulty in identifying suitable companies for synergies. IS relies on creating networks where one company's waste or surplus is another's resource. However, the identification of appropriate partners can be a complex and time-consuming process. Identifying and connecting with appropriate partners, are significant obstacles to IS (Golev et al., 2014). Companies must evaluate the compatibility of their waste streams, logistics, and regulations, which is often challenging process, that requires knowledge of other industries' needs and waste profiles.

Resource limitation such as financial, technological, and time constraints pose a major obstacle to the implementation of IS. To make waste streams usable by others technologically, companies may need to develop or adapt new processes, which can require specialized expertise and significant R&D investments. IS requires systemic innovation to transform waste into useful feedstock (Cervo et al., 2019). To foster technical and business model innovation companies need to establish cooperation with research institutions and innovators.

To successfully implement IS, companies require substantial support in discovering and developing innovative solutions that allow them to adapt their processes in ways that make waste streams usable for other industries. This adaptation often involves rethinking traditional production methods, engineering new technologies, or even redesigning products so that their by-products can be efficiently repurposed. However, many companies, may lack the internal resources, expertise, or technical know-how to explore such innovative solutions. To successfully reengineer their processes, companies often require access to specialized knowledge, advanced technologies, and research capabilities. However, these resources typically are beyond the boundaries of their internal expertise. As a result, collaboration with external partners becomes essential, particularly when implementing complex information systems. Open innovation models offer an effective way to bridge this gap, enabling organizations to leverage external competencies and drive innovation beyond their core capabilities.

The role of multi-stakeholder platforms

In the Baltic Sea region, governments are promoting IS by facilitating local and regional networks that foster close collaboration between authorities, universities, cluster associations, and green development hubs (Giacometti et al., 2025). Creating networks can encourage knowledge sharing among companies, facilitating connections and help identyfying partners. This collaborative environment can build confidence in the potential of IS by demonstrating successful examples of waste stream exchange, helping businesses understand how such practices can be integrated into their operations. As it has been seen from the studies (Giacometti et al., 2025) networks and multi-stakeholder platforms play a crucial role in shaping strategic directions and informing strategic decisions by bringing together diverse actors, including governments, research institutions, and industry representatives.

For example platforms like European Bioeconomy Network (EuBioNet, 2025), aggregating EU-funded projects, enhances bioeconomy awareness, knowledge sharing, and partnerships. However, while multistakeholder platforms excel at facilitating dialogue and knowledge exchange, they often struggle to drive business-driven innovation pilots due to a lack of direct business incentives, and generalized rather than practical outcomes. To bridge this gap, a more business-centric approach is needed by encouraging direct business involvement, integrating industry-led pilots, fostering real-world business innovation.

In this respect BioBoosters network – the partnership intiated by EU BSR Interreg project (Interreg Baltic Sea Region, 2025 a) address this gap by offering business-driven approach. The partnership unites

9 partners across 7 Baltic Sea Region countries focused on boosting circular transition and fostering bio-economy ecosystems. The network represents universities, clusters, development agencies, business associations representing different sectors and expertise within bioeconomy.

BioBoosters model is designed from a business perspective, ensuring clear value for companies by addressing their specific needs. The BioBoosters model effectively engages businesses by demonstrating return on efforts and time invested in search of innovative solutions.

BioBoosters model

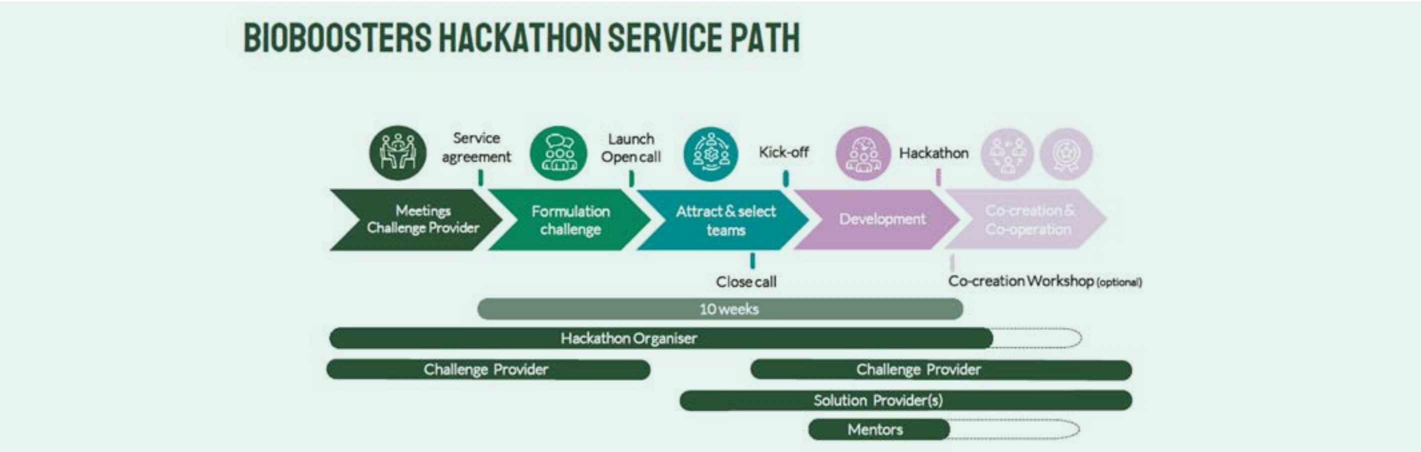
The role of the BioBoosters is to help building innovation partnerships that can enhance the circularity via optimization of the biomass use, material flow management, and the value created (Aalto, 2024). BioBoosters model has been designed by Jamk in Central Finland as bioeconomy business accelerator to unlock the innovation potential, A key feature of the BioBoosters model is its business-driven hackathon model, addressesing real-life challenges in bioeconomy has been tested in international cooperation to upscale the model to BSR dimenssion. Although hackathons are a common practice for promoting entrepreneurship and innovation, the distinctive feature of the BioBoosters model is its focus on creating conditions for lasting cooperation and ensuring continuity beyond the competition phase.

The process starts from the challenge in bio-economy of an industry-leader (Picture 1). This challenge often pertains to pressing issues such as sustainability, resource efficiency, circular economy practices, biotechnology innovations, or reducing environmental impact. Defining a challenge correctly is crucial, as it ensures that the problem being addressed is both relevant to the industry and capable of generating impactful solutions. During this phase, organizers work closely with the challenge provider to refine the scope of the challenge, ensuring that it is neither too broad nor too restrictive. Simultaneously, clear evaluation criteria are established to guide participants in developing their solutions. These criteria include feasibility, innovation, scalability, sustainability impact, and potential for commercialization. To enhance the long-term impact of the hackathon, organizers also secure commitments from the challenge provider, ensuring that a winning team receives continued support, which may include funding, mentorship, or collaboration opportunities to further develop and implement their solution.

Following the kickoff, teams enter an intensive development phase, during which they refine their solutions through research, prototyping, and continuous feedback from mentors. In between kick-off and hackathon hays there is a 3 weeks interwal during which selected teams can interact with mentors and a company - challenge provider, receive expert guidance on both technical and business aspects of and refine their solutions. This is important stage to enhance the quality and viability of proposed solutions.

During the hackathon days, teams, organizers, challenge providers, and mentors meet in person, with final mentoring sessions held individually with each team. Teams then finalize their solutions and pitch them to a judging panel of challenge provider company and experts, who select the most promising innovative solutions addressing the needs and situation of the company

The announcement of the winners marks the culmination of the hackathon, but it is also the beginning of new collaborations. The winning teams receive support from the challenge provider, enabling them to further develop, test, and potentially implement their solutions in real-world industrial settings. This structured approach ensures that the hackathon is not just a competition but a launchpad for meaningful innovation and long-term cooperation between industry leaders and emerging talent in the bio-economy.



Picture 1 BioBoosters hackathon model
Source: Aalto & Kumpulainen, 2024

Teams and mentors value the BioBoosters hackathon for its ability to foster dialogue with large companies, increase visibility, and validation of business ideas. Teams especially benefit from mentoring, gaining valuable expertise. Mentors appreciate the opportunity to expand their networks, and enhance their professional profiles. Both groups also highlight the importance of building partnerships for testing and commercialization. Ultimately, the hackathon provides impactful learning and innovation opportunities for all participants. Another important aspect of BioBoosters is international presence, allowing teams and mentors from across borders to participate in the calls, broadening the diversity of solutions and bringing in a wide range of expertise.

BioBoosters results and solutions for industrial symbiosis

The international testing phase of the BioBoosters model has delivered impressive results (Aalto, & Kumpulainen, 2024). Over the course of just 1,5 years, partners organized 13 international hackathons, leading to 17 official collaborations between winning teams and challenge providers. The initiative has already attracted more than 170 innovative solutions (Aalto, 2025)

According to a feedback survey, 96% of challenge providers reported a high or moderate impact in finding promising solution ideas, and 100% agreed that the hackathon is a valuable tool for large companies to expand both national and international RDI networks, connect with small-scale innovators, and gain fresh perspectives (Olesiak et al., 2024). Additionally, 96% of respondents indicated a strong likelihood of continuing collaboration with the organizers over the next three years.

The hackathons primarily focused on the valorization of biological side streams, optimizing the sustainable use of bioresources through digitalization and improved processes, and exploring new bio-based materials, ingredients, and products. This article examines five case studies that contribute tangible results toward advancing IS in the bioeconomy sector. Each case demonstrates how companies are transforming biological side streams into valuable resources, fostering cross-sectoral collaboration, and integrating circular practices into their operations, highlighting practical approaches to resource efficiency, innovation, and partnership building.

Innovative bioash utilization

Holmen, a leading forest production company in Sweden, relies on its vast forest holdings as the foundation of its business. As a key player in the bioeconomy, Holmen integrates most residual streams from its forests and industries into its operation, except for ash. Typically, ash derived from wood material is used in bioenergy, but Holmen approached BioBoosters for alternative solutions. Joining the Holmen's hackathon call AB Biocompost provided a solution, which suggested integrating ash into its composting process. This approach aimed to integrate ash into compost while also replacing a portion of the peat currently used in Holmen's nurseries. (Fridman et al., 2024)

With new solution instead of being discarded, ash from Holmen's operations is repurposed as a valuable resource in compost production, reducing waste and enhancing resource efficiency. Wider use of ash fertilization is being promoted as a strategy to boost forest growth and increase carbon sequestration in peatlands. The partnership opportunity between Holmen and AB Biocompost promotes IS, where waste from one industry becomes a resource for another, fostering innovation and sustainability.

Turning sugar beet residues into valuable resources

German company Cosun Beet Company is leading sustainable sugar beet processing, producing white sugar, bioethanol, and biomethane while playing a crucial role in the food, energy, and fuel sectors and generating various biogenic residues. The company approached BioBoosters to find solutions to transform sugar beet residues from waste into valuable resources. As part of this initiative, six key side streams from sugar, biogas, and bioethanol production, as well as wastewater treatment, were considered. The challenge was intended to address all six of these side streams. This lead to innovative solutions, including: a novel method to produce microbial biofertilizers from beet pulp; exploring mushroom cultivation using residues from the bioethanol plant; converting beet leaves into carboxylic acids, which serve as starting materials for high-quality chemicals.(Mernitz et al., 2024)

In terms of valorisation of side streams the solutions address 3 side streams beet pulp, beet leaves and residues from bioethanol production. Beet pulp converted into high-value microbial biofertilizers reduce waste and enhance soil health. Organic residues from bioethanol production support mushroom cultivation, creating a nutritious food source. while beet leaves are transformed into valuable carboxylic acids for the chemical and pharmaceutical industries, reducing waste and dependence on fossil-based materials.

These solutions suggest Cosun Beet Company can integrate this process into its operations, creating a circular economy model and offering sustainable agricultural inputs to farmers. New cooperation opportunities Or also Cosun Beet Company can partner with agricultural or food sector stakeholders to establish a commercial mushroom production system, adding economic and environmental value to its operations. Cosun Beet Company can establish strategic partnerships with chemical manufacturers to commercialize bio-based carboxylic acids, strengthening its position in the bioeconomy sector.

Tranforming greenhouse biomass into value

Võiste Greenhouse company of Estonia leading horticulture companies asked for solution to use horticultural residue biomass into valuable resources. Võiste Greenhouse has embraces smart production by investing in automation and precision fertilization to enhance efficiency while fostering research and innovation through spin-off ventures and university collaborations, transforming its production site into a living lab for sustainable development. However, greenhouse biomass holds potential for creating new value chains. By-products like stems, leaves, and unsellable produce can be repurposed into various valuable products such as salts for fertilizers, organic matter for growing media, bio-stimulants, fibres for sustainable packaging, proteins for food and feed, and compounds for cosmetics and pharmaceuticals. (Uusen & Knuuttila, 2024)

Though open BioBoosters hackathon process Voiste got a solution to convert greenhouse biomass into biochar which it can be used as a fertilizer, a soil improver. Solution offer a way to manage biomass waste sustainably, but it also created a new product that could enhance soil health and potentially generate additional revenue streams for the company.

This solution valorises greenhouse biomass turning organic waste into a valuable product. Instead of discarding the biomass, it's transformed into a soil enhancer and fertilizer, improving soil health and fertility. This not only reduces waste and supports sustainable agriculture but also opens up new revenue opportunities through the sale or use of biochar.

Turning waste wood into everyday essentials

Estonian company Fibenol is creating new ways to make eco-friendly materials from wood instead of oil. They turn wood into useful products like lignin, wood sugars, and special cellulose. These materials can be used in things like buildings, roads, packaging, plastics, cleaning products, and even cosmetics or food. Fibenol's factory runs fully on renewable energy and turns over 90% of wood into useful parts. They use a special

Sunburst technology that breaks down wood faster and better than other methods. Their research team is working on making even more high-quality materials from wood. Fibenol's announced a challenge was to discover high-value applications for valorising cellulosic sugars, lignin, and specialty cellulose in food and feed production. They aimed to explore the potential of woody biomass to develop innovative, high-quality bioproducts, such as alternative proteins and additives for food or animal feed. (Kepp et al., 2024)

With BioBoosters Fibenol launched an international challenge to find new ways to add value to woody biomass. Out of seven solutions, the Belgian team Novel Yeast stood out. They proposed using genetically modified, patented yeast strains to turn C5 sugars from Fibenol's leftover wood into xylitol. Xylitol is a valuable ingredient used in toothpaste, chewing gum, medicines, and food. Novel Yeast successfully addressed the challenge of converting a complex sugar stream into a widely used product. Following the hackathon, Fibenol and Novel Yeast began exploring joint funding opportunities through the Circular Bio-based Europe programme. (Kepp et al., 2024)

Utilizing wood side streams such as wood sugars promotes a circular model by ensuring efficient use of all biomass components, reducing waste, and maximizing resource utilization. By converting these side streams into commercially valuable products like xylitol, the solution not only opens new market opportunities in food, cosmetics, and pharmaceuticals but also fosters IS, linking biorefineries with industries seeking sustainable, bio-based ingredients and enabling new partnerships across sectors.

From hemp by-products to sustainable materials

Nordic Hemp Cooperation (Nordic Hemp), an Estonian company involved in sustainable hemp farming and production. Nordic Hemp also explores using hemp biomass and side streams in bioproducts, aligning with circular economy goals. With BioBoosters Hackathon, Nordic Hemp was exploring innovative solutions to improve the industrial hemp value chain. Their aim was to identify the most effective and efficient ways to utilize hemp fibers, dust, and hurd, which are by-products created during the decortication process of hemp stalks (Interreg Baltic Sea Region, 2025 b). The teams proposed creative ways to repurpose hemp by-product, such as fibers, dust, and hurds, into sustainable alternatives like bioplastics, leather substitutes, and fungal-based eco-materials. These innovations aimed to improve the efficiency and value of industrial hemp processing across various sectors. The standout solution from REvoltech integrates hemp fibers into LOVR™, a biodegradable, plastic- and animal-free leather alternative for use in fashion, interiors, and automotive design, promoting circularity and maximum resource efficiency.(Interreg Baltic Sea Region, 2025 c)

The selected solution demonstrates a strong commitment to circular bioeconomy by transforming leftover hemp fibers, typically treated as waste, into a high-value, biodegradable leather alternative. This not only closes the loop in hemp processing but also promotes IS by linking the hemp processing, fashion, and materials industries. Through this cross-sector collaboration, agricultural side streams are turned into innovative, sustainable products, showcasing how shared resources can drive circular innovation and reduce environmental impact.

Case studies' relevance to industrial symbiosis

Five companies joined BioBoosters with challenges asking to explore value of side streams (Table 1). All these companies have a strong commitment to sustainability and circular economy principles. They emphasize resource efficiency through reusing agricultural and industrial by-products, or employing renewable energy, or integrating smart technologies into production. Through their participation in BioBoosters, they sought to further enhance innovation, sustainability and resource efficiency through transnational collaboration and open innovation. Five hackathons on side streams focus showcased innovative solutions with potential for IS, highlighting cross-sectoral collaboration and circular value creation in the Baltic Sea region. These hackathons generated 71 unique solutions, of which 7 were selected to continue cooperation with companies. Over 52% of submitted solutions and 57% of selected solutions came from countries other than the challenge providers. This highlights the importance of international collaboration, in particular for small countries like Estonia as well as isolated or rural regions, as it enables access to larger networks and resources that might otherwise be unavailable.

The innovative solutions selected by Holmen, Cosun Beet, Fibenol, Võiste and Nordic Hemp demonstrate a shared commitment to valorising side streams and advancing IS. Each solution transforms what would otherwise be waste—such as beet residues, ash, wood sugars, hemp fibers, or greenhouse biomas into valuable products like biofertilizers, compost, xylitol, biodegradable materials, or biochar. This not only supports circular economy models within their own operations but also opens opportunities for strategic cross-sector partnerships, enabling resource sharing between industries such as agriculture, food, chemicals, fashion, and bioproducs. This thereby enhances sustainability, creates new market opportunities, and fosters interconnected, low-waste value chains.

Company	Country	Challenge	Solution	Solution provider	Applications	International
Cosun Beet	Germany	• Ash-to-Assets • Turning wood ash waste into valuable resource.	• Solution of ash-enhanced compost boosts nutrient value	• Biocompost AB from Sweden	12	16,6%
Võiste	Estonia	• Turning wood ash waste into valuable resource. • Transforming Sugar Beet Residues from Waste to Value (beet pulp) • Transforming Sugar Beet Residues from Waste to Value (beet leaves) • Transforming Sugar Beet • Residues from Waste to Value (residues from bioethanol production)	• Microbial biofertilizers from Beet Pulp • Mushroom cultivation on bioethanol residues • Carboxylic acid production from beet leaves	• Team n-fix from Belgium • Biberach University of Applied Sciences from Germany • Helmholtz Centre for Environmental Research UFZ & Biomass Research Centre DBFZ from Germany	25	52%
Fibenol EE	Estonia	• Mining the green gold from greenhouse biomass	• Biochar	• Bydgoszcz University of Science and Technology in Poland	12	66,7%
Nordic Hemp EE	Estonia	• Wood to Food: valorising wood sugars, lignin, cellulose for food	• Wood sugars into xylitol bioproduct	• Novel Yeast, company from Belgium	7	57%
Võiste	Estonia	• Hemp hack: innovate to elevate. Efficient methods to valorize hemp by-products	• Biodegradable, plastic- and animal-free leather alternative	• REvoltech, company from Germany	15	66%

Table 1 Summary of BioBoosters challenges and solutions with focus on side streams valorisation

CONCLUSIONS

For stimulating IS, it is important to support decentralised networks of diverse actors such as businesses, municipalities, universities, and cluster organization to lead initiatives based on their unique strengths and capacities. Fostering a collaborative and entrepreneurial culture, while encouraging closer inter-regional cooperation, not only raises awareness of IS but also serves as a powerful tool to drive innovation in that direction.

The BioBoosters model creates value for various stakeholders, including innovation and business support organizations, regional authorities, and sectoral agencies. By connecting industry challenges with innovative SMEs and startups, it has capacity for driving innovation. The model is problem-oriented, with companies acting as challengers who present their specific business needs. Participants, including researchers, SMEs and startups, work on real-life applications, ensuring that the solutions generated are practical and industry-relevant.

The international dimesion brings aditional value to BioBoosters hackathon model gathering together participants from diverse regions and disciplines, significantly expanding the variety and creativity of proposed solutions. By sharing global expertise and best practices, international teams enrich local innovation ecosystems and foster knowledge exchange. The local companies in particular value international visibility which can attract new projects and partnerships. Many challenger providers agreed that they would not reach such an outcome alone withouth support of BioBoosters network.

The BioBoosters initiative successfully demonstrated how transnational collaboration and open innovation can drive circular economy practices and IS across sectors. These outcomes suggest that collaborative innovation can address real sustainability challenges, and pave the way for new cross-sector partnerships that enhance resource efficiency, reduce waste, and foster resilient, circular value chains in the Baltic Sea region and beyond.

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Industrial symbiosis business model for high-purity quartz extraction from quartz mining waste

Daria Pilova
Department of Applied Economics, Entrepreneurship and Public Administration, Dnipro University of Technology, Dnipro, Ukraine
d.pilova@gmail.com

Andrii Cherep
Department of Surface Mining, Dnipro University of Technology, Dnipro, Ukraine
cherep.a.yu@nmu.one

ABSTRACT

Quartz mining generates significant quantities of waste materials, including tailings and dust, which are often viewed as environmental challenges. However, these residues possess untapped potential as valuable resources for high-purity quartz (SiO_2) extraction. The integration of industrial symbiosis business models enables resource sharing and optimizes the use of by-products, reducing waste generation and minimizing the need for mining of minerals. The feasibility of utilizing quartz sand waste as a by-product of ilmenite mining within industrial symbiosis (IS) models, demonstrating how collaborative networks between industries can transform waste into economic opportunities and environmental benefits, were explored in the case study of Ukrainian mining and processing companies. For that purpose, characteristics of the volumes of high-purity quartz consumption in the world (volumes of quartz consumption by industries, quartz content, etc.) has been analysed. The cases studies have been examined with the use of a comparative assessment of the following groups of indicators: 1) characteristics of quartz sand in tailings at mining and processing companies of Ukraine (volumes of tailings reserves, quartz content of tailings, etc.); 2) analysis of processing technologies of quartz sand in tailings for high-purity quartz extraction (comparative analysis of technologies and the possibility of their application for existing quartz sand tailings at mining and processing companies of Ukraine). For the data analysis, data from the following databases were used: Eurostat; Trade Map; The Atlas of Economic Complexity; Resource Trade Earth. The analysis of processing technologies of quartz sand in tailings for high-purity quartz extraction is based on a literature review. High-purity quartz has wide-ranging applications in advanced industries, including electronics, solar photovoltaics, and high-performance materials. The present study investigates the potential applications of processed quartz sand across various industrial sectors, while concurrently addressing strategies to mitigate the ecological impact associated with mining operations and economic viability within the framework of IS. Case studies of the mining industry highlight successful implementations of IS where quartz sand mining waste can be converted into high-purity quartz and integrated into downstream industries. These collaborations not only reduce environmental footprints but also enhance profitability through shared value creation and supply chains. The study also discusses the policy and regulatory implications of adopting IS models in the mining sector, emphasizing the importance of government incentives, supportive legislation, and stakeholder engagement. By unlocking the potential of quartz mining waste for high-purity quartz extraction, the study underscores the critical role of IS in driving the transition to a circular economy and mitigating the environmental impacts of mining activities.

KEYWORDS
Industrial Symbiosis - Business Model - High-Purity Quartz - Mining Waste

INTRODUCTION

Modern challenges of sustainable development require rethinking traditional approaches to the use of natural resources, in particular in the mining industry. In the context of growing demand for high-tech materials, high-purity quartz (HPQ) is of particular importance, as it is a critically important raw material for producing solar panels, semiconductors, optical glass and other products with high technical requirements. At the same time, global deposits of HPQ are extremely limited, which stimulates interest in finding alternative sources of its production, in particular from mining waste.

Quartz sand waste, which is formed during the extraction of titanium-ilmenite ores, is a potential source of high-purity quartz. The integration of industrial symbiosis approaches, based on cross-sectoral cooperation and waste reuse, opens up new opportunities for increasing resource efficiency, reducing environmental burden and creating added value within the framework of a circular economy.

Ukraine has significant accumulated quartz sand waste, which can serve as the basis for the development of industrial symbiosis business models to meet the global demand for high-purity quartz. Therefore, an analysis of the potential for using waste from Ukrainian mining and processing enterprises as a source of HPQ in the context of industrial symbiosis and an analysis of the global demand structure for high-purity quartz, modern technologies for its purification, as well as the suitability of quartz sand from Ukrainian deposits for use in high-tech production is a topical task for the development of industrial symbiosis business models and institutional infrastructure that will facilitate the introduction of circular economy approaches in the mining industry of Ukraine.

METHODOLOGY

The methodological basis of the study is based on an interdisciplinary approach that combines economic analysis, natural resource assessment, technological efficiency analysis, and circular economy principles. The main goal is to determine the feasibility of using quartz sand from the waste of the Ukrainian mining industry to obtain HPQ within the framework of industrial symbiosis models.

The following methods were used in the study:

- Analysis of secondary statistical data: data from international databases (Eurostat, Trade Map, Atlas of Economic Complexity, Resource Trade Earth) were used to assess the dynamics of global demand for HPQ, the structure of international quartz trade, and industry consumption.
- Assessment of the potential of Ukrainian resources: data on the characteristics of quartz sand waste at Ukrainian mining and processing enterprises (SiO_2 content, presence of impurities, mineralogical features, etc.) were collected and summarized.
- Comparative analysis of quartz purification technologies: based on a review of modern scientific literature, an analysis and comparison of existing methods of enrichment and purification of quartz sand to obtain HPQ was performed.
- Case Study Analysis: possible cases of integration of enterprises into the industrial symbiosis model for the joint use of quartz sand waste and the production of high-purity quartz were analyzed.
- Regulatory analysis: the existing regulatory framework of Ukraine in the field of waste management, circular economy and stimulation of environmental innovations was assessed, which affects the possibility of practical implementation of industrial symbiosis models in the mining sector of Ukraine.

The systematic combination of these methods allows for a comprehensive assessment of the technical and economic feasibility of processing quartz sand from mining waste into high-purity quartz in the context of sustainable development and industrial symbiosis in Ukraine.

RESULTS

High-purity quartz applications

Silicon is the second most abundant element in the Earth’s crust after oxygen. However, it does not occur in the free state in nature. Silicon is a component of various natural silicates and aluminosilicates, the most common of which is silica – numerous forms of silicon dioxide, including river sand, quartz, etc. (Figure 1).

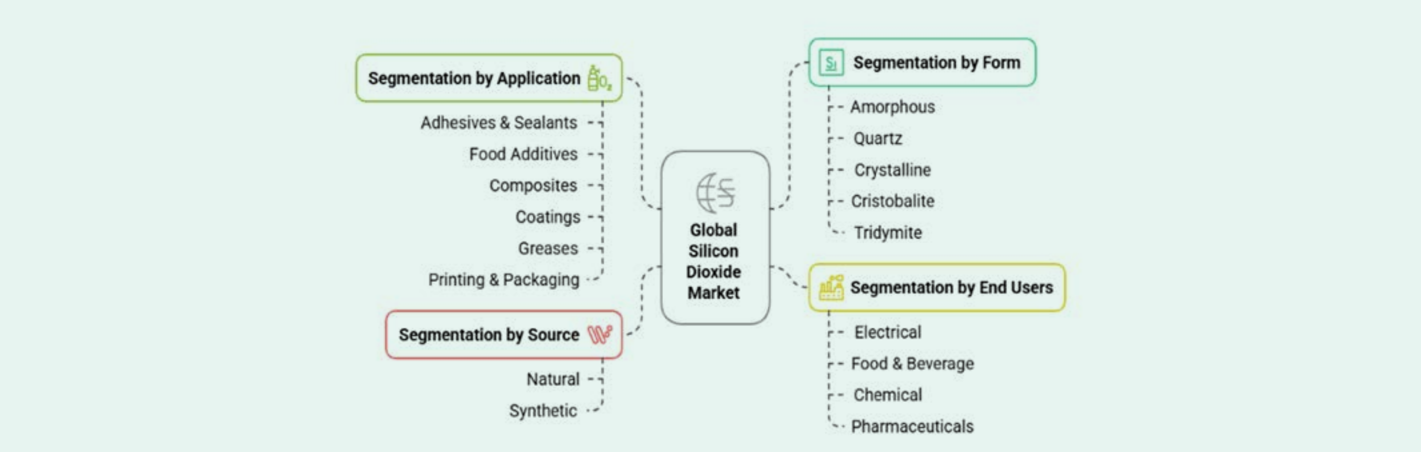

Figure 1 Global silicon dioxide (SiO²) market segmentation (GlobeNewswire, 2022).

Industrial silicon is produced in large quantities in electric furnaces by reducing silica with coal or coke. Semiconductor silicon is produced by reducing $SiCl_4$ or $SiHCl_3$ with hydrogen, followed by decomposition of the resulting SiH_4 at 400-600 degrees Celsius. High-purity silicon is produced by growing a single crystal from a semiconductor silicon melt in special growth furnaces.

The main feature of silicon production facilities is their very high energy intensity (12-18 kWh/kg), so the world's leading silicon producers have long been represented mainly by countries with developed energy sectors. Fuel (coke) costs are also significant in the production of silicon.

Pure silicon is a raw material primarily for two areas: solar energy and electronics. The production of solar module photovoltaic cells requires the highest quality silicon, the so-called monosilicon (Si content from 99.999 to 99.99999%). For electronics, a slightly lower quality product is acceptable - semiconductor silicon used as a raw material in the production of radio components and microcircuits. The market for semiconductor silicon continues to grow, as modern information technologies (computers, electronics, telecommunications, etc.) are based on its use and will continue to be based on it (Figure 2).

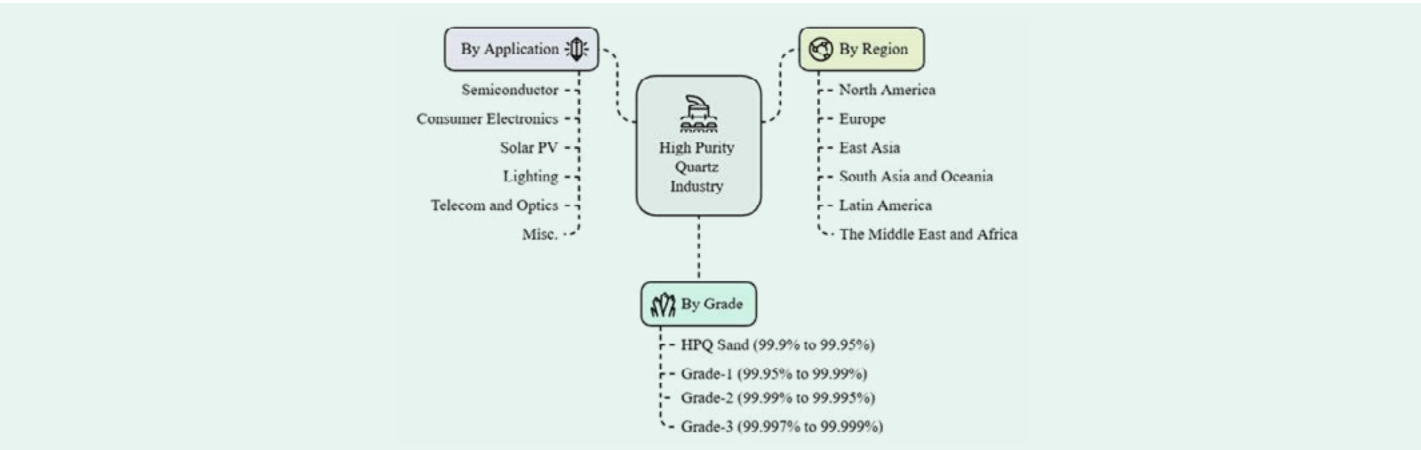

Figure 2 High purity quartz industry segmentation (Persistence Market Research, 2024)

Lower-quality technical silicon with a Si content of 96-99% is used in metallurgy, where it is used as a component of many steels and other alloys (in the smelting of iron, steels, bronzes, silumin, etc.). In addition, industrial silicon is used as a deoxidiser, modifier of metal properties or alloying element (increases mechanical strength and corrosion resistance, improves casting properties), as a raw material for the production of purer polycrystalline silicon, and as a raw material for the production of organosilicon materials and silanes.

Despite the fact that the global supply of raw materials for silicon production is considered to be quite high, the existing silicon production capacities, including polycrystalline silicon, are not enough. At the same time, the demand for it is extremely high from both the semiconductor industry and solar cell manufacturers. The silicon market is characterised by the fact that only a few countries in the world have the capability to produce it, and the relevant technologies are not sold.

Processing technologies for HPQ production

The production technology of HPQ includes several key components: raw material selection, processing technologies, processing equipment, and quality control systems. These elements form a comprehensive system consisting of independent yet interrelated and interdependent processes (L. Wang et al., 2014).

HPQ is characterized by an extremely low level of impurities (less than 20 ppm according to the Unimin IOTA CG standard) and is an essential material in many advanced optoelectronic industries. As noted in (Y. Zhang et al., 2023), in-situ analysis of muscovite and quartz may be useful for assessing the metallogenic potential of HPQ related to granite formations.

High-silicon iron ore tailings are traditionally considered unsuitable mining waste, occupying large areas and posing risks to human health and the environment. However, these tailings contain significant quartz reserves. Study (Y. Li et al, 2022) proposed a purification technology for such tailings using superconducting high-gradient magnetic separation (S-HGMS) combined with fluoride-free acid leaching. This approach enabled complete waste utilization without generating secondary waste and provided a theoretical and analytical basis for industrial-scale application.

In the Eastern Qinling region (China) – one of the leading metallogenic zones for rare metals – granite pegmatites are widely developed (Y. Zhang et al., 2022). One such pegmatite consists of quartz (39.8%), potassium feldspar (18.8%), albite (36.3%), and other minerals. Study (A. Müller et al., 2007) evaluated the kyanite quartzites of Norway as potential HPQ sources for specialized high-tech applications. According to laser ablation mass spectrometry, impurity content in the quartz samples ranged from 23.2 to 52.8 ppm, slightly higher than that of the Spruce Pine deposit in the USA (13.4–25.9 ppm), yet still indicative of HPQ potential.

The Marwit Rod El Leqah deposit was evaluated as a source of pegmatite quartz for high-tech uses based on geological, mineralogical, and geochemical analyses. The average SiO_2 content in the samples was 99.575%, with impurity minerals at approximately 0.422% (4220 ppm), classifying the deposit as medium-purity (S.S. Ibrahim et al., 2015, S.S. Ibrahim et al., 2015), which does not meet the minimum 99.8% SiO_2 requirement for solar and electronic applications.

Although quartz deposits are abundant in nature, deposits suitable for HPQ extraction are extremely limited. Therefore, efficient purification and processing of natural quartz into HPQ is a key research area in non-metallic mineral processing. As outlined in (R. Zhang et al, 2023), a review of quartz purification technologies in China highlights resource characteristics, geological origins, impurity types, and purification methods across five ore types: vein quartz, powder quartz, quartzite, granite pegmatite, and pegmatitic granite. One of the main challenges in HPQ development is the lack of standardized criteria for raw material selection. Modern purification methods face difficulties such as complex mineral separation, high acid consumption, high energy use, and long processing cycles. Furthermore, a lack of mineralogically based deep purification methods impedes industry growth. Given the diversity of quartz ore types, future research should focus on developing economically viable, environmentally safe, and technologically optimized purification techniques.

Rising demand for HPQ necessitates the exploration of new sources. In the Supe region (Cameroon), the presence of rutile, tourmaline, and muscovite inclusions negatively impacts quartz purity (A.N. Aloysius et al., 2022). Study (S. Cyrille et al., 2020) assessed the HPQ potential of a shear-zone-hosted quartz deposit in the Etam region of southwestern Cameroon. Based on trace element analysis used for HPQ classification, only some elements exceeded HPQ purity thresholds, while others fell within acceptable market standards. However, quartz quality can be improved to HPQ levels with proper purification. The quality and scale of quartz veins in this region suggest significant potential for HPQ exploration.

As noted in (G. Charalampides et al., 2020), quartz (crystalline SiO_2) occurs in nature with varying levels of purity and is under active investigation as a raw material for numerous technological applications. Chemical and mineralogical analysis revealed an absence of microcrystalline inclusions, qualifying it as high-purity α-quartz—potentially suitable for producing ultra-pure quartz if the deposit proves mineable.

Study (Y. Xie et al, 2024) examined two quartz veins from Hunza District (Gilgit-Baltistan, Pakistan) as HPQ raw materials. Several purification processes were studied, with roasting of quartz sand proving more effective in removing impurities than ore roasting.

The resulting quartz met the standards for industrial crucible production, with SiO_2 content in PK-JTLT sand reaching 99.991%, making it suitable for photovoltaic, electronic, and optical glass production.

Studies (M. Xia et al., 2024, I. Khan et al., 2025) investigated purification and HPQ potential of Pakistani vein quartz. Sand was processed using a combination of crushing, ultrasonic sorting, flotation, high-temperature roasting, water quenching, pressure acid leaching, and chloride calcination. Impurities could be further reduced through deeper purification. Results indicate that the purified sands meet HPQ standards required for industrial crucible manufacturing, confirming the high potential of these quartz veins as HPQ sources.

HPQ is a critical raw material with widespread applications in modern high-tech industries. Since HPQ is derived from high-quality natural quartz, selecting suitable raw material is a key success factor. Among the most promising types is hydrothermal vein quartz due to its high SiO_2 content. Study [6] evaluated quartz vein tailings from Chibougamau (CBG) and Tianjingshan (TJS) as promising HPQ sources, enabling effective tailings reuse and improved mining efficiency.

Authors of (H. Shao et al., 2022) achieved 99.994% purity quartz via alkali corrosion and acid leaching of vein quartz, meeting modern HPQ standards. Studies (Q.D. Zhang et al., 2017, T. Zhong et al., 2022) implemented integrated purification processes including roasting, quenching, flotation, acid leaching, and subsequent cleaning with alcohol-deionized water.

Study (A. Müller et al, 2012) proposed HPQ quality criteria based on threshold impurity concentrations. The primary factor influencing HPQ quality is intracrystalline impurities, which are not removed by conventional purification and significantly affect end-product quality.

Technological development depends on various factors, including geological and economic conditions. In Indonesia, a method has been developed to produce high-purity silicon dioxide from quartz sand for solar cell applications. The process involves roasting, dissolving sodium silicate in boiled water, followed by leaching, precipitation, and repeated washing using hydrochloric acid (A.B. Prasetyo et al., 2023). Study (T. Zhong et al., 2024) explored the use of quartz sand obtained from dredging operations. SiO_2 content in the samples reached 92.31%, presenting opportunities for secondary use and environmental benefits. The effectiveness of microwave-assisted impurity removal was experimentally confirmed using SEM, TG-MS, and in-situ XRD analysis, offering a promising route for producing HPQ from lower-grade sources.

As high-grade quartz deposits become depleted, the need to process lower-grade quartz increases. Study (Y. Gui et al., 2025) proposed an environmentally friendly fluorine-free acid leaching method with mechanical activation (F-free MA-AL), which yielded high-purity silica with 154.18 ppm impurities and a 97.76% removal rate. This approach supports efficient utilization of lower-quality raw materials and lays a theoretical foundation for industrial processing.

Study (H. Zhang et al., 2023) evaluated three quartz-bearing geological materials from Canada – vein quartz, massive quartz from a rare-earth deposit, and quartz sands – for their suitability for HPQ production. Samples underwent crushing, grinding, roasting, quenching, acid leaching, wet high-intensity magnetic separation (WHIMS), and reverse flotation. Both vein quartz and quartz sand met HPQ standards post-purification, making them viable for use in semiconductor filters, LCDs, and optical glass. However, higher aluminium levels were observed in vein quartz samples, with many impurities incorporated in the crystal lattice, requiring further deep purification to meet HPQ industrial standards.

Despite extensive studies on HPQ mineralogy and purification, impurity control at various stages and its impact on applications in photovoltaics, electronics, and optics remains underexplored. Study (H. Long et al., 2024) highlights the negative effects of impurities such as aluminium, iron, and sodium on manufacturing processes, emphasizing their critical role in reducing product quality. The study also discusses the environmental and economic aspects of HPQ production, underscoring the need for greener, cost-effective purification technologies.

Study (Y. Yang et al., 2024) summarizes common purification flowsheets and main methods used in China, including pretreatment, ultrasonic leaching, and chloride roasting.

The ongoing search for HPQ deposits and sources is driven by a shortage of suitable "clean" quartz deposits that meet modern industry standards. Therefore, choosing a specific beneficiation technology for HPQ depends on the deposit's geological structure, ore type, environmental impact of the processing method, and its cost-effectiveness within the operational context of a mining enterprise.

High-purity quartz demand

The rapid growth of the semiconductor and electronics industries (Figure 3) is significantly increasing the demand for ultrapure quartz materials, which are essential for producing modern microchips. At the same time, the development of the solar photovoltaics (PV) sector remains a key driver of demand growth, as the manufacture of solar panels and advanced renewable energy technologies requires high-quality quartz.

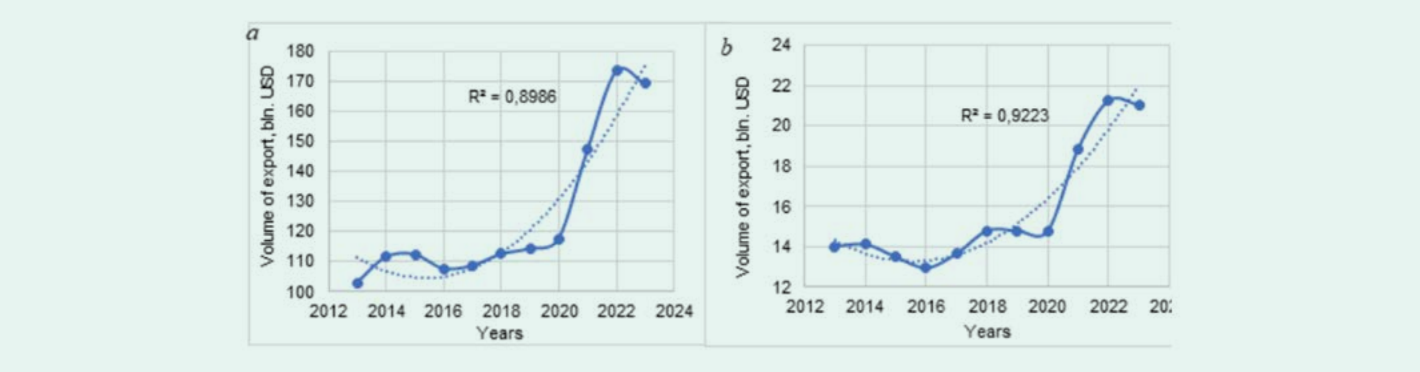

Figure 3 Export volume of semiconductor devices (a – World, b – EU) (International Trade Centre, 2025)

The demand for high-efficiency photovoltaics (HPV) in the production of photovoltaic cells has grown significantly, largely driven by active government support and the development of solar power in the US, which is projected to exceed 35 GW by the end of 2023. This growth underlines the key role of government initiatives in promoting renewable energy technologies.

Asia-Pacific is expected to see a surge in solar power plant installations, which will drive innovation and stimulate market growth. Asia-Pacific is projected to account for around 63% of the global market by 2024, with a CAGR of approximately 6.5% between 2025 and 2032. The main drivers of regional growth include the rapid expansion of solar PV installations and the growing use of HPV in the industrial and semiconductor sectors, particularly in China, India and Japan.

It is worth noting that China's solar power capacity has exceeded 500 GW, which indicates the country's significant investment in the development of renewable energy infrastructure. This large-scale expansion of generating capacity, in turn, has increased the demand for ultra-pure quartz (HPQ) for the production of solar cells, further integrating HPV into China's energy strategy.

In addition, the 'Make in India' initiative is fuelling industrial growth by attracting significant investment in semiconductor manufacturing. The allocation of USD 10 billion in 2023 to support domestic fabs demonstrates India's strategic commitment to developing its own semiconductor industry, which is likely to drive demand for high-performance materials, including HPQ.

Japan's developed electronics sector, coupled with rapid industrialisation in the Asia-Pacific region, is also contributing to the growth in demand for HPQ. This demand is not only a result of the increasing number of solar installations, but also a reflection of the broader shift to advanced technologies in the solar and semiconductor industries (Figure 4).

In conclusion, the interplay of government policies, investment activity, and technological advancements is shaping the high-efficiency photovoltaics (HPV) market. Significant growth potential in Asia Pacific, along with strategic initiatives in the US and India, underscores the critical role of ultrapure quartz (HPQ) as a driver of innovation in renewable energy and semiconductor technologies. As these trends continue to evolve (Figure 5), it is important for all stakeholders to remain flexible and ready to take advantage of the opportunities presented by this dynamic market (Persistence Market Research, High purity quartz market size, share and growth report, 2024).

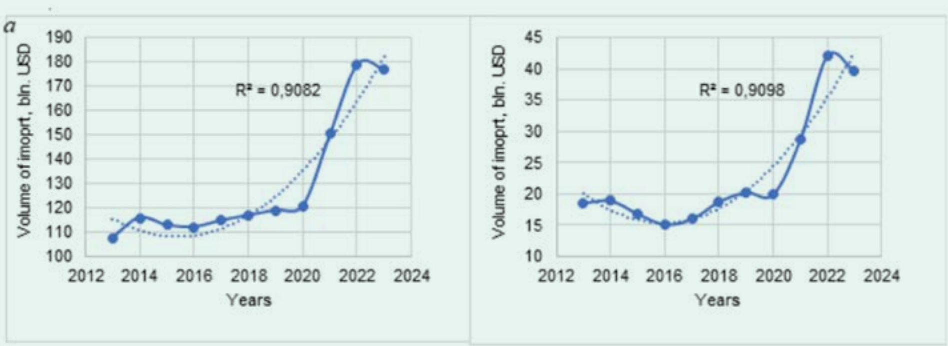

Figure 4 Import volume of semiconductor devices (a – World, b – EU) (International Trade Centre, 2025)

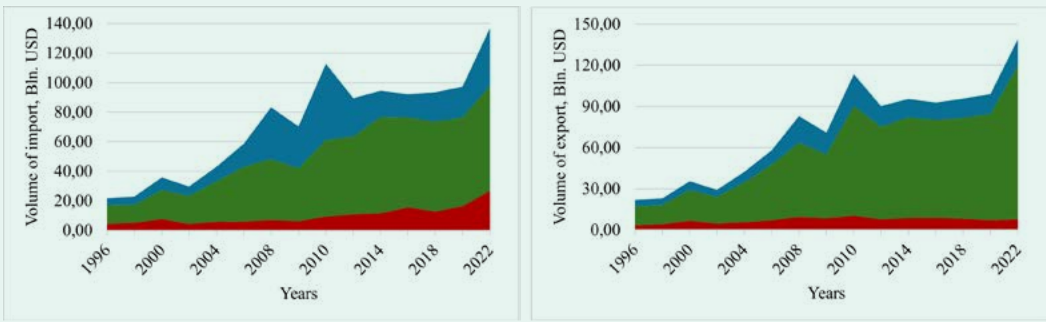

Figure 5 World trade of semiconductor devices by regions, 1995-2022 (Growthlab, 2025)

The optical and laser technology sectors are also showing a growing demand for ultra-pure quartz (HPQ) due to its high purity, excellent performance, low impurity content, thermal stability and optical transparency. These properties make it indispensable for the production of optical fibres, lenses and laser components, especially in the context of 5G, data centres and telecommunications.

At the same time, the limited number of HPQ deposits is a significant challenge for the industry's growth. Only two major deposits - Spruce Pine (USA) and Kyshtym (Russia) - account for about 95% of the world's ultra-pure quartz production. High levels of quartz purity are critical for applications such as semiconductors and solar panels. Limited supply reduces competition in the market and makes it difficult for small businesses to enter the industry.

HPQ's potential as a cleaner alternative to traditional energy-intensive purification methods is attracting the attention of mineral technology innovators. Growing concerns about the environmental impact of existing quartz mining and processing methods are driving companies to adopt sustainable practices. Increased focus on low-carbon and energy-efficient mining technologies is driving demand for HPQ in industries such as semiconductor, solar and optical technologies, promoting greener approaches to quartz purification.

Case study of the Ukrainian mining sector

Ukraine's total reserves of quartzite, the main raw material for silicon production, exceed 180 million tonnes. The deposits are located in Dnipropetrovs'k, Zhytomyr, and Kirovohrad regions (Ovruch, Tovkachiv, Bilokorovytske, Vasylkiv, and Ivanivske). The Ovrutske quartzite deposit has no analogues in Europe in terms of crystalline quartzite quality and reserves. The SiO2 content is 98.8%, with proven reserves of over 150 million tonnes and estimated reserves of 500 million tonnes.

In 1936, a quartzite mining, processing and enrichment enterprise was established on the basis of this deposit. Today it is OJSC Ovruchsky GOK Quartzite. The company specialises in open-pit mining using drilling and blasting. Currently, the company extracts and enriches up to 2 million tonnes of crushed quartzite, 300,000 tonnes of ground quartzite and 1 million tonnes of crushed stone per year.

The total reserves of quartzite sandstones in Ukraine are more than 9.5 million tonnes, with deposits in Sumy region (Banitske and Matskovske). The estimated reserves of the Matskovske deposit of silicon raw materials are approximately 100 thousand tonnes of rich quartz-bearing ores. The Banitske quartzite deposit is larger, with reserves of over 600 thousand tonnes. (BAU.ua, 2011).

There is a potential for solar panel production in Ukraine. Solar panels are made primarily of silicon (Si), which accounts for about 90% of the total composition of solar panels, steel and aluminium for 5-7%, glass for 3-5%, and plastics and polymers for 1-2%. These materials are used to produce various parts of the panels, including protective layers and insulation.

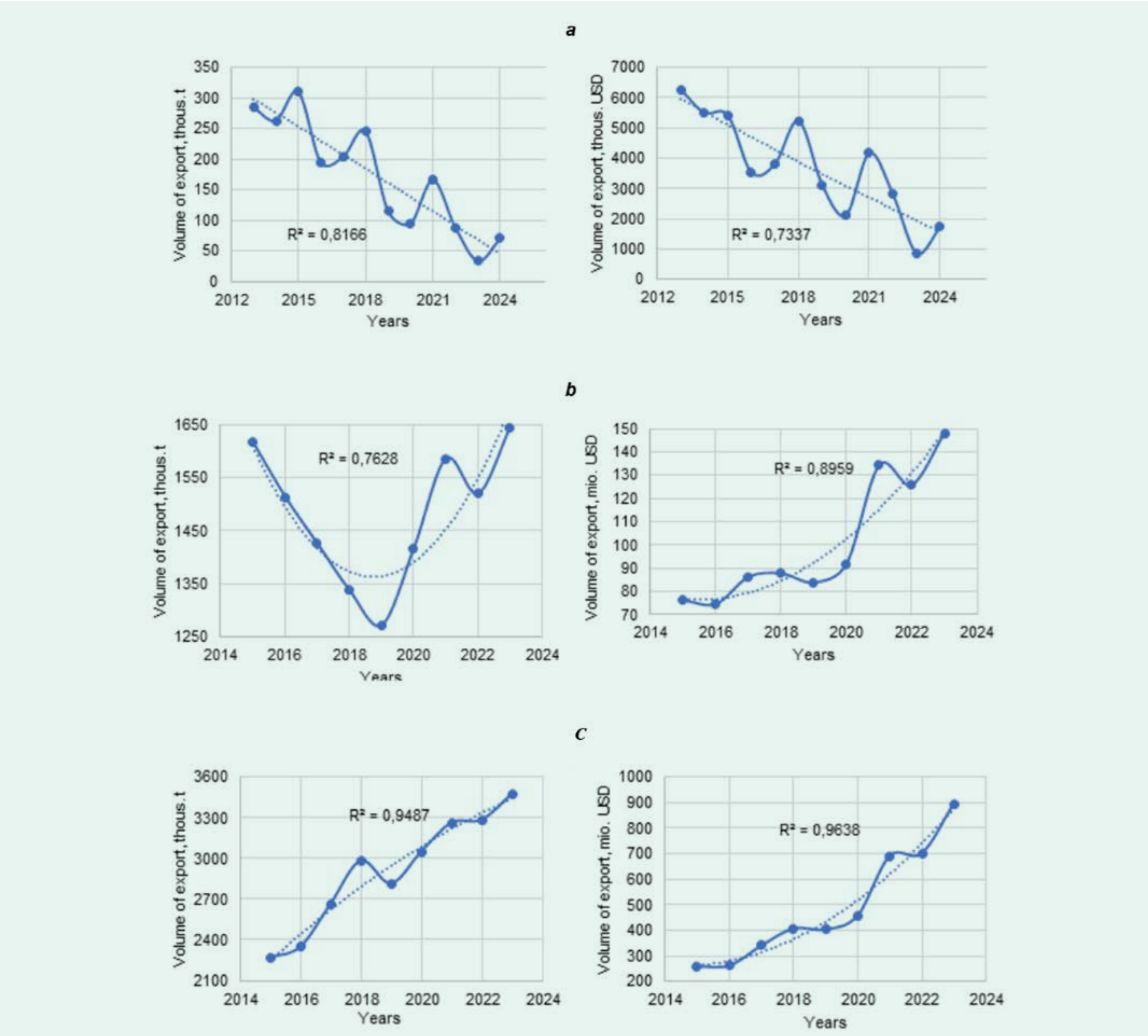

Figure 6 Volume of exported quarz products by Ukraine (a), EU (b) and World (c) in the category: 2506 Quartz (excluding natural sands); quartzite, whether or not roughly trimmed or merely cut, by sawing or otherwise, into blocks or slabs of a square or rectangular shape (International Trade Centre, 2025)

The share of copper, silver and gold is less than 1%. Due to their high conductivity, these metals are used to create contacts and wires. The main material used to create photovoltaic cells is silicon, as it efficiently converts sunlight into electrical energy. Silicon can be either mono- or polycrystalline, depending on the production technology.

In Ukraine, silica (silicon dioxide, SiO_2) is mined mainly in the form of quartz and quartz sands. In the Zhytomyr region, the Volyn deposit produces high-quality quartz, morion and related minerals such as rock crystal, beryl and topaz. In Zakarpattia region, there is the Sokyrnytsia deposit of zeolites, which contain a significant amount of silica. In Donetsk Oblast, there is the Krasnohorivka quartz sand deposit. Ternopil, Khmelnytsky, Ivano-Frankivsk and Lviv regions are home to major limestone deposits that also contain silica. In general, Ukraine has significant reserves of silica in the form of various minerals and rocks, which meets the needs of industry and creates the potential for the development of new industries, including solar energy.

Considering the increasing demand for high-purity quartz (Figure 6) as both a raw material and as a product of its processing, as well as the long-term growth trends in this sector, a preliminary study has been conducted to explore the feasibility of obtaining high-purity quartz from the tailings of placer titanium-ilmenite deposits in Ukraine. This investigation aligns with the broader transition to "clean" energy sources, the reduction of CO2 emissions, the minimization of industrial waste (particularly from the mining sector), and the shift towards new business models such as industrial symbiosis for industrial and energy enterprises.

The tailings in question are currently being processed as raw material for the production of glass containers and further refined to yield titanium-ilmenite concentrates. Preliminary research indicates that the quartz found within these tailings exhibits a relatively "clean" composition, containing minimal amounts of impurities such as titanium (Ti) and natrium (Na) at concentrations of ≥0.0n-0.1 wt%. This suggests a promising potential for the extraction of high-purity quartz.

Moreover, the processing of this quartz to achieve HPQ is deemed feasible through the use of gravity and magnetic separation techniques within strong and weak fields. The application of these enrichment strategies could significantly enhance the purity levels of the quartz, aligning with current market demands and sustainability goals.

In summary, the exploration of high-purity quartz extraction from titanium-ilmenite tailings not only addresses the growing market needs but also contributes to environmentally sustainable practices within the mining industry. As industrial operations shift towards more responsible production methods, the integration of such innovative approaches could yield significant benefits for both the economy and the environment.

Regional policy should be based on mapping the economic potential of regions and creating industrial hubs specializing in the production of specific products. Western regions of Ukraine can become a center for the production of high-tech components. A good example is the assembly of automotive parts and processing plants. Eastern regions of Ukraine should develop metallurgical production with an emphasis on the circular economy and clean technologies (M. Bevz, 2025).

The integration of industrial symbiosis business models enables resource sharing and optimizes the use of by-products, reducing waste generation and minimizing the need for mining of minerals. The feasibility of utilizing quartz sand waste as a by-product of ilmenite mining within industrial symbiosis (IS) models, demonstrating how collaborative networks between industries can transform waste into economic opportunities and environmental benefits, were explored in the case study of Ukrainian mining and processing companies.

Policy and regulations for adopting IS models in the Ukrainian mining sector

The mining industry is one of the most resource-intensive and environmentally sensitive sectors of the economy, requiring the implementation of circular economy principles to reduce waste and optimize resource use. One promising approach is industrial symbiosis business models that promote cross-sectoral cooperation and reuse of waste as secondary raw materials. In the case of quartz mining, the use of quartz sand from tailings as a source of HPQ can help minimize environmental impact and increase economic efficiency of enterprises. However, the effective implementation of such business models in Ukraine requires favourable regulatory and legal regulation and stimulating political initiatives.

In Ukraine, the concept of a circular economy is gradually being integrated into national legislation through the adoption and adaptation of regulatory legal acts aimed at conserving resources, minimizing waste and promoting sustainable development, in particular:

- Law of Ukraine "On Waste Management": this law establishes the legal framework for preventing waste generation, its collection, transportation, processing and disposal in order to reduce the negative impact on the environment and human health, and also promotes the transition to a circular economy.
- Law of Ukraine "On the Basic Principles of State Climate Policy": this law introduces the concept of "circular economy" and expands its content from traditional waste management to the concept of low-carbon development aimed at reducing greenhouse gas emissions and rational use of resources;
- National Waste Management Strategy in Ukraine until 2030: defines the main directions of state policy in the field of waste management, including the implementation of the principles of the circular

economy, in particular by reducing waste generation and stimulating its reuse and recycling;

- Concept for the implementation of state policy in the field of climate change for the period until 2030: this document is aimed at reducing greenhouse gas emissions and introducing environmentally friendly production using “green” technologies in all sectors of the economy, which is consistent with the principles of the circular economy;
- Strategy for the low-carbon development of Ukraine until 2050: the strategy provides for measures to reduce leakage in the gas sector, reduce leakage during gas transportation and use, as well as introduce technologies that promote the reuse and recycling of waste, which are key elements of the circular economy.

In July 2024, a draft law of Ukraine “On Amendments to the Law of Ukraine “On Industrial Parks” was developed to improve the functioning of industrial parks and introduce an eco-industrial park model”.

Despite progressive changes in legislation, Ukraine still does not have clear mechanisms to stimulate industrial symbiosis, as implemented in EU countries.

Despite in existing legislative acts, there is a need to further develop the regulatory framework for the full implementation of industrial symbiosis and circular economy in Ukraine. In particular, there is a need to create incentives for enterprises that use secondary raw materials and to improve the waste management system of the mining industry.

CONCLUSIONS

The results of the study confirm the high potential of using waste from the mining industry of Ukraine, in particular quartz sand from titanium-ilmenite deposits, as an alternative source of HPQ. It is substantiated that the use of industrial symbiosis models will simultaneously solve the environmental, economic and resource challenges associated with traditional methods of quartz extraction and processing.

The analysis of processing technologies showed the presence of effective technological solutions that can be adapted to the existing conditions of Ukrainian enterprises. At the same time, industrial symbiosis business models will contribute to the creation of new value-added chains and the reduction of industrial waste volumes by reusing them in production processes.

An important factor for the implementation of such approaches is the formation of a favorable regulatory environment. Although Ukraine is gradually implementing the principles of a circular economy, there is still a need to improve legislation, create financial incentives and develop inter-sectoral cooperation.

Thus, the transition to waste-based HPQ extraction and processing under industrial symbiosis is a promising direction for the development of Ukraine’s mining industry. This will contribute not only to increasing the efficiency of resource use, but also to the integration of Ukrainian enterprises into global supply chains of high-tech products in a sustainable development environment.

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