Bridging Traditional and Digital Industrial Symbiosis: Comparative Insights From Croatia and Slovenia in the ESG and Digital Transformation Era

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In the era of ESG and AI, industrial symbiosis (IS) represents a key strategy for achieving sustainable management. This paper presents a comparative analysis of two national approaches, Croatia's traditional, material-based IS model and Slovenia's digitally supported e-Simbioza platform, to explore how analogue and digital pathways can both contribute to ESG goals. Through qualitative analysis of secondary data and case studies, the research highlights how digitalization, including the use of ICT and potential applications of AI, can enhance symbiotic networks through improved coordination, transparency, and predictive analytics. While Croatia demonstrates strong industry-led practices, Slovenia's approach emphasizes digital facilitation. The findings reveal a complementary relationship between traditional and digital models of IS, suggesting that AI and digital tools can gradually augment established IS practices. Despite regulatory and infrastructural barriers, this study offers insights for policymakers and businesses aiming to scale circular economy practices in the context of the green transition and digital transformation.

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1 Introduction

Industrialization and urbanization have significantly increased carbon dioxide emissions and require solutions that balance economic growth and environmental sustainability. Industrial symbiosis has proven to be an effective strategy as it enables companies to exchange materials, energy, water and by-products, thereby reducing waste, lowering emissions and optimizing resource use. Recognized by the European Commission as a key component of the circular economy, industrial symbiosis supports both economic and environmental sustainability.

In Croatia and Slovenia, industrial symbiosis plays a crucial role in promoting Environmental, Social, and Governance (ESG) objectives by integrating environmental innovation into industrial processes. This paper examines how cross-industry collaboration promotes sustainable economic models and strengthens regional resilience. This paper explores how industrial symbiosis contributes to ESG-oriented sustainability through two distinct approaches: a traditional material-exchange model (Croatia) and a digitally enhanced coordination model (Slovenia). The central research question is: "How do different models of industrial symbiosis, one analogue and one digital, support the achievement of ESG goals and what lessons can be drawn from their comparison?"

The paper is structured as follows: The first chapter of this paper is the introduction. The second chapter provides an overview of the relevant literature on industrial symbiosis and its ESG implications. The third chapter outlines the research methodology, data sources, and analytical approaches. The fourth chapter presents the findings, focusing on case studies from Croatia and Slovenia, while the fifth and the sixth chapter discuss the key findings, challenges, and potential solutions. The conclusion summarizes the research contributions and suggests directions for future studies.

2 Theoretical Background / Literature review

A system of production and consumption known as the circular economy (CE) encourages the long-term use of products, boosts resource efficiency, and decreases waste (Erceg et al., 2024). In contrast to the linear model (produce, use, throw away), CE promotes recycling, repairing, and reusing materials in order to reduce the

consumption of natural resources and the negative impact on the environment. CE is applied in various sectors including consumer goods, electronics and textiles, and is based on five models: 1) circular supply, 2) resource recovery, 3) product life extension, 4) sharing, and 5) product service models.

As Erceg et al. (2024) state, the collaboration between industrial businesses, when waste or by-products from one company become raw materials for another, is known as industrial symbiosis (IS), which is a subset of industrial ecology (IE). This model improves resource efficiency, decreases waste, and generates financial gains. In order for companies to reduce the costs of raw materials and waste disposal, companies located close to each other work together in IS and exchange resources (materials, energy, water). The most important goals of IS include increasing competitiveness, extending the life of materials in the economic cycle, and maximizing the use of natural resources. The "3–2 heuristic" is often used to distinguish IS from other types of exchange where at least three entities and at least two types of resources are involved in the exchange (Chertow, 2000).

The most common definition of industrial symbiosis (IS) comes from Chertow (2000), who describes it as the collaboration of traditionally separate entities through the physical exchange of materials, energy, water and by-products, where cooperation and synergy, often enabled by geographical proximity, are key elements (Erceg et al., 2024; Martin, 2020). Lombardi & Laybourn (2020) have proposed a more recent definition of IS, which has been adopted by the Journal of Industrial Ecology. The same definition is summarized by Eomenech et al. (2019), stating that IS is a systematic approach to a more sustainable industrial system that identifies business opportunities through the use of unused resources (materials, energy, water, capacity, know-how, etc.). IS involves organizations from different sectors exchanging resources for the reuse of waste and by-products in order to optimize the value of remaining materials in production processes (Castiglione, 2021).

Industrial symbiosis (IS) involves cooperation between industrial companies through the exchange of materials, energy, water, and by-products, as well as the shared use of services and infrastructure (Van Eetvelde, 2018). An important prerequisite for successful IS is the identification of opportunities for such exchange. The types of resources achieving synergy in the exchange of materials and waste can be raw materials, by-products, waste materials, energy, and water (Erceg et al., 2024).

Figure 1: Examples of Country-Specific Numbers of European Industrial Symbiosis
Source: Erceg et al. (2024)

The best-known example of IS, mentioned by Bilić et al. (2024), Al-Quradaghi et al. (2020), and Gulipac (2016), is the Kalundborg Eco-Industrial Park in Denmark. Kalundborg Symbiosis (see Figure 2) includes both world-leading and smaller companies, but regardless of size, the benefits of industrial symbiosis are clear: cost reduction and lower emissions, growth with fewer resources, more competitive companies, and more resilient societies and businesses.

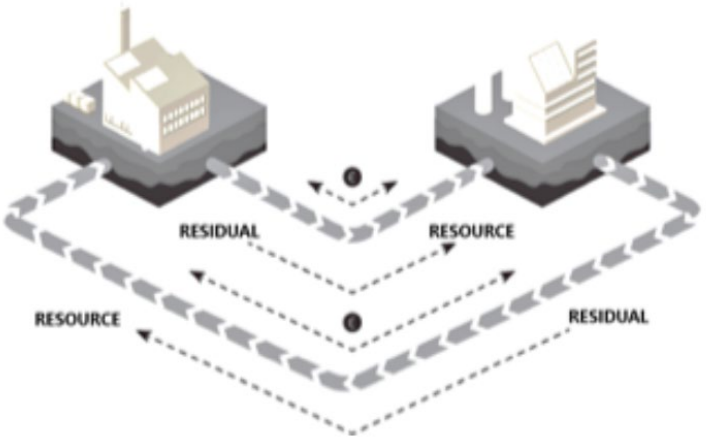

Figure 2: Simplified View of the Kalundborg Symbiosis
Source: Danielsson (2017)

2.1 Industrial symbiosis in Croatia

The model of industrial symbiosis in the Republic of Croatia, illustrated by a concrete example of the use of wood biomass ash (WBA) from power plants in the construction industry (Štirmer et al., 2020), represents a modern form of sustainable management based on the principles of the circular economy. It is a collaboration between the energy sector, which produces WBA as a by-product, and the construction sector, which uses this waste as a substitute raw material in the production of concrete. In this way, the ash, which would otherwise end up in landfill sites and cause environmental pollution, is converted into a valuable resource. From an economic point of view, this model of industrial symbiosis has numerous advantages. On the one hand, power plants save money by not having to pay for waste disposal, while the construction sector saves money by not needing costly primary raw materials like natural sand. On the other hand, new prospects enhance the creation of inventive and eco-friendly building materials, increasing the competitiveness of the home sector. Industrial symbiosis encourages the development of new market niches, boosts local employment, and aids in regional growth. Furthermore, as is the case with the project to create new construction products using PDBs, these models make it easier to secure money from national grants and European funds meant for sustainable development initiatives. The implementation of industrial symbiosis improves resource utilization efficiency while lowering environmental and regulatory expenses. The Republic of Croatia's long-term sustainable development is based on this model, which not only helps the EU achieve its environmental protection and renewable energy goals, but also demonstrates how cross-sectoral cooperation can produce tangible economic and environmental benefits.

2.2 Industrial symbiosis in Slovenia

In Slovenia, urban strategies are being used to explore the potential of industrial and urban symbiosis. Momirski et al. (2021) highlight issues such as a lack of regulations, inadequate waste-to-energy conversion, and low by-product reuse. However, there are chances for better waste management and brownfield redevelopment. The two most crucial elements are greater awareness and the alignment of laws with EU regulations. According to Momirski et al. (2021), industrial symbiosis in Slovenia is an integrated model of collaboration between various industrial sectors and urban

areas that permits more economical resource use and a smaller ecological footprint. This model turns waste, water, energy, and by-products from one production process into valuable inputs for other processes inside linked organizations. This directly supports the objectives of circular economy by reducing the need for new raw materials and creating closed material flows. The creation of the *e-Simbioza* digital platform, which connects various businesses to share resource information, is one of the most significant instances of industrial symbiosis in Slovenia. This platform provides a useful tool for symbiosis implementation at the territorial and industrial zone levels.

From an economic point of view, this model has a number of advantages. Firstly, it makes it possible to reduce companies' operating costs, as the use of by-products or waste as raw materials reduces expenditure on the purchase of primary resources. Secondly, industrial symbiosis increases the competitiveness of companies as it enables them to develop innovative products and business solutions that meet market demand for sustainable practices. Thirdly, companies will have the opportunity to access funding from European and national funds that promote green transitions and sustainable projects. In addition, new space is created for the development of business models based on reuse, remanufacturing, and recycling, which further strengthens the economy's resilience to resource and energy crises. Ultimately, industrial symbiosis in Slovenia not only contributes to sustainability and the reduction of environmental impact, but also creates economic added value through more rational management of resources and new development opportunities for entrepreneurship.

3 Methodology

This paper uses a qualitative methodology based on a descriptive and comparative analysis of secondary data. The aim is to analyse and compare industrial symbiosis models in Croatia and Slovenia in the context of sustainable management, with a particular focus on ESG principles and the concept of circular economy.

The analysis is based on scientific articles, official EU documents, national reports, and case studies, including the application of wood biomass ash in Croatia and the development of the *e-Simbioza* digital platform in Slovenia. A comparative approach was used to explore similarities and differences in institutional, technical, and

regulatory aspects while analysing potentials and challenges, especially in the application of digital technologies to optimize resource flows and connect industrial enterprises. The research question is: How can industrial symbiosis, supported by digital tools, contribute to the achievement of ESG goals in the industry of Croatia and Slovenia? The application of digitalization was analysed qualitatively, as its role in industrial symbiosis is still at an early stage of development and the available data is mostly descriptive and conceptual, which makes quantitative analysis difficult.

Limitations of secondary analysis include the inconsistent methodological approaches of sources, limited access to internal company data, and the possibility that the latest trends and innovations are not yet adequately documented. Despite these challenges, the qualitative approach enabled a deeper understanding of digitalization in industrial symbioses, the identification of key barriers and opportunities, and laid the groundwork for future empirical research that could include quantitative methods and primary data.

4 Results

The research results show that industrial symbiosis is an effective tool for achieving the goals of sustainable management within the framework of ESG in Croatia and Slovenia. Although the two case studies from this paper represent different national and sectoral contexts, they illustrate complementary stages of IS evolution. The Croatian case, on the one hand, exemplifies a conventional, material-based industrial symbiosis model in which industries work directly together to reuse resources. The Slovenian case, on the other hand, is a prime example of the shift to a more digitally integrated model, where ICT support allows symbiotic exchanges to be mapped and activated through platforms like *e-Simbioza*. This distinction is consistent with recent research that acknowledges the digitization of IS as a step in the direction of more intelligent and adaptable symbiotic systems (Lombardi & Laybourn, 2012; Domenech et al., 2019). These cases offer insights into how digital tools can gradually improve traditional IS models rather than reflecting disjointed efforts. Successful industrial symbiosis practices are already in place in both countries, according to an analysis of theoretical sources, industry practices, and case studies. The use of wood biomass ash (PDB) as a substitute raw material in the production of concrete in Croatia highlights the synergy between the energy sector and the construction industry, which has both economic and environmental benefits. One

notable outcome in Slovenia is the digital platform *e-Simbioza*, which links industrial businesses and makes it possible to find possible symbiotic partnerships. Through the reduction of waste, CO_2 emissions, and primary resource consumption, the promotion of local production and employment, and the enhancement of resource management efficiency and transparency through digital tools and technologies, industrial symbioses directly contribute to ESG goals. Digitalization and the application of digital solutions increasingly contribute to the optimization of IS models and enable improved resource coordination, predictive analytics and real-time decision making. Economic benefits include lower operating costs, the development of new market niches for green products and access to funding from EU funds and national sustainable development programs. However, implementation challenges have also been identified, such as a lack of standardized procedures and regulations, limited awareness and knowledge in the industry, and technical and infrastructural barriers, especially for smaller companies.

5 Discussion

This research confirms that industrial symbiosis (IS) plays a key role in achieving ESG goals, with a particular focus on digital technologies as tools to increase efficiency and operational integration of symbiotic models.

From an environmental perspective, IS enables the reduction of waste, emissions, and the consumption of primary resources through the reuse of by-products, energy, and water. The example of the use of ash from wood biomass in the Croatian construction industry confirms the environmental value of IS by reducing the need for primary raw materials.

From a social point of view, IS stimulates employment, strengthens local production chains and enables the revitalization of industrial areas, which is particularly evident in Slovenian urban strategies. Linking different sectors such as energy, construction, and utilities opens up new opportunities for cooperation and sustainable development.

From an administrative perspective, the information society contributes to more transparent and efficient resource management. Digital platforms, such as the Slovenian e-Symbiosis, facilitate the identification and exchange of resources

between companies, improving compliance with ESG requirements and EU regulations.

The role of digitalization further strengthens IS models and enables predictive analytics, logistics optimization and the identification of hidden synergies. Digital systems can support sustainable decision-making and the development of intelligent symbiotic networks that will automate and customize the exchange of resources.

Although IS brings numerous benefits, the main challenges include the lack of regulatory requirements, the low level of digital maturity of companies, limited awareness of the benefits of IS, and resistance to changing business models. Slovenia shows greater institutional support through strategic documents and digital tools.

This comparative perspective reveals that industrial symbiosis evolves along a continuum—from physical, analogue interactions between companies, as seen in Croatia, to more digitally enabled frameworks, as exemplified by Slovenia. While digital platforms do not replace traditional IS models, they enhance them by facilitating faster identification of synergies and enabling data-driven decision-making. Thus, the integration of ICT and AI in IS practices should be viewed as a means of strengthening and scaling up existing symbiotic relationships.

It can be concluded that industrial symbiosis, supported by digital solutions, has significant potential to achieve ESG goals, but requires an interdisciplinary approach, strong political will and active collaboration between industry, regulators, and academia.

6 Conclusions

The paper concludes that industrial symbiosis in Croatia and Slovenia contributes significantly to ESG goals by enabling the reduction of waste, emissions, and business costs. In Croatia, industrial symbiosis practices are industry-led, while Slovenia focuses on digital platforms such as e-Symbioza. Artificial intelligence (AI) has the potential to optimize resource flow and decision-making, but its application in industrial symbiosis is still limited due to a lack of regulatory support, standardized procedures, and awareness in the industry.

The main limitations include the lack of primary data and the variability of methodological approaches in the available literature, making quantitative analysis difficult.

Future research should focus on empirical verification of the role of AI in industrial symbioses and comparative analysis with other EU countries to identify best practices and enable wider adoption of sustainable industrial models.

These findings provide a practical contribution to understanding how sustainable management practices can be enhanced in the age of ESG and AI, aligning with broader European green transition goals.

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