ENABLING CIRCULAR ECONOMY THROUGH INDUSTRIAL SYMBIOSIS PLATFORMS: A QUINTUPLE HELIX AND EDUCATIONAL PERSPECTIVE

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Abstract
Current economic development is experiencing a significant transformation in the European Union. For the last decade, it has become explicitly clear that the linear business model is no longer valid, as it leads to such factors as overconsumption, overproduction, natural resource scarcity, and extensive waste generation. The circular economy is seen as one of the practical solutions, offering a range of business models that can overcome these issues. This research examines the transformative potential of Industrial Symbiosis in the transition to a Circular Economy by applying the Quintuple Helix approach. The research aims to identify different tools and enablers for Industrial Symbiosis adoption, emphasising the role of digital platforms and educational initiatives that promote resource sharing and cross-sectoral collaboration. The methods used within this research are evaluating secondary data, including policy document analysis and small and medium company surveys. The study enhances stakeholder awareness and skills in implementing Industrial Symbiosis principles by assessing the educational gaps and a range of digital tools that different Stakeholders can apply in various manners, thus still fostering Industrial Symbiosis. Research findings highlight the importance of stakeholder education and technology-driven solutions in overcoming Industrial Symbiosis implementation challenges. Interdisciplinary learning promoting and integrating sustainability and circular economy aspects in study curricula can result in more qualified employees possessing the ability to see the big picture and comprehend the benefits of cross-sectoral cooperation and resource efficiency on local, regional, and national levels.
Keywords: circular economy, industrial symbiosis, digitalisation.

Introduction

It is becoming more and more evident that Circular Economy business models will have a long-term impact on the present economic model and that the countries will have to adopt new ways of thinking and management, in particular when tackling resource efficiency and recovering the value of by-products and materials before becoming waste (Yazan & Fraccascia 2019; Ghisellini et al., 2016; EC, 2014). The researcher considers Industrial Symbiosis a significant mind shift and facilitator for such a transition (Kiesnere et al., 2024). It requires certain preconditions to be met, but for such a geographically small country as Latvia, this could become a country-wide Project or a set of Sandboxes across the country. Social, economic, and environmental modifications of current legislation, business practices, mindsets, and infrastructure might be required to implement Industrial Symbiosis in real-time. Considering current trends within the European Green Deal and the latest Clean Industrial Deal, setting targets such as an increase of circular material use rate from 11.8% in 2025 to 24% by 2030, Industrial Symbiosis may be an efficient way for the national economies to move forward. Therefore, Industrial Symbiosis may be an efficient pathway for national economies, including Latvia, to advance toward a more circular and resource-efficient economy. This research aims to explore and design effective mechanisms for enabling Industrial Symbiosis in Latvia, focusing on digital platforms and educational tools that promote cross-sectoral collaboration, resource efficiency, and sustainable development. The author identifies the following main objectives of the research:

- To identify key enablers and barriers to Industrial Symbiosis adoption in Latvia.
- To evaluate the role of digital technologies and educational initiatives in facilitating Industrial Symbiosis.
- To analyse case studies and existing Industrial Symbiosis platforms to identify best practices.
- To develop a conceptual framework integrating Industrial Symbiosis within Latvia's national circular economy agenda.

Present research has identified three main research questions:

1. What tools and practices are most effective for enabling Industrial Symbiosis in the context of Latvia's bioeconomy?
2. How can digitalisation and education support cross-sectoral engagement in Industrial Symbiosis?
3. What are the practical steps and preconditions needed to scale up Industrial Symbiosis across Latvia?

Industrial Symbiosis concept

Industrial symbiosis is an innovative concept that promotes resource sharing and waste exchange among industries, leading to sustainable and efficient operations, thus contributing to the Waste Framework Directive by focusing on the best possible waste treatment option – waste prevention. This research is relevant and novel because it addresses the growing need for more sustainable practices in the manufacturing sector and the necessity to optimise resource consumption by producing more with fewer virgin materials. Furthermore, Industrial Symbiosis contributes to the circular economy by promoting the reuse and optimisation of resources, reducing waste generation and greenhouse gas emissions. The research on Industrial Symbiosis is crucial in understanding and promoting the transition towards a more sustainable and

integrated industrial system. The latest research discusses the surge of Industrial Symbiosis development in Europe and highlights its importance in fostering circular and sustainable practices in the manufacturing sector and beyond (Uvarova et al., 2020; Jiao & Boons, 2021). The research on Industrial Symbiosis is topical as it provides an updated overview of the activity in Europe, mapping key networks and studying prevailing typologies, size, geographical distribution, and resources traded. It also identifies obstacles and challenges facing Industrial Symbiosis development in Europe, such as weak economic incentives, geographical variations in incentives and drivers, and legislative complexities that hinder cross-border transport (Lawal et al., 2021). The research on Industrial Symbiosis provides valuable insights into the potential of this approach to contribute to the transition to a Circular Economy. It is crucial in understanding and promoting the transition towards a more sustainable and integrated industrial system. In the global arena, it is also important to seek solutions to foster Industrial Symbiosis and avoid barriers to its implementation. With this respect, the researcher also considers a 'sandbox approach' to be a very beneficial tool for the stakeholders to be on the same page and avoid potential administrative burdens and potential fines from the regulatory authority. The sandbox approach, often utilised in business and technology contexts, involves creating a safe and controlled environment for testing new ideas, products, or services before full-scale implementation (Johnson et al., 2008; Spitsin et al., 2024). It provides organisations with a structured framework to experiment with innovative solutions and assess their feasibility, functionality, and potential impact without risking disruptions to existing operations or stakeholders (Islam, 2024).

When assessing Latvia's case, specific examples of industrial symmetry may be found, but they are pretty small-scale and mainly limited to resource exchange between just two companies. However, the current assessment of statistical data, particularly Latvian ratios in material consumption and resource efficiency, shows the urgent necessity for improvement. Latvia's resource efficiency was about 0.93 Eur/per capita in 2020. In contrast, the EU average was 2.19 Eur/per capita, and according to the latest data, the figures have reached 0.94 Eur/kg and 2.7 Eur/kg, respectively (CSP, 2024; Eurostat, 2024). At the same time, material consumption reaches approx. 16t/capita, whereas the EU average is 14 t/capita. The 8th Environment Action Programme aims to significantly reduce the EU's material footprint, meaning the amount of raw material extracted to produce goods and services. The per capita material footprint remained stable from 2010 to 2022 and dropped by 4.5% in 2023. Raw material extraction was 14.1 tonnes per capita in 2023, which is considered unsustainable and above the global average (EEA, 2024). This leads to the conclusion that Latvia uses many primary resources ineffectively. The researcher sees that Industrial Symbiosis may be a tool to improve the aforementioned ratios, implement the Circular Economy business model into practice, and boost Latvian companies' competitiveness in the EU and Global market.

Table 1

Assessment of a sample of physical and digital Industrial Symbiosis Cases

Industrial Symbiosis Name	***Type of Symbiosis***	***Country of Origin***	***Years in Operation***	***Key Performance Indicators (KPIs)***	***Additional Information***
Kalundborg Eco-Industrial Park	Physical resource exchange (water, energy, materials)	Denmark	Since 1970s	Over 30 symbiotic exchanges; significant reductions in CO_2 emissions; increased resource efficiency.	One of the earliest examples of industrial symbiosis, with long-standing partnerships between companies.
Kemi-Tornio Industrial Symbiosis	Physical resource exchange (materials, energy)	Finland	Since early 2000s	Involves over 700 companies; over 5,000 resources registered; over 2,500 synergy opportunities identified.	Developed to increase energy and resource efficiency in the region. Activities include joint use of utilities, collective waste management, combined transport, and shared facilities.
Finnish Industrial Symbiosis System (FISS)	Facilitated resource exchange and co-development	Finland	Since 2013	Over 30 workshops conducted in 14 regions; over 700 companies involved; over 5,000 resources registered; over 2,500 synergy opportunities identified.	FISS is based on active facilitation of symbioses and co-development. It brings together regional actors in a network to promote new business opportunities, re-use of waste, and reduction in the use of natural resources.

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Śmiłowo Eco-Industrial Park	Physical resource exchange (materials, energy)	Poland	Since 1982	Utilizes 300,000 tons of meat waste/year; produces 110,000 tons of meat and bone meal biofuel; uses 120,000 tons of pig manure as fertilizers; produces 460,000 GJ of bioenergy; eliminates 92,000 tons of CO_2 emissions.	The park covers the entire lifecycle of products, from plant cultivation to animal feed preparation, livestock breeding, meat processing, and waste utilization for biofuel and fertilizers.
Sfridoo Marketplace®	Digital marketplace for secondary resources	Italy	Since 2017	Thousands of material transactions; numerous companies participating in waste repurposing.	A SaaS platform for listing, buying, and selling industrial by-products.
ENEA Industrial Symbiosis Platform	Digital matchmaking for industrial waste utilisation	Italy	Since 2011	Connected 250 companies; facilitated over 2,600 resource exchanges.	Conducts resource audits and connects companies for sustainable waste utilisation.
Life M3P	An online matchmaking platform for industrial waste	European Union (Italy, Belgium, North Macedonia, Spain)	2016–2019	Optimised resource use in manufacturing; reduced landfill waste.	Focused on lowering virgin raw material consumption through industrial waste exchange.
SYNERGie® Platform	Digital industrial symbiosis tool	International	Since 2005	Over 100,000 resources listed; connected 34,000+ organizations across 23 countries.	Developed by International Synergies Limited, it is used globally for industrial matchmaking.

Materials and Methods

The present research focuses on secondary data analysis and monographic research to identify efficient solutions for Industrial Symbiosis in the digital era. In addition, the study covers a preliminary assessment of a survey disseminated in five countries among businesses related to Industrial Symbiosis. The quintuple helix framework allows researchers to look at the research topic from different angles and identify the most effective solutions that further need to be disseminated in the educational process. As the author is concerned, taking into consideration the global shift for businesses towards circular economy business models as well as a sustainable business practice in the long run, the topic of Industrial Symbiosis as well as digitalisation aspects must be integrated as cross-sectoral knowledge base not only for specific study programs but on a broader scale. Table 1 summarises sampled industrial symbiosis cases in both physical and digital marketplaces to broaden general awareness of types of symbiotic cooperations.

Results and Discussion

Incorporating digital technologies into Industrial Symbiosis frameworks can revolutionise cross-sectoral cooperations by improving data exchange, process optimisation, and overall network efficiency (Su et al., 2023). Digital technologies enhance Industrial Symbiosis by developing specific match-making solutions, i.e. identifying symbiotic opportunities (Makropoulos et al., 2024), as well as allowing for real-time information exchange (Akrivou et al., 2022) and supporting companies through different digital platforms (Cecelja et al., 2015). Industrial Symbiosis also allows information and communication Technology to step in and combine with the Internet of Things to create more resource-efficient production and management systems (Grant et al., 2010). During the desk research, using secondary data and monographic research method, a range of digital technologies have been identified as the ones that can significantly impact Industrial Symbiosis digitalisation:

Digital Platforms and Information and Communication Technology (ICT) Systems

Digital platforms and ICT systems can become centralised hubs for data exchange among companies and industries. These platforms offer real-time information exchange regarding available resources and arising waste streams and highlight potential synergies, enhancing collaboration and decision-making processes. One example worth mentioning here is the CORALIS project, which stresses the importance of standardised sharing protocols and common ICT platforms to improve company mutual trust, process efficiency, and innovation implementation within Industrial Symbiosis networks (Krom et al., 2022; Riesner et al., 2025).

Blockchain Technology

Blockchain technology is another considerably innovative solution offering a decentralised and secure method for saving transactions and tracking resources managed within Industrial Symbiosis networks. It is also being seen as enabling the technology of Industry 4.0 to disseminate industrial symbiosis practices (Ciano et al., 2025). Blockchain can enhance transparency, traceability, and mutual trust among participating companies (which is especially important if the companies have not cooperated in the past and come from different industry sectors, regions, or even countries) by providing bulletproof records of resource exchanges. This technology allows for overcoming challenges linked to data confidentiality and integrity, which often become a cornerstone of why many companies are very reserved in engaging in Industrial Symbiosis (Parikshit et al., 2023; Aquilani et al., 2020).

Digital Twins

Digital twins are virtual representations of physical assets, processes, or systems that enable real-time data adjustment, monitoring, and simulation. In the framework of industrial symbiosis, digital twins can be applied to model a company's or an industry's resource flows, forecast outcomes of potential synergies, and optimise the company's operations. This tool allows for the development of the Sandbox approach by securing a controlled environment and possibilities to ensure real-time monitoring (Bandara & Buics, 2024; Mammun et al., 2021). The most common ways to apply digital twins are:

- Urban Planning: to simulate traffic, energy consumption, and infrastructure development, as well as city expansion planning and efficient existing resource management.
- Healthcare: to apply personalised treatment planning and predictive diagnostics.
- Manufacturing: to monitor equipment operation, forecast and divert failures, and optimise operations, thus reducing standstill time and operational expenditures.
- Retail: to optimise store layouts and enhance customer experiences.

Internet of Things (IoT) and Sensors

Diverse IoT devices and sensors allow for real-time data collection on resource consumption, waste generation, and identification of specific environmental conditions. This data can be further processed to monitor internal and external processes, detect inefficiencies in the latter, and identify opportunities for improvement as well as for symbiotic exchanges. The data flow from IoT devices, which is being performed in real-time, supports dynamic and proactive decision-making and enhances the responsiveness of Industrial Symbiosis networks (Mallawaarachchi & Jayakodi, 2023).

Data Analytics and Artificial Intelligence (AI)

Sophisticated data analytics and the application of specific AI algorithms can process large datasets to identify patterns, predict trends, and, as a result, optimise resource management strategies. In the Industrial Symbiosis context, efficient application of these technologies can identify potential synergies, forecast the benefits of cross-sectoral company collaborations, and support strategic planning on the company, regional, or even national levels. The integration of AI into the Industrial Symbiosis daily routine can lead to more efficient and sustainable cooperation networks that would be guided by data-driven decisions as well as the identification and implementation of symbiotic relationships (Hamidur, 2022; Chatzidimitriou et al., 2021). Table 2 provides the results of a comparative analysis of the existing digital technologies in Industrial Symbiosis that have been assessed above.

Table 2

Benefits and Drawbacks of Digital Technologies in Industrial Symbiosis

Digital Technology	***Benefits***	***Drawbacks***
Digital Platforms and ICT Systems	+ Enhance communication and data sharing among participants + Facilitate the identification of symbiotic opportunities + Improve coordination and efficiency	− Standardisation and interoperability required − Potential resistance to technology adoption − Dependence on reliable digital infrastructure
Blockchain Technology	+ Ensure data security and transparency + Build trust among participants + Provide immutable records of transactions	− High energy consumption − Complexity in implementation − Scalability concerns

Digital Technology	***Benefits***	***Drawbacks***
Digital Twins	+ Enable real-time monitoring and simulation + Optimize resource flows and processes + Predict outcomes of potential synergies	– High initial setup costs – Continuous data input required – Complexity in creating accurate models
IoT and Sensors	+ Provide real-time data collection + Monitor environmental conditions + Detect inefficiencies promptly	– Data privacy and security concerns – High costs of deployment and maintenance – Potential data overload without proper analytics
Data Analytics and AI	+ Identify patterns and predict trends + Optimize decision-making processes + Enhance strategic planning	– Large datasets for accuracy required – Potential biases in algorithms – Skilled personnel to interpret results needed

When applying the Quintuple helix approach to the results of this research, one can identify the digital tools that each of the Stakeholders can apply and identify overlaps that can lead to applying one or another technology. Based on the literature research on the tools used by different stakeholders, the author has developed Figure 1, which depicts the correlation of the digital tools with the Quintuple Helix stakeholders, which will be further approbated during the follow-up research.

Figure 1

Digital tools application by Quintuple Helix Stakeholders

Digital Technology	Government	Industry	Academia	Civil Society	Environment
Digital Platforms and ICT Systems	Policy-making, regulation, public data platforms	Supply chain management, resource exchange platforms	Research collaboration, data sharing	Community engagement, transparency	Environmental monitoring, sustainability reporting
Blockchain Technology	Secure transactions, policy enforcement	Supply chain transparency, smart contracts	Research on secure data exchange	Consumer trust, fair trade verification	Tracking resource flows, reducing waste
Digital Twins	Urban planning, infrastructure simulation	Production optimization, waste reduction	Research on predictive analytics	Public engagement in city planning	Ecosystem modeling, climate impact assessment
IoT and Sensors	Smart cities, regulatory compliance	Process automation, real-time monitoring	Experimental testing, research data collection	Citizen science, real-time awareness	Pollution tracking, biodiversity monitoring
Data Analytics and AI	Policy analysis, forecasting	Market predictions, efficiency optimization	Machine learning research, knowledge discovery	Public sentiment analysis, behavioral insights	Climate modeling, predictive sustainability metrics

In addition, the author has assessed the results of a survey on Industrial Symbiosis among small and medium companies in five different countries – Latvia, Norway, Slovenia, Poland, and Italy. The number of respondents in the interim stage, as the survey period is still in process, is 72. The author would like to highlight three main aspects that the survey has revealed. First, regarding overall awareness of Industrial Symbiosis, it can be noted that 43% of respondents had not heard of the concept of Industrial Symbiosis before the survey; 38% selected the 'somewhat familiar' option, and only 19% stated that

they are very familiar with the concept.

Another aspect that arose from the survey is the knowledge gaps identified by the companies:

- 56% - Understanding industrial symbiosis and circular economy basics;
- 56% - Identifying resource-sharing opportunities;
- 50% - Benefits of IS/CE for cost savings and business growth;
- 47% - Digital tools that support IS (e.g., tracking waste, finding partners);
- 41% - Complying with environmental regulations.

This result reveals an impressive knowledge gap and a call to action for the Higher Education Institutions and trainers. Even though the surveyed companies stated a lack of general knowledge on the topic in the first place, the assessment of these gaps proves that the companies are ready and would be interested in knowledge-building as it may result in economic efficiency, value creation, and cost optimisation for OpEx. This led to the necessity to offer market-specific stand-alone on-demand courses on circular economy and Industrial Symbiosis. This also signals that this knowledge may be lacking in the overall education system. Taking into consideration the latest developments in terms of sustainability, circular economy, European Green Deal, etc., it is becoming more and more important to revise the study program curricula and implement the latest trends on the aforementioned topics not only in specific study programs, but horizontally into all study programs to broaden the general society knowledge on these topics, so it is further transferred and applied in the business sector.

Conclusions

The present research explored how digitalisation and education can be key enablers for industrial symbiosis implementation in Latvia's transition toward a circular economy. By applying the Quintuple Helix model and analysing secondary data alongside preliminary survey insights from SMEs across five countries, several important conclusions emerged:

1. Digital technologies - including platforms, blockchain, IoT, digital twins, and AI - demonstrate strong potential to facilitate resource-sharing, enhance transparency, and optimise symbiotic cooperation across sectors. However, effective implementation depends on overcoming interoperability, data security, and digital infrastructure challenges.
2. The Quintuple Helix model proved helpful in identifying how different stakeholders - academia, industry, government, civil society, and the environment - can apply or benefit from IS-related digital tools. This intersection strengthens policy integration, innovation uptake, and cross-sectoral learning.
3. The survey results confirmed that many SMEs lack awareness and practical knowledge about Industrial Symbiosis, particularly regarding digital tools, environmental compliance, and circular business opportunities. This underscores the urgent need for targeted educational initiatives and training.
4. Integrating Industrial Symbiosis into higher education and vocational programs is essential to fill knowledge gaps, foster sustainable mindsets, and create a future workforce supporting a circular and digitally enabled economy.

Future research will focus on testing digital tools in educational 'sandboxes' and developing modular training materials to support Industrial Symbiosis implementation in practice and foster its popularity within Latvian policy planning, municipalities, society, and business sectors.

Acknowledgements

The research is financed by the Recovery and Resilience Facility project 'Internal and External Consolidation of the University of Latvia' (No.5.2.1.1.i.0/2/24/I/CFLA/007)., LU-BA-ZG_2024/1-0008.

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