Proceedings Book

Industrial Symbiosis from a technical perspective: challenges and opportunities

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LIAISE
Cooperation, development
and cross-border transfer
Of industrial symbiosis

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Content

Artificial intelligence supporting industrial symbiosis

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ABSTRACT

This paper explores the opportunities, challenges, and barriers associated with implementing Industrial Symbiosis (IS), specifically focusing on utilizing Artificial Intelligence (AI) technologies. IS, which involves exchanging materials, energy, and resources between different industries to promote sustainability and efficiency, presents significant potential for enhancing resource utilization and reducing environmental impact. However, the successful implementation of IS faces various challenges and barriers, including technological, organizational, regulatory, and cultural factors. This paper investigates how AI technologies can address some of these challenges and facilitate the adoption of IS practices. By leveraging AI for data analytics, optimization, decision-making support, and predictive modeling, industries can enhance the identification of symbiotic opportunities, optimize resource exchanges, and improve overall efficiency.

Furthermore, AI can help overcome barriers such as information asymmetry, complex network dynamics, and uncertainty associated with IS implementation. Despite the promising potential of AI in advancing Industrial Symbiosis, several challenges remain, including data availability, interoperability, privacy concerns, and ethical considerations. This paper provides insights into the role of AI in enabling and accelerating the implementation of IS while also highlighting the need for interdisciplinary collaboration, policy support, and ethical guidelines to maximize its benefits and address potential risks.

Keywords: Artificial Intelligence; Circular Business Model; Circular Business Model Innovation; Circular Economy; Industrial Symbiosis; Circular Manufacturing; Manufacturing; Sustainability; Literature Review

KEYWORDS
Artificial Intelligence; Circular Business Model; Circular Business Model Innovation; Circular Economy; Industrial Symbiosis; Circular Manufacturing; Manufacturing; Sustainability; Literature Review

INTRODUCTION

Industrial Symbiosis (IS) is a collaborative approach that enables industries to utilize by-products and waste from other industries as raw materials, thus promoting sustainability and efficiency (Minde & Bäcklund, 2023). This model reduces waste, minimizes environmental impact, and enhances industry resource utilization. Despite its potential, the successful implementation of IS is fraught with technological, organizational, regulatory, and cultural challenges.

McKinsey estimates that in Europe, 44% of material value – i.e., €78 billion – is lost annually due to inefficient use of steel, plastics, and aluminum (Enkvist et al., 2022). This loss highlights the significant value the Circular Economy can bring to industries, society, and the environment. Many scholars link a successful industrial transformation toward a Circular Economy with digitalization (Bressanelli et al., 2022; Liu et al., 2022; Neligan et al., 2022; Parida et al., 2019). Researchers

Table content

have recognized the potential of Artificial Intelligence (AI) to enhance circularity by identifying patterns and trends, forecasting future demand and supply, and automating processes (Chauhan et al., 2022; Kristoffersen et al., 2020). These capabilities unlock several opportunities, including circular business operations, circular products, components, and material designs, and infrastructure optimization to facilitate circular resource flows (Ellen MacArthur Foundation, 2019)

Artificial Intelligence (AI) technologies have the potential to address many of these challenges, enabling the identification of symbiotic opportunities, optimizing resource exchanges, and improving decision-making processes. This paper explores the opportunities, challenges, and barriers associated with implementing IS, focusing on how AI can facilitate and accelerate this process.

Methodology

Digitalization presents new opportunities for adopting Circular Business Models (CBMs) in industrial companies by enabling sustainable and profitable practices. Among digital technologies, AI stands out for its exceptional value-adding potential (Brock & von Wangenheim, 2019). Defined as “the use of digital technologies to innovate a business model and provide new revenue streams and value-producing opportunities in industrial ecosystems” (Parida et al., 2019: 12), digitalization fundamentally transforms how industrial companies can boost productivity, foster growth, enhance customer value (Björkdahl, 2020), and reshape business models to create, deliver, and capture value (Iansiti & Lakhani, 2014). This transformation facilitates the implementation of innovative and disruptive CBMs that were once considered purely theoretical (Neligan et al., 2022; Neri et al., 2023; Rosa et al., 2020).

In Industrial Symbiosis, digitalization is crucial in optimizing resource and knowledge exchange among partners, essential for enhancing recycling and establishing more complex symbiotic systems (Kristoffersen et al., 2020; Liu et al., 2022). For instance, connected sensors enable real-time tracking, monitoring, and controlling of resource flows, thus supporting human decision-making and optimizing material usage (Ingemarsdotter et al., 2019; Kristoffersen et al., 2020; Rosa et al., 2020). Furthermore, digital platforms facilitate information sharing between diverse industries, helping businesses discover new ways to exchange resources across sectors and match supply with demand (Liu et al., 2022). Enhanced human-machine interaction also improves workplace conditions, advancing Industrial Symbiosis’s economic, social, and environmental aspects (Scafà et al., 2020; Sjödin et al., 2018).

AI further elevates the disruptive potential of digitalization by enabling systems to perform sophisticated analytics, learn, generalize from data, and execute tasks autonomously (Iansiti & Lakhani, 2020). AI refers to technologies and methods that enable systems to perform human-like cognitive functions, such as learning and reasoning (Ellen MacArthur Foundation, 2019). In this context, AI is discussed as “strong” AI, encompassing methods like Machine Learning and Deep Learning. Thus, AI is defined as a “system’s ability to interpret external data correctly, to learn from such data, and to use those learnings” (Kaplan & Haenlein, 2019: 17).

RESULTS

AI can be leveraged to improve or enable the Circular Economy in several ways:

- AI can revolutionize material cycling by predicting future material flows and optimizing product end-of-life strategies (Kristoffersen et al., 2020). For example, AI-powered vision systems can enhance waste management by accurately identifying and sorting different materials, conducting automated waste audits, and efficiently processing mixed waste, thus increasing the amount of recycled material and improving processing efficiency (Martinez et al., 2022; Nañez Alonso et al., 2021).
- AI-driven condition-based and predictive maintenance can significantly extend product lifespans (Liu et al., 2022). For instance, Rolls-Royce uses AI-enabled maintenance services that analyze data from hundreds of sensors on aircraft engines to forecast maintenance needs, reduce delays caused by gas turbine defects, and extend the intervals between repairs (Lee et al., 2019).
- AI can enhance the sharing economy by improving trust, matching resources and prices, and understanding user preferences and behaviors (Chen et al., 2022). For example, Volvo Construction Equipment uses AI to manage risks and maximize heavy equipment utilization in rental, leasing, or performance-based contracts. This is achieved through advanced pricing and demand forecasting, predictive maintenance,

and intelligent inventory management (Sjödin & Vinit, 2021).
- AI plays a crucial role in maximizing the potential of software for resource optimization and dematerialization (Neri et al., 2023). For example, General Electric uses sensors and AI to improve wind turbines' maintenance, performance, and utilization, enabling power companies to increase energy production without additional hardware (Iansiti & Lakhani, 2014).

CONCLUSIONS

AI offers significant potential to enhance the implementation of Industrial Symbiosis by addressing technological, organizational, regulatory, and cultural challenges. By leveraging AI for data analytics, optimization, decision-making support, and predictive modeling, industries can identify and exploit symbiotic opportunities, optimize resource exchanges, and improve efficiency. However, the successful integration of AI in IS requires interdisciplinary collaboration, supportive policies, and adherence to ethical guidelines to maximize its benefits and address potential risks. With the right approach, AI can be pivotal in advancing sustainable industrial practices and promoting a Circular Economy.

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Bridging the gap: Overcoming barriers to industrial symbiosis implementation insights from the inset project

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ABSTRACT

Industrial Symbiosis (IS) holds promise for revolutionizing resource management, environmental stewardship, and economic vitality. However, successful implementation is hindered by multifaceted challenges, as revealed by stakeholder engagements in the INSET project.

The INSET project (Industrial Symbiosis Capacity Building for Enterprises and related sectors through a disruptive, digital and pragmatic training and awareness approach), catalyzed by funding from the Erasmus + program's 2023 call, embodies a visionary initiative aimed at bolstering Industrial Symbiosis through an innovative blend of disruptive, digital, and pragmatic training and awareness methodologies tailored to enterprises and their affiliated sectors.

Central to our investigation are the formidable barriers hindering IS realization. The acute shortage of dedicated personnel proficient in IS methodologies is among these challenges, exacerbated by a glaring deficiency in understanding the intricate web of technologies underpinning Industrial Symbiosis frameworks. Moreover, economic hurdles loom large, impeding the widespread adoption of IS practices, while administrative inadequacies pose formidable roadblocks to fostering IS initiatives effectively.

Our inquiry unveils a nuanced landscape wherein stakeholders spanning diverse sectors - from administration and academia to business support ecosystems - grapple with distinct challenges compared to businesses and their associated networks. Consequently, bespoke strategies tailored to the unique needs of each stakeholder cohort emerge as imperative for navigating the complex terrain of IS implementation.

In charting a path forward, our study underscores the imperative of nurturing two foundational capacities pivotal to IS advancement: the art of designing IS, fostering collaboration and resource exchange among disparate actors, and the science of managing IS implementation, encompassing robust coordination, regulatory frameworks, and vigilant monitoring mechanisms.

In conclusion, while the barriers to IS are significant, they are not insurmountable. The findings from the INSET project illuminate the critical areas requiring targeted intervention. By addressing the personnel and technological gaps, alleviating economic constraints, and streamlining administrative processes, stakeholders can pave the way for robust IS implementation. Ultimately, fostering a collaborative environment and equipping stakeholders with the necessary skills and knowledge through innovative training and awareness initiatives will be vital to unlocking the full potential of IS, leading to a more sustainable and economically vibrant industrial ecosystem.

KEYWORDS
Industrial Symbiosis; Challenges; Stakeholder Engagement;
INSET Project; Implementation Strategy; Resource Management

INTRODUCTION

Circular Economy (CE) practices, defined as the logical and viable alternative to the shortcomings of the linear economy “take-make-consume-dispose” model, overcome some of the significant environmental issues of humanity: the rise in average temperatures of the planet due to rising CO_2 emissions, the burden on natural resource extraction or the increasing production of waste. The Energy Transitions Commission believes that, by developing a CE strategy, there is a potential to decarbonize the industry by 40%, apart from reducing waste production (Smeets et al., 2021).

Circularity and sustainability will make the business environment more competitive in the long term, and to achieve this, it is necessary to evolve business practices and create new business models based on best practices in circularity. Under this framework, business models based on Industrial Symbiosis (IS) are an enabling factor that could achieve green growth and accelerate the implementation of CE. IS is a business opportunity for ecological innovation, and its implementation can lead to lower production costs while creating environmental and social benefits for the involved companies (Lombardi & Laybourn, 2012). IS is an enabling factor that could achieve green growth and accelerate the implementation of Circular Economy (CE), as underlined in EU strategies such as the CE Action Plan, the Green Deal Industrial Plan or the EU Mission 1 (Friant, 2021).

Over the last few years, several contributions and projects on IS business models have been carried out, such as INSIGHT (2019-1-BE01-KA202-050439) or SPIRE-SAIS (612429-EPP-1-2019-1-DE-EPPKA2-SSA-B).

Nonetheless, IS development is still hampered by different barriers. There is a lack of interest and trust in IS implementation due to a lack of knowledge at corporate, occupational and community levels (Neves et al., 2019).

In this sense, it is essential to understand how these disruptive business models promote the industry’s circularity towards a sustainable and competitive economy. These new business models are affecting the job profiles and skills required by the workforce, decreasing low-skilled activities and stimulating the need for training programs better suited to requalification and upskilling. For this reason, understanding the relationship between trends, job profiles, skills, and training programs can help encourage and support the creation of a skilled workforce under a lifelong learning system focused on a circularity model for the future (European Commission, 2023).

With a disruptive, digital, and practical approach to capacity development for businesses and related actors, the INSET (N/A) project seeks to execute this circular business model to fulfill the demand for raising awareness of and the genuine use of IS in the business network.

This project will, therefore, help business networks and related actors. Still, it will also promote among VET providers, public authorities and other stakeholders the importance of promoting lifelong learning to achieve a complete and resilient workforce for future crises that can survive in this globalized world through innovation, creativity and cooperation.

METHODOLOGY

The primary goal of the INSET project is to implement Industrial Symbiosis (IS) through a disruptive, digital, and practical approach to training and awareness of enterprises and their associated players.

This goal is compatible with Vocational Education and Training (VET)’s aims of improving education’s attractiveness, adjusting it to labor market demands, and combating climate change. Moreover, the goals of the project INSET are aligned with the following Sustainable Development Goals (SDGs) (Figure 1).

Figure 1. SDG goals to which INSET contributes

To achieve this goal, the NES project partners worked on defining the methodology that best enables the capacity building of enterprises and related innovation actors to achieve a green and sustainable transformation of industry through IS. This methodology was mainly based on the definition of a Joint Curriculum that includes all the needs and gaps identified for the project's target groups during the preparation of the proposal and its implementation. This Joint Curriculum will train those interested in applying IS to solve the current (energy crisis, lack of raw materials, etc.) and future context.

The first step in that procedure was to define an Industrial Symbiosis competency map, which is an updated analysis of needs and gaps apart from in-depth research of the enablers and barriers of IS. Three steps defined this competency map:

1. Conduct desk research to analyze the state-of-the-art industrial symmetry within the consortium's territory (France, Italy, Latvia, Slovenia, and Spain).
2. Identify critical stakeholders of the Industrial Symbiosis in various spheres of the quadruple helix: producers and service providers; research and development organizations and education providers; business support system and policymakers; local/regional community.
3. Distribute a questionnaire among target groups and stakeholders to collect information about the gaps and needs on barriers to IS implementation.

All the information gathered and analyzed served to prepare the competency map for the project partner territory and the level of the project partnership covered territories. Based on the analysis of the competency map, some learning outcomes (specific knowledge, skills, and competencies) were defined to train target groups in the IS topic and its implementation. In addition, a Joint Curriculum (JC) was prepared based on a complete structure in the form of modules, units, etc., considering specifications such as duration and weight. It is harmonized based on the European Qualification Framework (EQF).

RESULTS

After defining the research methodology, it was implemented, and the first results were obtained, as detailed below:

INSET Competency Map

Desk Research

According to the methodology, each partner has conducted desk research about the situation of IS within their territory. For this purpose, each partner examined at least 1 study/paper about the industrial ecosystem of their territory (region) and at least one media article for each of the spheres of the quadruple helix regarding the IS. Overall, the partnership reviewed 70 documents to research IS's situation within their respective regions/countries, as presented below in Table 1.

Table 1. Breakdown of the reviewed documents in the desk research

International	3		
Europe	4		
National	43	France	19
		Italy	4
		Lithuania	5
		Slovenia	6
		Spain	9

Regional	18	Italy	1	Lombardy	1		
		Slovenia	1	Podravje	1		
		Spain	16	Andalusia	1		
				Asturias	1		
				Catalunya	6		
				Extremadura	2		
				Murcia	3		
				North Spain	1		
				Valencia	2		
Local	2	Slovenia	1	Podravje	1	City Of Maribor	1
		Spain	1	Murcia	1	Murcia City	1
Total	70						

This allowed the partnership to determine the most critical aspects of IS applicable to their regions:

- Understanding IS as a general concept and as part of Circular Economy,
- Understanding resource management,
- Managing IS,
- IS Framework,
- Case studies of IS,
- Capacity building for IS implementation.

Screening the territory

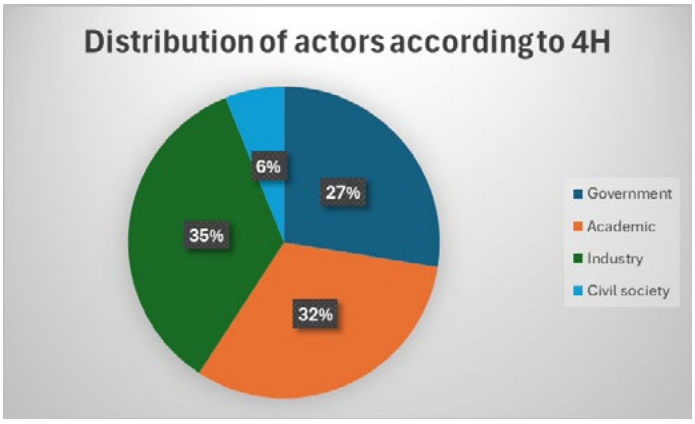
Each partner prepared the territorial screening, which was ready with a list of IS actors, considering the quadruple helix distribution of the actors in the region. This way, the collection of IS stakeholders was prepared, and each partner's decision was made on who to include in the following activities. The screening was done with the help of the following matrix, presented in Table 2.

Table 2. Territorial screening matrix

Project partner / Country	Identified actor	Sphere of the actor	Previous collaboration (Y/N)	Contact info of the actor	Scope of the actor	Estimated difficulty in establishing contact (1 – easy to reach / 4 - difficult to reach)

A total of 106 IS actors were identified through the screening process. They represent all four helixes of the quadruple helix system, with most belonging to the sphere of Industry (35%), followed by Academia (32%), Governance (27%), and the least represented Civil Society (6%).

Figure 2. The main activity of the stakeholders analyzed in the territorial screening



Questionnaire

The project partners have been collecting answers from the stakeholders identified through each partner's desk research. In total, 44 responses were collected. Different stakeholders collected the answers from all four helixes of the quadruple helix system and the partnership internal indicator of collecting 30 responses on the partnership level.

- An overview of the stakeholder responses clearly shows that:
- There is a lack of people explicitly dedicated to the processes of IS.
- There is a lack of knowledge of existing technologies supporting IS.
- There are economic barriers to the implementation of IS.
- There is a low capacity to foster IS at the administrative level.

These are the barriers to the implementation of IS.

However, different stakeholders are facing different challenges concerning IS and can be grouped into two categories:

- Administration, academia, and business support ecosystem.
- Businesses, business clusters/associations/networks.

Therefore, the capacity in two significant fields needs to be developed to foster IS:

- Designing the Industrial Symbiosis among various actors and
- Managing the process of implementing Industrial Symbiosis.

Following the analysis, a suggestion for two new job profiles was prepared, which will answer the identified needs in the fields of designing and managing IS for the two major target groups:

- Industrial Symbiosis Planner
- Industrial Symbiosis Project Manager

Table 3. Territorial screening matrix

IS Planner	IS Project Manager
The general context of IS	The general context of IS
Case studies of IS	Case studies of IS
Understanding resource management	Managing IS
Capacity building for IS implementation	IS Framework

INSET Joint Curriculum

Based on the competency map, the Consortium defined the INSET training program to equip target groups with essential knowledge, skills, and competencies related to Industrial Symbiosis (IS) principles. Firstly, they defined specific learning outcomes from the competency map, covering knowledge, skills, and competencies necessary for proficiency in IS practices.

Table 4. IS Planner Learning Outcomes

Knowledge	Skills	Competencies
• The learner understands... • Methodologies and strategies for identifying, prioritizing, and mapping resource opportunities in IS, including techniques for visualizing resource data. • Criteria for assessing territory readiness and sector compatibility in IS planning. • Governance structures and mechanisms for managing IS projects at different levels.	• The learner is empowered to... • • Implement sustainable resource management practices. • Implement governance frameworks to manage and coordinate IS projects effectively.	• The learner conducts the following tasks... • Manage and optimize resources and processes within IS frameworks, assessing benefits and barriers to IS adoption and developing strategies to overcome challenges. • Utilize systemic vision and data collection methods to gather relevant information on resource inputs and outputs, identifying and leveraging opportunities among industries within specific territories. • Prioritize IS opportunities based on feasibility, impact, and strategic importance, collaborating with stakeholders to define clear roles and responsibilities in governing IS initiatives.
Knowledge	Skills	Competencies

• The learner understands… • The significance of IS "Intrapreneurship." • Business models in IS project planning. • Strategies for monitoring and impact calculations in IS initiatives. • Methodologies of reporting and certification in IS projects.	• The learner is empowered to… • Identify the characteristics of an IS Intrapreneur • Apply business models to IS projects • Utilize key performance indicators (KPIs) to measure IS project impacts. • Understand the importance of reporting and certification in IS projects.	• The learner conducts the following tasks… • Apply business models effectively for IS projects and apply monitoring and impact calculations within IS initiatives. • Develop reporting and certification strategies for IS projects.

Secondly, they outlined the structure of the Joint Curriculum, detailing modules, duration, credits, and training pathways. Finally, they emphasized the harmonization of the Joint Curriculum with the European Qualifications Framework (EQF) to ensure compatibility with various national qualification systems.

Table 5. Structure of Joint Curriculum

Module	Name	Total training duration (hours)	Relative weight (%)	Number of credits	Training pathway
Module 0	Introduction to the course	4	4%	0.16	IS Planner IS Project Manager
Module 1	The general context of IS	24	24%	0.96	IS Planner IS Project Manager
Module 2A	Designing IS projects	24	24%	0.96	IS Planner
Module 2B	Managing IS	24	24%	0.96	IS Project Manager
Module 3	Legal and financial issues	12	12%	0.48	IS Planner IS Project Manager
Module 4	Communication and soft skills	12	12%	0.48	IS Planner IS Project Manager
Total		100	100%	4	

INSET aligns closely with the attributes specified for EQF level 5, emphasizing substantial and specialized knowledge applicable to professional fields. This level signifies a robust understanding of theoretical foundations and practical applications for planning and managing complex projects. Given that the target audience for INSET includes future IS planners and all partners unanimously agree upon IS project managers, EQF level 5. This level ensures that learners acquire the depth of knowledge and breadth of skills necessary to navigate dynamic work environments effectively.

CONCLUSIONS

The INSET project represents a significant advancement in promoting Industrial Symbiosis (IS) as a viable model for enhancing Circular Economy (CE) practices within various industrial sectors. This paper highlights how IS can catalyze sustainable growth by facilitating resource exchange and collaboration among diverse stakeholders. As the introduction outlines, transitioning from a linear economy to a circular framework is critical for addressing pressing environmental challenges like climate change and resource depletion. The findings from the INSET project underscore that implementing IS can lead to substantial benefits, including reduced production costs and enhanced environmental and social outcomes.

Through a comprehensive methodology that involved stakeholder engagement, desk research, and the development of a competency map, the project identified key barriers to IS implementation, such as insufficient knowledge, a lack of dedicated personnel, and economic constraints. The engagement with stakeholders revealed that distinct challenges exist across different sectors, necessitating tailored capacity-building strategies. The project also highlighted the critical need for fostering collaboration among the quadruple helix stakeholders - industry, academia, governance, and civil society - to create a supportive ecosystem for IS.

A significant outcome of the INSET project was the establishment of a Joint Curriculum designed to equip future IS planners and project managers with the necessary skills and knowledge. The curriculum, structured around specific learning outcomes, aligns with the European Qualifications Framework (EQF) at level 5, ensuring learners possess theoretical foundations and practical skills relevant to IS. By addressing the skills gap and promoting lifelong learning, the INSET project aims to develop a resilient workforce capable of navigating the complexities of modern industrial practices in a Circular Economy context.

Based on this defined Joint Curriculum, in the coming months, the Consortium will work on validating it with stakeholders to have a final confirmation that its content aligns with the real needs of those involved. Subsequently, the Consortium will work on designing the curriculum and bringing it to light as a successful and innovative case of training related to the Industrial Symbiosis theme.

Hence, the INSET project demonstrates that while barriers to IS implementation are significant, they can be effectively addressed through targeted interventions and capacity-building initiatives. The emphasis on innovative training methods and stakeholder collaboration is essential for overcoming challenges and unlocking the full potential of IS. By fostering a culture of collaboration, innovation, and continuous learning, stakeholders can contribute to a more sustainable industrial ecosystem that aligns with the broader goals of the Circular Economy. The insights gained from this project advance the understanding of IS and provide a roadmap for future initiatives to promote circularity and sustainability across industries. As the global community continues to confront environmental crises, the principles and practices emerging from the INSET project will be invaluable in shaping a sustainable and competitive industrial landscape for the future.

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Deepening human security and industrial symbiosis in the context of the EU enlargement

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ABSTRACT

The socio-political, economic, cultural, religious, ethical, mental or technological-communicative differences, with a significant impact on the standard of living and the quality of life in the human communities that populate the planet Earth, contribute to strengthening the potential of humanity to face the most violent and destructive effects and results of the multidimensional global crisis, through the diversity of chances and identities it generates. The multifaceted global crisis is primarily generated by normative, axiological and moral disorientation and relativization, and the loss and devaluation of society's most fundamental values such as science, knowledge, the meaning of development and progress.

The process of reorganization and renewal of contemporary society must begin with concern for man and his primary interests and needs, such as safety and security. The central concern in the process of building national security as a state policy must converge to the strengthening of human security in the context of deepening Industrial Symbiosis with its new aspects at the regional level, in the context of the EU enlargement approach, to build a knowledge-based society in this area, a morally renovated community, rebuilt based on no spheric and bioethical principles, starting with the states of Eastern Europe targeted by the prospects of EU enlargements, such as Ukraine and the Republic of Moldova, as well as several states from the Western Balkans.

The bioethical and human security problematics are defending social equity and human rights and pleading for eliminating human risks in the context of global changes.

The social, economic, political, military, cultural or environmental processes, phenomena and events are interdependent and inter-influencing. The contemporary global crisis is characterized by complexity and multi-dimensioning, determining the appearance of new types of risks and menaces to national, regional or even international security. The imperative necessity of contracting contemporary global threats at the level of protection of the human person can be fulfilled through re-conceptualization at local, regional and global scales, in methodological and bioethical ways, of the perspectives of strengthening human security (Sprincean, 2017).

The necessity to focus on the states of Eastern Europe for the creation of the Industrial Symbiosis and a knowledge-based society is justified by the need to resolve first the biggest discrepancies and the most severe deviations from ensuring human security, especially appeared because of the continuation of the war launched by Russia against Ukraine in February 2022. More significantly, this concern for the strengthening of personal safety and human security will become actual for the entire EU but especially in Eastern Europe in the context of the effort of the community of Western states to restore all spheres of social life in Ukraine and its neighboring countries in the post-war period. The renewed society needs to be grounded in objectives such as improving environmental sustainability while achieving economic benefits.

Inclusiveness of the research methodology in the investigation becomes a fundamental theoretical requirement since only a holistic and generalized approach can provide a sufficient conceptual framework to understand and analyze the totality and depth of the issues at hand. The investigation results include practical recommendations for all involved stakeholders and different actors at national and EU levels responsible for efficiently functioning a knowledge-based society as an inclusive system of producing and implementing knowledge and innovations.

KEYWORDS
Human Security; EU enlargement; Eastern Europe; Industrial Symbiosis; Knowledge-based Society; Multidimensional Crisis

INTRODUCTION

The social, economic, political, military, cultural or environmental processes, phenomena and events are interdependent, inter-influencing. The contemporary global crisis is characterized by complexity and multi-dimensioning, determining the appearance of new types of risks and menaces to national, regional or even global security (Sprincean & Mitrofanov, 2021: 56). The imperative necessity of contracting contemporary global threats at the level of protection of human person can be fulfilled through re-conceptualization at local, regional and global scales, in methodological and bioethical ways, of the perspectives of strengthening human security (Sprincean, 2017). Bioethical, Industrial Symbiosis and human security problems are defending social equity and human rights and pleading to eliminate human risks in the context of global changes.

The necessity to focus on the states of Eastern Europe for the creation of the Industrial Symbiosis as an association between industrial facilities in which the waste or by-products of one become raw materials for another and a knowledge-based society is justified by the need to resolve first the biggest discrepancies and the most severe deviations from ensuring human security especially appeared as a result of the continuation of the war launched by Russia against Ukraine in February 2022. More significantly, this concern for the strengthening of personal safety and human security will become actual for the entire EU but especially in Eastern Europe in the context of the effort of the entire community of Western states to restore all spheres of social life in Ukraine and its neighboring countries in the post-war period. The renewed society needs to be grounded in objectives such as improving environmental sustainability while achieving economic benefits.

Inclusiveness of the research methodology in the investigation becomes a fundamental theoretical requirement since only a holistic and generalized approach can provide a sufficient conceptual framework to understand and analyze the totality and depth of the issues at hand. The investigation results include practical recommendations for all involved stakeholders and different actors at national and EU levels responsible for efficient functioning of a knowledge-based society as an inclusive system of producing and implementing knowledge and innovations.

A series of principles (of interdisciplinarity, complementarity, humanism, correspondence, continuity and discontinuity, compatibility), approaches (political, systemic) and universal methods (synergetics, dialectics, hermeneutics), general-scientific (structural-functional, institutional, comparative, realist-empirical, historiographical method, analysis and synthesis, induction and deduction), as well as particular-scientific ones (political science, event analysis, bioethical, security method, security risk assessment, security threat analysis). The complex and extensive nature of the research object explains the broad spectrum of principles, approaches, and methods used in the present research.

The investigations undertaken were based on systemic methodology that emphasizes the correlation and interconnection between the parts of a whole. Thus, personal, political, community, economic, environmental, health security and food security represent the elements of the human security system, according to the UN methodology, which is closely interdependent. On the other hand, freedom from fear and need and respect for human dignity represent the components of Industrial Symbiosis, human security and bioethics, linked together by a systemic connection (Sprincean, 2020a: 264). Analyzing at a higher level, bioethics, as a science of the survival and securing of the person, the Industrial Symbiosis, and human security, as integral conceptions of the multilateral well-being of the human individual, represent new components that are systemically connected, contributing to the formation of new conceptual constructions, such as bioethics politics in the context of post-industrialism, for example (Sprincean, 2016: 82).

In the context of the EU enlargement approach, returned to the forefront of the EU agenda in the conditions of the war in Ukraine deliberately started by the Putin regime, a sustainable edification, social management based on knowledge, a morally renovated social relations, rebuilt based on deliberative principles and values and democratic, noospheric and bioethical, including in Eastern European states, targeted by expansion prospects, such as Ukraine and the Republic of Moldova, as well as several states in the Western Balkans, become a priority objective of crucial importance for European civilization (Thomas & Tow, 2002: 180).

Human security

Ensuring human security is a primary concern for contemporary society, threatened by new dangers and security risks, most of which are determined by the uncontrolled progress of technologies. In this context, the person's safety becomes the central element of human concern for ensuring security in society. In a broader context, the person's well-being becomes a primary objective in achieving the desired personal safety.

For Ukraine and the Republic of Moldova, its relationship with the European Union was crucial regarding development potential in all spheres of social life. When analyzing the complex relations of Ukraine and the Republic of Moldova with the European Union, it becomes essential to adopt and apply the holistic approach, which expresses these relations in detail and as a whole. Respect for human rights, freedoms, and the safety of the human person and the citizen is correlated with promoting the sovereignty and national security of the Republic of Moldova and Ukraine.

The strengthening of democratic trends in Ukraine and in the Republic of Moldova aims to modernize the social system, including the electoral one, by increasing the extent of citizens' participation in democratic electoral exercises and in the process of adopting social and political decisions (Sprincean & Sohotci, 2020: 77). Elections are analyzed in the article as an essential mechanism for increasing the democratic participation of citizens in significant changes in the social and political field. The strengthening of national sovereignty is analyzed as a lever of fundamental importance for the profound multilateral development of society. The Republic of Moldova, in its history of the last three decades, has recorded particularly favorable occasions and opportunities for sustainable democratization and a rapprochement with European social and political values (Sprincean, 2019a:402). However, the opportunities were only partially and selectively exploited. In the future, the acceleration of the strengthening of democratic, participatory mechanisms and the consolidation of national sovereignty in a European integrationist context is foreseen (Sprincean, 2019b: 12).

The European integration of Ukraine and the Republic of Moldova implies a convergence of common standards and values for the European Union and these new candidate states. In the context of the European integration of Ukraine and the Republic of Moldova, these states unilaterally commit themselves to align their national policies, to allocate a good part of their national state budget to achieve these objectives and to pursue a foreign policy following the outlined objectives, towards to build a society with a high level of civilization and well-being. In this context, the safety of the person, as an integrationist objective, induces a broad spectrum of new valences and levels of the human security system in the context of the human need to live with dignity, these being the main pillars of the conceptualization of the state of human security.

The specificity of the accession process of Ukraine and the Republic of Moldova to the European Union is researched by resorting to a series of approaches, methods, and techniques of scientific investigation, which are selected considering several general principles of scientific research. In the context of the European integration process of these Eastern European countries, a rapprochement with the common socio-political standards and values for the European Union and these states is assumed (Sprincean, 2023a: 28). This kind of policies in various social fields is expected to be promoted in the governance process during the exhaustive implementation of the provisions agreed in the diplomatic documents.

Ensuring the security of human persons and securing the development of humanity, deepening democratic processes and positively solving the dilemmas of democracy by overcoming them globally, raising the standard of living of the Earth's population, promoting a healthy way of life and protecting health, providing a sustainable long-term development perspective, promoting the fundamental interests of social science (Suhrke, 1999: 271).

It is rightly seen that the essential purpose of strategies and policies in the spheres of human security, Industrial Symbiosis, bioethics and biosecurity of the activities of the institutions in these sectors does not consist in conferring an abstract and false sense of comfort and safety both for the human individual and for the community. The destructive impact of global threats and dangers is at everyone's level. For this reason, the thorough research of the issue of human security, Industrial Symbiosis and bioethics in a political, but also sociocivilizational, interdisciplinary, systemic and comparative context is a viable solution, along with other levers, as well as a safe way out of the multifaceted world crisis that marks human civilization, in their last centuries, but especially in the recent period of human history.

At the end of the XIX century - the beginning of the XX century, in the condition of deepening of the global crisis, a series of events took place that later determined the worldwide affirmation of the social-political and academic movement for the edification of the noosphere theory and the foundation of bioethics as an academic discipline, for a better and safer future for the generations to come. As premises for the emergence and launch of these social-political and academic movements, we will note the following facts:

First, it is about the application of eugenic policies and mass sterilization of the population in the USA, the context of the end of the XIX century, and in some open European states from the interwar period (Scandinavian states), but also Soviet Russia.

Secondly, numerous inhumane experiments on living subjects were carried out in the Nazi concentration camps during the Second World War, for which the decision of the Nuremberg Tribunal convicted the essential Nazi doctors involved.

Thirdly, the establishment of the iron curtain between the East and West geopolitical blocs immediately after the Second World War and the initiation of the arms race and the danger of nuclear war as a factor of extreme instability and insecurity in the world (Sprincean, 2023c:43). This was triggered after the completion of the "cold war" and determined the evolution of the national security paradigm from this exclusive base on military force to one centered on the human individual (Buzan, 2000: 107).

Fourthly, the continuous and unprecedented degradation of the state of the environment, climate change and global warming due to anthropogenic and natural causes, the aggravation of problems for the planet's population, the aggravation for most of the planet's population of access to drinking water, the increase in the number of new diseases due to technological and ecological reasons. These facts determined the rejuvenation of many diseases, such as oncological, cardiac or related metabolic disorders, etc. According to forecasts, all of these will make human life on Earth impossible, drastically influencing the quality of life, the security of human health, food, etc.

Fifthly, the onset of the energy and natural resource crisis is due to the exponential increase in human consumption of natural resources and the non-renewable nature of most of them.

Sixthly, the deepening of demographic discrepancies between various regions of the world, when in some areas, such as Eastern Europe, including the Republic of Moldova and in Ukraine, there is a depopulation of territories (because of various reasons, but mainly due to distorting influence in the region of the Russian Federation), a sudden aging of the population. The Eastern Europe region became predominantly socioeconomically underdeveloped and depopulated in conditions of a galloping increase in the planet's population. This demographic phenomenon endangers the efforts of governments and institutions to implement the world strategy regarding sustainable development and the control of social processes for a realistic and adequate forecast of the evolution of sociopolitical processes to avoid the most pessimistic future scenarios (Sprincean, 2024: 234).

There is an apparent lack, both at the international level, but especially in the Eastern Europe, including the Republic of Moldova and in Ukraine, of a normative and legislative framework appropriate to the gravity of the situation created in terms of the current low level of human security, an aspect that can be improved through the methodological and logistical contribution of bioethics for counteracting the most severe security threats to the human person, and contemporary post-industrial society, which are analyzed in the present work through the prism of their relevance in a bioethical and security sense (Sprincean 2019c: 30). This lack of an adequate normative framework in the field of human security led to the establishment of some social and political practices harmful to the stability, prosperity, progress and cohesion of society in the Eastern Europe, including the Republic of Moldova and in Ukraine, such as those related to the tacit acceptance in local society of some forms of corruption, nepotism or cronyism, excessive tolerance of the population towards bad governance and deviation from the moral norms of the political class and social elite, the indifference and disappointment of the electorate, in most cases, towards the need for personal involvement, as a civil society, in matters of public or national interest (Sprincean, 2021: 9).

At the same time, the promotion and entrenchment of some social habits and customs, very often degrading for the human being and discouraging for the simple citizen, concerning the civil servant, with the state bodies and public and constitutional order supervision bodies, such as those mentioned, appeared as a result of the low level of sociopolitical and security culture, both of the majority of the population, in the Republic of Moldova and Ukraine, of the political class and elites (Sprincean, 2017: 180). This situation is due both to the moral and identity crisis in the autochthonous society, as well as to the lack of an adequate level of competence of civil servants and state representatives in the fields of human security, ecological economy, Industrial Symbiosis, human rights, but especially in that of bioethics as a normative regulation methodological tool, as well as the lack of knowledge, in acceptable measure, by them of the international norms related to the regulation of the given domains (Sprincean, 2022: 211). On the other hand, the work given aims to determine the main stimulating factors for politicians, politicians, and civil servants to know and improve themselves in the field of knowledge and the application of bioethics and human security norms.

Analysis of the situation in the field of political research of human security, industrial symbiosis, bioethics, and the identification of research problems

The practical challenges to human security, humanity in general and its future were doubled by the theoretical-methodological ones (Thakur, 1997: 54). The scientific community reacted promptly to these challenges and made significant efforts to adapt to the priorities of the practical moment. All the causes and premises listed above were the basis for the emergence in 1969 of the bioethical discipline, founded by the American oncologist V.R. Potter as a "bridge to the future" and, in his more recent works, as a "global science", which in the meantime also becomes an essential sociopolitical and institutional movement, supported by civil society initiatives, in order to optimize normative and legal practices with a biomedical and ecological character relating to the biosphere, life, man (Sprincean, 2020b: 48). Later, the growing scale of the global challenge, such as the need to improve the situation regarding human rights, the theory and practice of sustainable development, generated the emergence of the concept of human security that changed the emphasis in the national security paradigm as well, replacing the state as the object of security activities by applying military force, with the human individual, multilaterally protected (Sprincean, 2023b: 160). For the first time, the concept of human security was proposed in 1994 in the UN Human Development Report.

The evolution of human security in theoretical and practical terms has been rather arduous in the last twenty years since the launch of the term by the UNDP. However, the given conception made visible progress through its acceptance in large part through the extraordinary effort of the UN (Boutros-Ghali, Annan, Ogata, Sen, etc.), the world scientific community, and security practitioners, by entirely including this concept in the security strategies of the most critical states on the globe and the most influential international security structures. The concept of human security had a particular resonance among the world academic community (B. Buzan, O. Wæver, B. Møller, L.C. Chen, L. Axworthy, M. Kaldor, K.P. Bajpai, R. Thakur, A. Suhrke, J. Nef, J. Leaning, E. Neuman, C. Thomas, J. N. Voïnov Kohler, A. Hammerstad, G. King, Ch. Murray, etc.), by launching numerous works dedicated to the methodological development of the concept and its applicative valences in solving pressing problems around the globe by restoring equity and human dignity, defending and assuring people against various suffering and security or environmental threats.

The theoretical significance of the research resides in the elaboration and presentation of a well-grounded theoretical-methodological and conceptual complex framework, with a multidisciplinary, transdisciplinary and interdisciplinary character in the analytical-epistemological plane of scientific exploration of the issues of Industrial Symbiosis, human security and bioethics from a political perspective. The developed conceptual framework more adequately reflects the trends of the post-non-classical scientific approach and the global realities under the conditions of the world crisis to carry out a comparative analysis of the various aspects of Industrial Symbiosis, human security and bioethics in the context of the most significant and representative security and sociopolitical phenomena and processes.

CONCLUSIONS

The system of ensuring security, both on an international and national scale, required major adjustments after the end of the "Cold War" in the '90s of the last century, so that at the contemporary stage, the concepts of Industrial Symbiosis, eco-innovation and long-term culture change, as well the human security come to replace that of national security based on military force, promoting the human person with his specific interests, as a central element in the system of ensuring security, replacing in this position the state and national interests that transform from a central element of the security system during the "cold war" into a fundamental mechanism for promoting human security.

The process of modernization and adjustment to the imperatives of the time of the international and national security system is a continuous one and constantly requires new ideas and proposals for improvement and efficiency because, in the contemporary period, ensuring human security and industrial ecology become a complex and multidimensional concern, incorporating such components such as personal, environmental, health, food, community, political and economic security. Consequently, the present research aims to delineate the prospects for improving the domestic/local and international normative framework to strengthen human security by involving bioethics in Industrial Symbiosis.

The applied value of this research consists in the elaboration and presentation of scientific results of the study of a specific feasible value that can be used for the development, promotion and implementation of state policies and strategies in the fields of Industrial Symbiosis, human security, national security or in the field of bioethics with a normative and regulatory extension in various sectors of social activity.

This study familiarizes the public opinion and experts from the fields of Industrial Symbiosis, security and bioethics, but also from the adjacent ones, regarding the new knowledge obtained, data and valuable information regarding Industrial Symbiosis and human security in the context of connecting to bioethical principles and imperatives, which will inevitably lead to the reformation democratic development of the security sector in Eastern Europe, as well in Ukraine and the Republic of Moldova, by emphasizing the unique and central role of the citizen in the context of the security strategy that comes to replace the paradigm of state security at the expense of the interests of the human person.

The methodology and concepts, developed by applying an extensive set of principles, approaches and study methods, ensured the scientific research of risks, threats and dangers to human security on the world map and in Eastern Europe, especially in the countries that are for now candidate states for joining EU, in connection with Industrial Symbiosis based on bioethical issues and principles. This fact tends to exert a significant impact on social stability and the efficiency of the political decision-making process, which will contribute to the dissemination of fundamental knowledge and the training of practical skills in the field to civil servants and decision-makers in the sphere of countering security threats and risks, including environmental, societal, and political, the dangerous consequences of global problems manifested at the local level, in the countries which are candidate states for joining EU, such as the Republic of Moldova and Ukraine.

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Implementing/facilitating water-related industrial symbiosis as solution for circular water resources management

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ABSTRACT

There is a growing concern about the water shortage, which will deepen in the context of climate changes and population growth in the urban environment. The 5Rs (Reduce, Reuse, Recycle, Restore and Recover)-based circular water management is proposed based on closing loops to minimize water abstraction and pollution within the water usage cycle. Considering the main role of water authorities, including water supply and sewage operator, in integrated water resources management, Industrial Symbiosis (IS) as self-organized/planned and facilitated is considered a solution to achieve more sustainable water management. Several water innovation practices of water/wastewater treatment and reuse, including utility sharing for alternative water supply and wastewater treatment, water recovery, energy recovery from water, material/nutrients recovery from wastewater, and material/waste exchange for advanced water/wastewater treatment, are analyzed. The water-energy-material nexus is considered for establishing a local network of specific companies as physical exchangers to achieve environmental and competitive benefits in a collective approach. Also, regional water supply and sewage operators are analyzed for IS facilitating as a business and intelligence development opportunity. In particular, the role of the municipal wastewater treatment plants, through their involvement in public-private partnerships for implementing or facilitating IS, is assessed. Several case studies, e.g., eco-industrial parks and European research projects, are considered to examine the role of water innovation in Industrial Symbiosis. Challenges, solutions, and future priority in water related IS implementation considering water reduction/reusing/recycling/restoring and recovery are systematically presented to enhance potential developments on symbiotic water innovation and the potential of Industrial Symbiosis for achieving water sustainability goals. For example, reusing water in industry, especially within a Circular Economy, should address the increasing water efficiency challenge. However, there is no universal solution for water reusing, which requires finding individual solutions customized based on industry type and location, existing infrastructure and boundary conditions.

KEYWORDS
Circular Water Management; Industrial Symbiosis; Water/wastewater Treatment; Water Reuse; Water Innovation Practices; Resource Recovery

INTRODUCTION

Water has to be considered and treated as a scarce resource (UN Water, 2021) within the context of climate changes, industrial activity intensification and population growth in the urban environment. Also, intensive water usage by various sectors, e.g., agriculture, industry etc., necessitates an integrated approach to water management. Thus, integrated water resources management (IWRM) is considered a holistic approach at the government level to match the needs and demands of different users, including the environment (UNEP, 2021). Global Water Partnership has defined IWRM as “a process which promotes the coordinated development and management of water, land and related resources, to maximize the resultant economic and social welfare equitably, without compromising the sustainability of vital ecosystems” (Agarwal et al., 2000). This addresses the impacts of water-related challenges of climate change and rapid urbanization to ensure sustainable water security, which plays an essential role in IWRM (Becker et al., 2019). Considering the high requirements of water in various industrial activities, another approach of integrated industrial water management (IIWM) has proposed considering the many functions of the water, e.g., raw material, carrier for energy and materials and auxiliary material for cleaning and cooling (Ante et al., 2017; SustainWATER, 2016). In this context, the primary efforts have been directed at reducing freshwater demand and wastewater release, considering the eco-efficiency in industrial water management.

Technological and non-technological aspects must be considered to achieve sustainable water management in industry sectors. In the framework of IIWM, interactions, interdependencies, and synergy potentials between different measures related to water quantity demand and quality through water/wastewater treatment at various scales, from process to plant, site, local and regional level, are considered. IIWM should be regarded as and continuously improved in the context of climate change and Sustainable Development Goal 6-SDG6 (Clean Water and Sanitation).

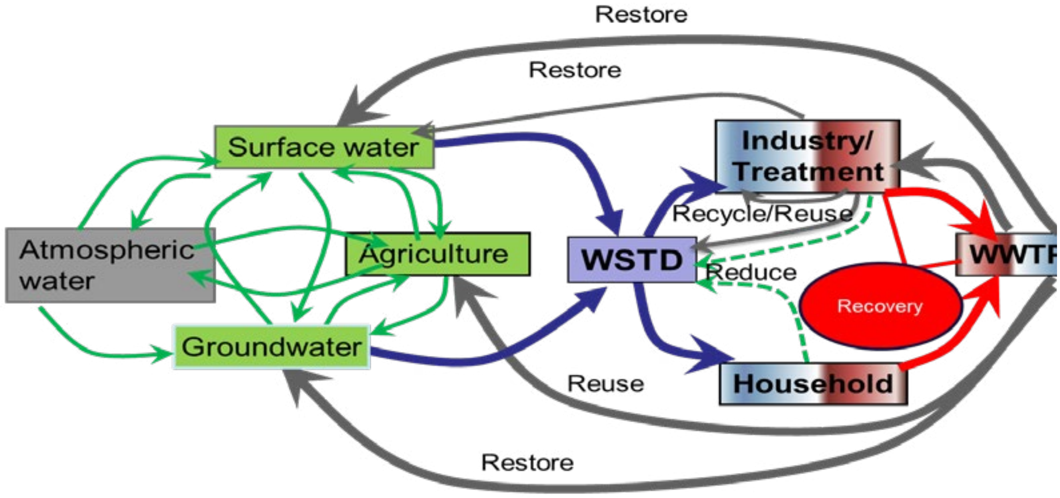
METHODOLOGY

em et al., 2023; Elazzouzi et al., 2021), textile water (Ardhan et al., 2014; De Maman et al., 2022), surface water (Idusuyi et al., 2022), Ni-EDTA containing wastewater (Ye et al., 2016), petroleum wastewater (Akkaya al., 2022). Also, EC using commercial soluble anodes (Fe, Al, Mg) have been reported as very promising for the recovery of nutrients (nitrogen and especially, phosphorous) (Kobya et al., 2021; Zhu et al., 2021; Lakshmi et al., 2013; Elazzouzi et al., 2019). Some studies were carried out in our Politehnica University of Timisoara laboratory related to using Mg scraps as soluble anode to generate Mg^{2+} ions to precipitate P and ammonium as struvite (Figure 5b).

Circular water resource management

According to the vision of Water Europe (Water Europe Water Vision, 2023, in line with the European Green Deal (European Green Deal, 2019), the value of water is at the heart of an intelligent society. This core value reflects the centrality of water as a human right and its fundamental role in our society. A multifaceted role that includes the activation of all economic activities, supporting societal functions related to the health and well-being of citizens while representing a source of monetary value generated from the extraction and valorization of raw materials and kinetic and thermal energy contained in systems of water, thus providing a unique, sustainable source to serve a Circular Economy (CE). Therefore, the circular water management approach is considered based on the characteristics and principles of CE that are applied to water resources. It focuses on the interface between natural water and managed systems and how CE can improve their interactions and interfaces. To distinguish the concepts applied as sustainable circular water management practices, the International Water Association (IWA) developed the 5Rs approach to water management linked to the Circular Economy: *reduce, reuse, recycle, restore, and recover*. Considering the role of water, according to the World Business Council for Sustainable Development (WBCSD) and Cramwinckel et al. (2017), the *reduced* approach refers to the mitigation of water loss and consumption, boosting water efficiency, *restoring* means to return water of a specific quality to where it was taken from; *reuse* considers water reusing without any supplementary treatment for the same or different process; *recycle* approach necessitates wastewater treatment to recycle water or resources. A simplified representation of the 5Rs approach in the water use cycle is given in Figure 1.

Figure 1. A simplified representation of the 5Rs approach in the water use cycle



WSTD- water storage/treatment/distribution
WWTP-wastewater treatment plant

The circular wastewater concepts integrated within the IWRM approach should maximize economic and social prosperity, considering access to finite water resources (UNEP, 2012). Water circularity largely builds upon participatory processes and stakeholder engagement to develop sustainable water circular management solutions. There are strong links between SDG6-Clean Water and Sanitation and the Circular Economy for developing sustainable water practices (Bakan et al., 2022; Schroeder et al., 2018). The 5Rs approach to circular water management reduces water quality and quantity pressure, simultaneously considering the nexus between water, energy, materials and waste (Cramwinckel et al., 2017). There are numerous social, economic, and environmental benefits for reuse and recycling. The 5Rs approach implies innovative tools and methodologies to generate water-related innovative solutions.

The main difference between water reusing and recycling is that reusing does not imply a water treatment while recycling considers reusing treated wastewater for beneficial purposes (EPA, 2018). For example, the minimum quality of the treated urban wastewater has been considered for agricultural and landscape irrigation (REGULATION EU, 2020). Also, these practices should be regarded as for industrial processes and other services.

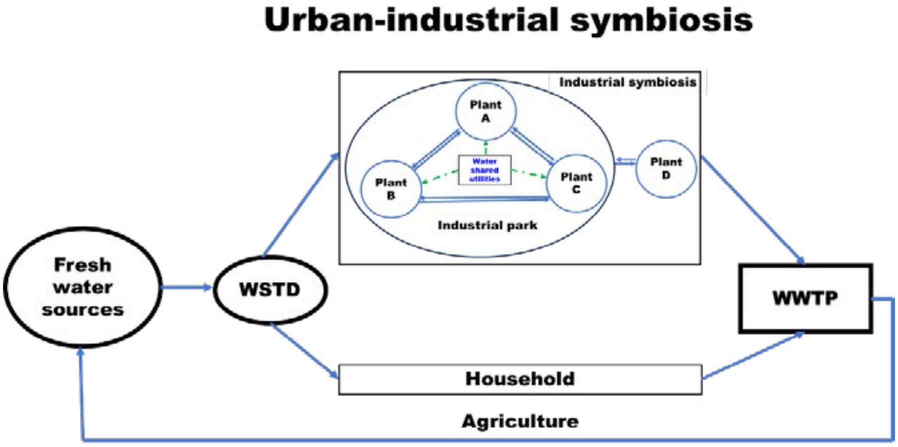
An example of the social benefits of reusing and recycling water is the possibility of decreasing the demand for potable and fresh water. Inter-sector collaboration offers the chance to use treated wastewater to supplement or replace the water demand that does not require drinking quality water, such as industrial and agricultural applications. Furthermore, reusing and recycling wastewater can ensure a reliable water supply and independence from seasonal weather and climatic conditions (Cramwinckel et al., 2017).

Industrial/urban symbiosis. Water-related symbiosis

water plays a critical role in industrial and urban symbiosis, given its essentiality in industrial processes and human health, including its socio-environmental aspect. Industrial Symbiosis offers a platform for innovative water approaches in industrial activities, including establishing networking of water exchanges between companies and reducing the demand for fresh water and water pollution by preventing wastewater discharge.

Considering that circular water management should be viewed from a systems approach, the water system represents main components in various domains, from which each can be viewed as a system that interacts with each other, e.g., environmental systems, industrial systems, agricultural systems, and municipal systems. The water-related interactions within these systems have generated the concept of industrial/urban symbiosis (Figure 2).

Figure 2. The concept of urban-Industrial Symbiosis in the water use cycle



A promising strategy for reducing water use and enhancing water management in cities has been identified as urban symbiosis (Wadström et al., 2023). Under this strategy, several urban organizations, including municipal governments and authorities, businesses, households, and agriculture, work together to share and utilize water resources. Urban symbiosis enhances water management due to its ability to facilitate the reuse and recycling of water, mitigate water losses through distribution networks, and reduce water consumption. All these targets force water-related innovation and create novel opportunities for sustainable water management.

The effective management of water resources at the industrial and city levels is one of the main advantages of industrial/urban symbiosis. Industrial/urban symbiosis can help industrial and metropolitan areas use sustainable water by facilitating efficient water usage, minimizing wastewater generation, and facilitating water reuse/recycling (Estévez et al., 2022).

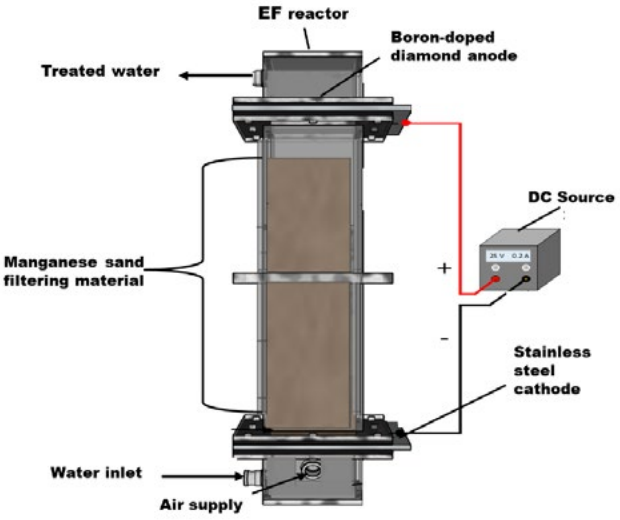
The potential benefits of adopting industrial/urban symbiosis in water management include creating more efficient and sustainable water systems, including reducing freshwater resource demand and water pollution, promoting circular economies, and reducing waste through innovative practices and technologies. However, specific barriers need to be addressed when implementing urban symbiosis. One of the most critical issues is the lack of institutional and regulatory frameworks for supporting collaborative resource exchange and management in accessing the infrastructure and resources required to develop symbiotic partnerships. The involvement of stakeholders in building support for cooperation represents the main challenge because there is no sufficient trust. Moreover, it is essential to consider the financial and economic barriers because symbiotic relationships may be more expensive than traditional water management strategies. In addition, the attitudes and ideas about ownership, competition, and privacy may limit collaboration and sharing of resources (Yatawatta et al., 2023).

However, it is essential to highlight the water innovation practices in this context of industrial/urban symbiosis. Also, one of the most recent research projects on Water Europe (ULTIMATE WATER) is dedicated to Industrial Symbiosis and considers several case studies for implementing advanced treatment processes or innovative approaches. Ramin et al. (2024) have reviewed all types of water innovation practices organized based on water-related synergies. Thus, **shared alternative water resources and wastewater treatment** have been identified as *shared utility types, and water recovery, energy recovery from water, material recovery from water, and material exchanges enhance water/wastewater treatment by type of material exchange* synergies.

However, **waste valorization by developing processes for wastewater treatment** has not been mentioned before because most studies are only at the lab or pilot scale. This water-related synergy refers to creating the methods for the nexus of water-energy materials. For example, the electrochemical-based processes represent the category that can integrate waste-derived electrodes to design the reactor architectures and the electrode configuration specific to different water-related applications (e.g., three-dimensional electrochemical filter, electrocoagulation/electrodosing of the coagulants, electroreduction, water electrolyzer for H_2 generation; electrooxidation).

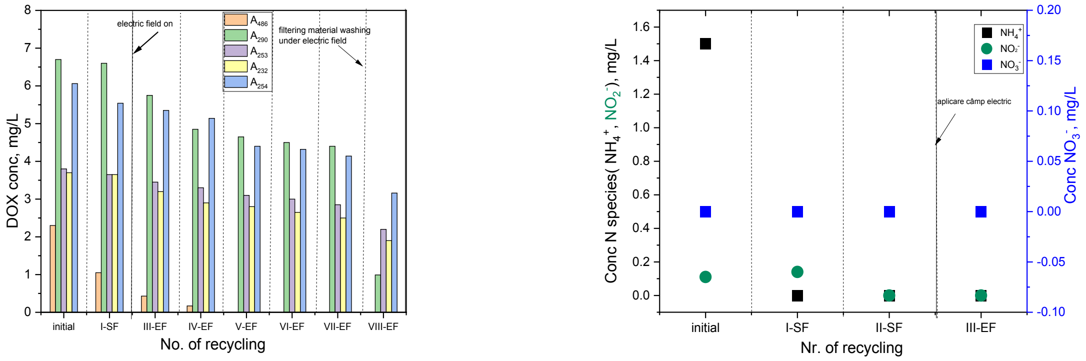
Three-dimensional electrochemical filter validated at lab scale at Politehnica University of Timisoara within the project 3DSAPECYT (3DSAPECYT, 2019; Manea et al., 2022), presented in Figure 3a) that contains an electrochemical reactor with a Ti/SnO_2-Sb_2O_4-La porous anode, a stainless steel cathode and a particulate electrode consisted of either manganese sand **as a waste of drinking water plant from Timisoara city using manganese containing groundwater source,** or natural zeolite, or activated carbon, or their multi-layers as filtering materials, was tested for the advanced treatment of water containing cytostatic as emerging pollutants, natural organic loading (e.g., humic acid), ammonium and microorganisms.

Figure 3a. Three-dimensional electrochemical filter for advanced wastewater treatment



Properties, including high electro-catalytic activity and good conductivity, have increased the current efficiency and promoted the particle electrode's heterogeneous characteristics, enhancing the performance of 3D electrode technology. The role of waste-derived particle electrodes (manganese sands) as sorbent and catalyst has been proved for doxorubicin removal, degradation, and ammonium oxidation (Figures 3b, c).

Figure 3 b,c. Results obtained for the application of the simple filtering process (SF/NM) and electrochemical filtering (EF) using the Ti/SnO2-Sb2O4-La porous anode under operating conditions: supporting electrolyte 0.1M Na2SO4 + 0.05M NaCl, Ci, AH = 10 mg/L, Ci, DOX = 5mg/L, Ci, NH4+ = 1.5mg/L, Q= 6.01L/h, U=28V, I = 0.485A;



b) Time evolution of humic acid (AH) and doxorubicin (DOX) concentrations after water filtering through the electrochemical filtration system.

c) Time evolution of N species concentrations (NH_4^+, NO_2^-, NO_3^-) after water filtering through the electrochemical filtration system

Based on the results presented in Figure 3b, a weak catalytic effect of manganese sand waste can be observed in the DOX degradation process (only for color removal) and not for its advanced degradation. At the same time, electrochemical filtering and recirculation allowed a progressive decrease in DOX concentration. Also, washing with ten mg/L NaCl supporting electrolytes under an electrical field generated HOCl with an oxidizing character, which improved the DOX degradation process. The significant catalytic effect of manganese sand waste was found for the ammonium nitrification process by applying the simple filtration process due to the catalytic activity of MnO_2 in the ammonium nitrification process, which is following the literature (Liu et al., 2022; Gang et al., 2023). These results have shown the promising potential of manganese sand to be used as a filtering material for the treatment of NH_4^+-containing groundwater or other types of industrial water with low NH_4^+ concentration, envisaging N removal and not its recovery. The synergies should consider the mitigation of the wastes in the plant for drinking water that operates groundwater source characterized by manganese presence and providing the filtering materials for other drinking water treatment plants that use ammonium-containing groundwater sources or other industrial or agricultural wastewater treatment plants. Also, developing an electrochemical filtering system is an advanced process for water treatment that exhibits great performance for application of water and wastewater for many purposes (e.g., wastewater reuse, recycling or restoration by aquifer recharge).

Another example of an electrochemical system studied in our laboratory in the context of industrial/urban symbiosis is electrocoagulation (EC), which has been used as an alternative to chemical coagulation for the conventional treatment of wastewater for the removal of suspended solids, organic loading, iron, heavy metals etc. Various types of wastewaters generated from several industrial applications have been treated successfully using EC, e.g., wastewater from textiles (Sheng et al., 1997), petroleum and oily wastewater, etc (Botte et al., 2017).

EC involves the in-situ generation of coagulants by electrically dissolving the soluble anodes, e.g., Al, Fe, Mg (Pisoi et al., 2011; Baciu et al., 2015).

The generation of metal ions takes place at Mg, Al and Fe anodes in either alkaline or acidic media, according to:

-cathode: $2H_2O + 2e^- \rightarrow H_{2\,(g)} + 2OH^-_{(aq)}$

(1)

-soluble anodes:

For Mg: $Mg_{(s)} \rightarrow Mg^{2+}_{(aq)} + 2e^-$

(2)

Bulk: $Mg^{2+}_{(aq)} + PO^{3-}_{4(aq)} + NH^+_{4(aq)} + 6H_2O \rightarrow MgNH_4PO_4 \cdot 6H_2O_{(s)} \downarrow$

(3)

For Fe : $Fe \rightarrow Fe^{2+}_{(aq)} + 2e^-$

(4)

Bulk: $Fe^{2+}_{(aq)} + 2OH^- \rightarrow Fe(OH)_{2(s)} \downarrow$

(5)

$4Fe^{2+}_{(aq)} + O_{2(g)} + 10H_2O \rightarrow Fe(OH)_{3(s)} + 8H^+$

(6)

For Al: $Al \rightarrow Al^{3+}_{(aq)} + 3e^-$

(7)

Bulk: $Al^{3+}_{(aq)} + 3OH^- \rightarrow Al(OH)_{3(s)} \downarrow$

(8)

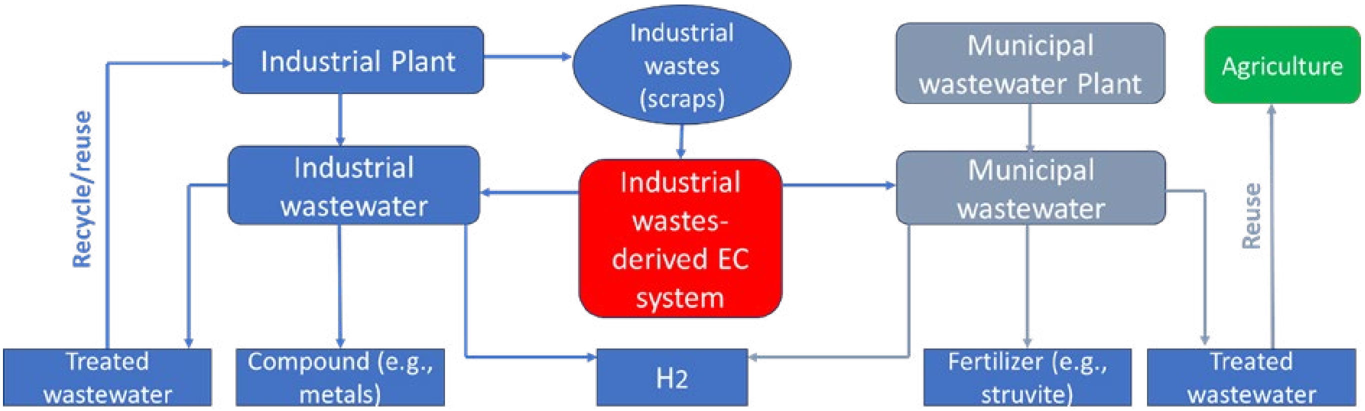
The oxidation reaction occurring at the soluble anode competes with O2 evolution according to:

$$2H_2O \rightarrow O_{2(g)} + 4H^+ + 4e^-$$

(9)

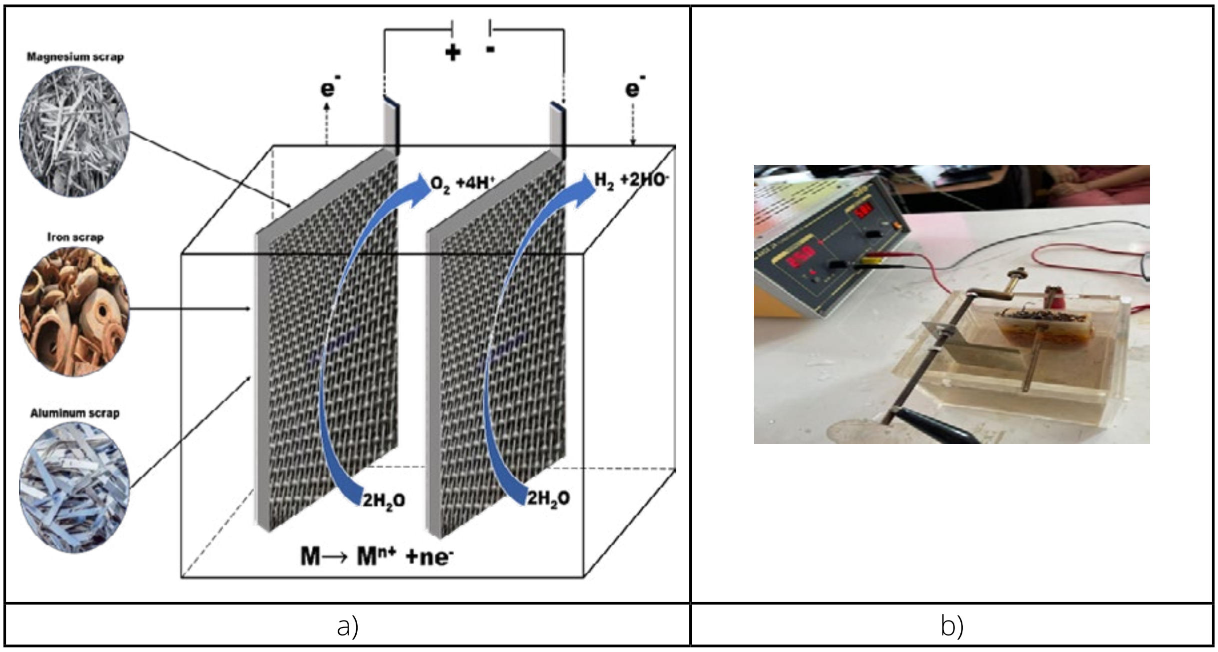
Recently, many research studies have highlighted the great potential of electrochemical methods, especially of EC, to align with the Circular Economy approach, considering circular wastewater management. Moreover, EC can be regarded as a state-of-the-art Circular Economy-driven green technology for both water/wastewater treatment and refinery for water reusing/recycling/restoration, including recovery of nutrients or other materials and hydrogen production by using H_2 as a by-product from the electrocoagulation process as alternative energy resource (Figure 4).

Figure 4. Industrial wastes-derived EC for wastewater recycle/reuse-material recovery-H2 recovery

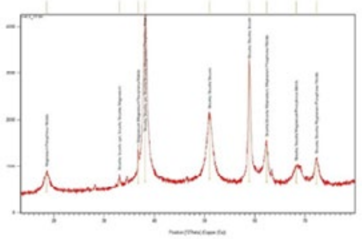


EC process can be regarded as a green alternative to chemical-based FePO$_4$·2H$_2$O recovery from acidic phosphate-rich waste streams (Nouran et al., 2024) and Mg-struvite recovery that is the most widely implemented technology among commercialized phosphorus recovery techniques due to its simplicity, with struvite crystals forming at pH ≈ 9 (Arseto et al., 2022; Bagastyo et al., 2023). The simplified scheme of the industrial waste valorization by type of Al, Fe, and Mg scraps into soluble anodes to generate the EC process is given in Figure 5a). Studies for applying Al, Fe, scrap cans and bars have been reported for treating various types of water bodies: greywater and urban water (Bani-Melhem et al., 2023; Elazzouzi et al., 2021), textile water (Ardhan et al., 2014; De Maman et al., 2022), surface water (Idusuyi et al., 2022), Ni-EDTA containing wastewater (Ye et al., 2016), petroleum wastewater (Akkaya al., 2022). Also, EC using commercial soluble anodes (Fe, Al, Mg) have been reported as very promising for the recovery of nutrients (nitrogen and especially, phosphorous) (Kobya et al., 2021; Zhu et al., 2021; Lakshmi et al., 2013; Elazzouzi et al., 2019). Some studies were carried out in our Politehnica University of Timisoara laboratory related to using Mg scraps as soluble anode to generate Mg^{2+} ions to precipitate P and ammonium as struvite (Figure 5b).

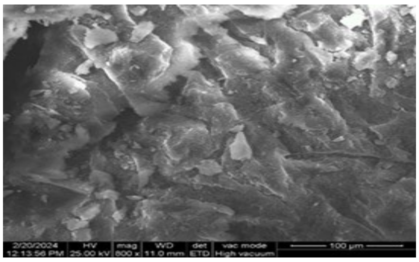
Figure 5. Schematical representation of Mg/Fe/Al scraps-derived soluble anodes for EC process (a); A picture of Mg scraps-derived EC applied in the batch regime for struvite precipitation (b); XRD of precipitate obtained by EC (c); SEM image of precipitate obtained by EC (d)



a) b)



c)



d)

Production of H_2 from EC as a by-product is a promising approach for simultaneously removing/recovering the chemicals from water/wastewater and generating clean H_2 under safety conditions, high selectivity, and environmental friendliness. Nowadays, the techno-economic analysis emphasizes that producing H2 resulting as waste from electrochemical water treatment is economically feasible. Several papers have reported H_2 production yields as a by-product of the EC process using commercial electrodes (Lakshmi et al., 2013; Sharma et al., 2021; Phalakornkule et al., 2010; Deghles et al., 2017) and not derived from industrial wastes. Different results for EC-based H2 generation byproduct-based energy production have been reported, ranging from 10% (Sharma et al., 2021) to more than 100 % (Lakshmi et al., 2013) of the requirement energy for EC functionality and water treatment efficiency.

However, further research is required to optimize reactor configuration, electrode geometries and operating conditions to implement the electrochemical process in water-related industrial-urban symbiosis at the industrial scale.

CONCLUSIONS

This paper highlights the implementation of Circular Economy concept through circular water management in water use cycle. The integrative management of water resources at the industrial and city levels should generate water-related industrial/urban symbiosis, which will improve the sustainable use of water in both industrial and metropolitan areas, facilitating efficient water usage, minimizing wastewater generation, and water reuse/recycling.

Considering the water innovation practices to create industrial-urban symbiosis, waste valorization by the development of processes for wastewater treatment, which was not mentioned before because of the low maturity of technology (most validated at lab or pilot scale), was proposed in our study for electrochemical processes (electrochemical filtering and electrocoagulation) as an emerging technology for water treatment. An electrochemical filtering system that included manganese sand (by-product of Fe, Mn-containing water source for drinking from Timisoara city, Romania) as filtering material with the role of the particulate electrode provided promising results for advanced treatment of wastewater containing cytostatic and ammonium, which should be proposed as finishing step in wastewater treatment considering its reuse/recycling. An electrocoagulation system developed based on Mg/Al/Fe scraps can be operated to assure the water treatment at the quality suitable for reuse/recycling, the recovery of material (e.g., P as struvite, or FePO4, or AlPO4) and recovery of energy resulted from H2-as by-product of EC. However, further research is required to optimize the electrochemical reactor, electrode geometries beyond conventional commercial electrodes (morphologies, density) and operating conditions following the wastewater effluent quality specific to each case study. Also, a framework for sustainability assessment of water innovations for circular water management in industrial/urban symbiosis should be developed.

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▲ Table content

Industrial symbiosis awareness: economic kpis perspective with eu circular economy policies

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ABSTRACT

Industrial Symbiosis fosters resource efficiency among industries, which promises to strengthen economic prosperity with the principles of a Circular Economy. This study reveals the critical drivers between Industrial Symbiosis awareness, economic Key Performance Indicators (KPIs), and European Union (EU) Circular Economy policies. EU countries' Circular Economy initiatives and statistical analyses of economic indicators such as real Gross Domestic Product (GDP) per capita, municipal waste generation, renewable energy sources, research and experimental development, and material footprint explain the impact of symbiosis practices on economic performance. The findings provide significant positive correlations between GDPs per capita, waste generation, material footprint, and resource productivity, emphasizing the relevance of symbiosis in fostering economic resilience and sustainability within EU member states. Based on these results, strategies for enhancing symbiosis awareness are needed to optimize economic KPIs such as cost reduction, revenue generation, resource efficiency, and competitiveness. The study contributes to a deeper understanding of how Industrial Symbiosis awareness can progress economic growth while advancing the Circular Economy in EU countries and beyond. Fostering Industrial Symbiosis and sustainable resource management requires implementing demonstration projects that can effectively provide the practical benefits of symbiotic relationships within targeted sectors or geographical areas. Furthermore, establishing robust monitoring and evaluation mechanisms is crucial for assessing the impact of awareness strategies and symbiosis initiatives, allowing for continuous advancement and improvement based on feedback, ensuring long-term success and sustainability.

KEYWORDS
Circular Economy; Industrial Symbiosis; Economic KPIs; Symbiosis Awareness; Resource Efficiency; Resource Productivity

INDUSTRIAL SYMBIOSIS AND AWARENESS

Industrial Symbiosis is the association between industrial facilities or companies in which the waste or by-products of one become raw materials for another (Chertow, 2000). Industrial Symbiosis can be described as a collaboration between several different, often geographically proximate entities, i.e., companies and factories closely co-located in clusters or industrial parks exchanging resources (e.g., materials, energy, water and by-products) that can be used as substitutes for products or raw materials, which would otherwise be imported from elsewhere or treated as waste (Clift & Druckman, 2015). Industrial Symbiosis has been an integral part of the Circular Economy concept for the last decades. Firstly, we must understand the importance of Circular Economy and industrial symbioses (as a more advanced and specific step). Based on the Circular Economy, products are designed for disassembly and reuse, shifting from end-of-life to restoration. Four sources of value creation are highlighted: minimizing material usage, maximizing consecutive cycles and time in each cycle, diversifying reuse across the value chain, and maintaining uncontaminated material streams. These principles drive material productivity and offer long-term advantages over traditional linear business models (Lamba et al., 2024). The Ellen MacArthur Foundation (2019) outlines three fundamental principles for a Circular Economy: 1) design out waste and pollution, 2) use and reuse products and materials, and 3) regenerate natural systems. The first principle underscores the importance of considering environmental impacts during the design phase to reduce the use of pure raw materials and minimize waste generation. The second principle focuses on prolonging the life cycle of products and materials through strategies such as reuse, repair, and remanufacturing. The third principle emphasizes avoiding environmental harm and actively improving the environment by returning valuable nutrients to ecosystems (Sihvonen & Ritola, 2015).

Circularity is crucial in transforming industries towards climate neutrality and long-term competitiveness. It can lead to significant material savings across value chains, create additional value, and open economic opportunities. This includes exploring options to promote circular practices within industrial processes, fostering Industrial Symbiosis through a reporting and certification system, supporting the sustainable bio-based sector, leveraging digital technologies for resource tracking, and encouraging the adoption of green technologies (Streimikiene et al., 2023). European Environment Agency (2019) shows that over the past 50 years, there has been an unprecedented increase in global material demand, leading to doubled goods production, tripled material extraction, and quadrupled economic development measured by GDP. This growth has contributed significantly to biodiversity loss, water stress, and climate change drivers. Global material use is projected to nearly double by 2060, accompanied by a substantial increase in greenhouse gas emissions. The Circular Economy aims to mitigate these trends by recycling materials, reusing products, and extending their lifespans, yielding economic and environmental benefits. Achieving a Circular Economy requires systemic changes across the value chain, including product design, technology, business models, consumer behavior, education, etc. The EU launched its Circular Economy package in 2015 to address sustainability challenges and establish concrete measures spanning consumption, production, waste management, and secondary raw material markets (Nainggolan et al., 2019). The Circular Economy is integrated better with climate policies if countries can take some crucial steps, including coordinating between countries, using models to identify impactful actions, integrating Circular Economy policies into climate mitigation reporting, evaluating the need for additional legislative proposals, monitoring policy progress, and continuously refining and developing integration strategies (EEA, 2024).

Based on this overview of the Circular Economy in the EU, Industrial Symbiosis is an up-and-coming part of it with excellent development potential. Some potential industries could engage in Industrial Symbiosis:

- Agriculture and Food Processing: Food processing products can be used for animal feed or bioenergy production.
- Chemical and Pharmaceutical: Different chemical processes can share Waste heat and by-products.
- Construction and Demolition: Recycled materials from demolition can be used in new construction projects.
- Energy Production: Excess heat from power plants can be used for district heating or industrial processes.
- Metal Manufacturing and Recycling: Waste slag from metal production can be used in construction or as raw material for other industries.
- Paper: Waste from paper production can be used in energy production or as raw materials for other industries.
- Textiles: Waste fibers and dyes can be reused in other textile production processes or in creating new materials.
- Water Treatment and Management: Treated wastewater can be reused for irrigation or industrial processes.
- Electronics Manufacturing: Electronic waste can be recycled for precious metals and other reusable components.
- Automotive: Scrap materials and by-products from car manufacturing can be recycled or used in other industrial processes.
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- Industrial Symbiosis offers numerous benefits for businesses, enhancing their operational efficiency and sustainability (Cardoni et al., 2020). Some key benefits are:
- Cost Savings: Reducing costs for raw materials by utilizing other industries' by-products and lowering waste disposal expenses through waste exchange and reuse.
- Revenue Generation: Potential new revenue streams from selling by-products to other businesses and developing new products from waste materials.
- Resource Efficiency: Optimizing the use of resources, leading to less waste and higher productivity, and improving supply chain efficiency by sourcing materials locally.
- Environmental Impact: Reducing carbon footprint and environmental impact through waste reduction, enhancing corporate sustainability and compliance with

environmental regulations.

- Innovation and Competitiveness: Fostering innovation through collaborative problem-solving and new business models and promoting competitiveness by adopting sustainable practices and technologies.
- Risk Management: Diversifying supply chains, reducing dependency on single sources of raw materials, and increasing resilience to market fluctuations and resource shortages.
- Corporate Image and Branding: Improving public perception and brand value by demonstrating a commitment to sustainability and environmentally conscious customers and investors.
- Industrial Symbiosis offers a range of benefits that extend beyond individual businesses to positively impact the entire economy (Zhang et al., 2015). Some of these economic benefits of Industrial Symbiosis are:
- Economic Growth: Stimulating economic activity through new business opportunities and markets and increasing productivity and competitiveness of industries.
- Job Creation: Generating employment through developing new industries and services and supporting jobs in recycling, resource recovery, and sustainable technologies.
- Resource Efficiency: Enhancing the efficient use of resources, reducing dependency on imports. Moreover, lowers the overall consumption of raw materials, decreasing costs for industries.
- Waste Reduction: Minimizing waste generation, reducing the economic burden of waste management, and promoting recycling and reuse, turning waste into valuable resources.
- Innovation and Technology Development: Encouraging innovation through collaborative research and development and supporting the growth of green technologies and sustainable business practices.
- Environmental Protection: reducing environmental degradation and associated economic costs, fostering compliance with environmental regulations, and avoiding penalties and fines.
- Energy Savings: Lower energy consumption through more efficient industrial processes, use renewable energy sources, and reduce energy costs.
- Regional Development: Stimulating regional economic development by creating industrial clusters and promoting regional economic resilience through diversified industrial bases.
- Circular Economy Context: Facilitating the shift towards a Circular Economy, where materials are reused and recycled, supporting long-term economic sustainability by reducing resource depletion.
- Public-Private Partnerships: Fostering collaboration between public and private sectors, enhancing economic development initiatives by public investment in infrastructure to support Industrial Symbiosis projects.
- Industrial Symbiosis awareness educates and informs industries about the benefits of resource-sharing collaborations. It aims to increase understanding of how exchanging materials, energy, and by-products can reduce waste, enhance sustainability, and drive economic gains, fostering a culture of environmental responsibility and innovation in industrial practices. Some aspects of this awareness are:
- Government and Policy Initiatives: Developing and implementing policies, funding and grants to support incentives in Industrial Symbiosis.
- Industry Collaboration: Encouraging industry groups to promote best practices and facilitate resource exchange networks.
- Research and Case Studies: Publish case studies and research findings showcasing successful Industrial Symbiosis examples.
- Public Awareness Campaigns: Traditional and social media, community meetings, etc., to highlight success stories and the positive impacts of Industrial Symbiosis.
- Education and Networking: Workshops and Seminars, Symposiums and Conferences, University Curricula, etc.
- To identify areas for improvement, demonstrate economic and environmental benefits, and ensure sustainable practices, ultimately fostering efficient resource use and long-term sustainability in industrial operations, we need Key Performance Indicators (KPIs). KPIs in Industrial Symbiosis are crucial for assessing resource efficiency, waste reduction, and economic gains. They highlight collaborative practices' environmental, economic, and social impacts, guiding improvements and demonstrating the value of sustainable initiatives, thus fostering a Circular Economy and long-term sustainability. A complete analysis of these KPIs should be evaluated from five main dimensions (Yilmaz et al., 2016; Kantor et al., 2019):
- Legal and regulation KPIs: Legal framework, legal initiative, regulation and standards, etc.
- Economic and Organizational KPIs: Profit and revenues, investment and operating cost, return on investment, internal rate of return, tangible environmental costs, financial impact, etc.
- Technical KPIs: Domestic material input, total water input, material efficiency, energy intensity and efficiency, etc.

Social and Cultural KPIs: Number of jobs, cross-industry knowledge, cultural diversity, etc.

Environmental KPIs: Direct greenhouse gas (GHG) emissions, global warming, respiratory organics and inorganics, carcinogens, ionizing radiation, aquatic and terrestrial ecotoxicity, ecosystem quality, climate change, etc.

Circular economic indicators in EU

All EU countries except Sweden have witnessed an increase in their municipal waste recycling rates since 2004, reflecting notable improvements in waste management. Particularly impressive gains have been observed in Slovakia, Lithuania, Slovenia, and Latvia, where recycling rates have surged by over 40%. However, a significant disparity in municipal waste recycling performance remains across countries. In 2021, recycling rates varied widely, from 68% in Germany to 11% in Romania. Nine countries, including Germany, Austria, and Slovenia, achieved recycling rates exceeding 50%, while four countries, Cyprus, Malta, Turkey, and Romania, recycled less than 20% of their municipal waste. Despite progress in some nations, others with lower recycling rates have shown minimal improvement over the past 15 years. Additionally, 18 EU countries were identified as at risk because they failed to meet the recycling target of 55% for municipal waste set in the Waste Framework Directive by 2025 (EU, 2020).

Recycling rates across Europe for packaging waste, electrical and electronic equipment waste, and municipal waste are crucial sources of secondary and critical raw materials and have been gradually increasing. This trend indicates a positive movement towards embracing waste as a valuable resource and advancing towards a Circular Economy. Despite this progress, the overall recycling rate, calculated as the ratio between total waste generated (excluding minerals) and the quantity managed through recycling, has remained below fifty percent of total waste generation over the available data period. Specifically, in 2016, the recycling rate stood at 48%. Recent years have shown notable progress in managing three key waste streams: packaging, municipal, and electrical and electronic waste. However, despite this advancement, their recycling rates still fall below the halfway mark of the waste generated, except for packaging, which reached a recycling rate of 66% in 2018.

Resource productivity is a crucial measure of material usage, defined as the gross domestic product (GDP) ratio to domestic material consumption. In developed countries, resource productivity typically increases over time. This upward trend is driven by efficiency improvements resulting from innovation, a shift in economic structures towards more service-oriented industries, and the outsourcing of extraction activities. Table 1 below shows the Circular Economy indicators in EU countries.

Table 1. Circular Economy indicators in EU.

Indicator	Description	Mean	St. Deviation	Time series
Resource productivity (% of GDP)	Total amount of materials directly used by an economy (measured as domestic material consumption) in relation to GDP	2.03	0.22	2010-2022
Circular Material Use Rate (in %)	Biomass	9.07	0.43	2010-2021
	Fossil energy materials/carriers	2.49	0.40	2010-2021
	Metal ores (gross ores)	23.58	1.39	2010-2021
	Non-metallic minerals	14.64	0.66	2010-2020
Waste generation (in 2010 value is 100)	Waste generation includes all materials discarded, whether they are later recycled or disposed of in a landfill.	103.57	4.08	2010-2022
Residual waste per capita (kg per capita)	Incineration (including energy recovery)	302.67	15.81	2010-2020
	Landfill and another disposal	2155.67	191.38	2010-2020

Recycling rates (in %)	Electrical and electronic waste	33.82	5.21	2010-2020
	Municipal waste	43.77	3.87	2010-2020
	Overall recycling rate	45.52	1.43	2010-2020
	Packaging waste	64.03	4.07	2010-2020
Material Footprint (in million tons of raw material equivalent)	Biomass	1410288.79	38240.75	2010-2020
	Fossil energy materials/carriers	1402435.00	98419.73	2010-2020
	Metal ores (gross ores)	610056.81	28939.06	2010-2020
	Non-metallic minerals	2924868.92	171870.92	2010-2020

Source: Author's summary and data from European Environment Agency, Indicators 2010-2021.

Resource productivity, measured as the ratio of gross domestic product (GDP) to domestic material consumption, is a crucial indicator of material efficiency. A study in the United States found long-term and short-term relationships between GDPs per capita and renewable energy consumption and resource productivity (Upadhayay et al., 2023). An increasing ratio over time suggests decoupling economic growth from resource consumption. Developed countries typically exhibit rising resource productivity due to efficiency gains from innovation, structural shifts towards services, and outsourced extraction activities. Monitoring the Circular Economy's contribution to resource productivity requires comprehensive analysis considering various causal factors. In the EU, resource productivity increased steadily by an average of 2.03% in 2010-2022. This indicates that for every kilogram of domestically used materials, two euros of economic activity are generated.

Circular material uses rates involve biomass, fossil energy materials/carriers, metal ores (gross ores), and non-metallic minerals. The EU's Circular Economy action plan targets doubling its circular material use rate over the next decade to alleviate pressure on natural resources. This entails augmenting recycled waste volumes or minimizing material consumption to curtail primary resource extraction and its adverse environmental and climate consequences. This indicator has an average of about 11.34% for the last decade, with a significant value for metal ores and less for fossil energy materials/carriers. Additionally, enhancing circular material utilization would lessen the EU's dependency on primary resources, including imported materials, bolstering its strategic autonomy. Between 2010 and 2022, there was a 3.57% increase in total waste generation across the EU countries. Major mineral wastes, primarily from the mining and construction sectors, constitute a significant portion of the total waste volume, which can skew interpretation of trends. These trends indicate that the EU is falling short of its waste generation reduction targets. Residual waste per capita (kg per capita) includes incineration (including energy recovery), landfill, and another disposal. Data reveals that the EU has averaged over 2,000 kilograms of waste per capita through landfilling or incineration, maintaining stability over the past decade. The EU aims to limit municipal waste landfilling to 10% by 2035, necessitating increased separate waste collection by citizens. Implementing financial incentives and investing in new technologies are crucial to diverting waste from landfills and incinerators and promoting circular waste treatment methods.

Recycling rates involve electrical and electronic waste, municipal waste, overall recycling rate, and packaging waste. Recycling rates for municipal waste, packaging waste, and electrical and electronic equipment waste are gradually increasing in the EU, signifying progress towards utilizing waste as a resource and achieving a Circular Economy. However, in the last decade, the recycling rate has remained below half of the total waste generation. At the same time, recent years have seen substantial progress in recycling rates for crucial waste streams such as packaging. The material footprint indicator relies on domestic extraction of materials and estimates of raw material equivalents for imports and exports. Material footprint (in million tons of raw material equivalent) involves biomass, fossil energy materials/carriers, metal ores (gross ores), and non-metallic minerals. From 2010 to 2020, the EU's material footprint remained relatively stable, decreasing by 7% from 2010 to 2016, then increasing by 5% until 2019, followed by a 5% decline in 2020 due to the COVID-19 pandemic's economic slowdown. Non-metallic minerals constitute the most significant footprint (50%), driving overall trends. Despite their considerable weight, they have a lower environmental impact than metals and fossil fuels.

METHODOLOGY

This study assesses the effect of Circular Economy in EU countries represented by the variable "resource productivity". Resource productivity and Industrial Symbiosis are linked through the efficient use of resources and waste minimization. Industrial Symbiosis enhances resource productivity by sharing by-products, reducing raw material consumption, and cutting disposal costs. This leads to cost savings, fostering innovation and collaboration between industries. The practice promotes sustainable, closed-loop systems, reducing environmental impact and ensuring resource availability for the future. Industrial Symbiosis maximizes resource output while minimizing waste and ecological harm, directly contributing to greater resource productivity. By monitoring resource productivity metrics, policymakers, businesses, and stakeholders can evaluate the effectiveness of Circular Economy initiatives and identify areas for improvement. Governments can use resource productivity data to adapt incentives and policies or regulations that promote the transition towards a Circular Economy. Consumers also benefit from increased transparency regarding the environmental performance of products and services, enabling more informed purchasing decisions. The sample consists of panel data from the European Union - 27 countries. The EU countries are Austria, Belgium, Bulgaria, Croatia, Republic of Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden. Table 2 below shows the analyzed data, time series 2000 – 2022 (with annual frequency), based on official publications of the Eurostat.

Table 2. Variables used in the model.

Variables	Description	Unit of measure
RP	Resource Productivity [The indicator is defined as the gross domestic product (GDP) divided by domestic material consumption (DMC). DMC measures the total amount of materials directly used by an economy (the annual quantity of raw materials extracted from the domestic territory of the local economy, plus all physical imports minus all physical exports).]	Euro per kilogram
GDP	Real gross domestic product (GDP) per capita [The indicator is the ratio of real GDP to the average population of a specific year.]	Euro per capita
MWG	Municipal waste generated [covers waste from households, including bulky waste, similar waste from commerce and trade, office buildings, institutions and small businesses, as well as yard and garden waste, street sweepings, the contents of litter containers, and market cleansing waste if managed as household waste.]	Thousand tons
ERS	Renewable energy sources [Share energy from renewable sources over total energy supply.]	Percentage
RD	Gross domestic expenditure on research and development [Research and experimental development (R&D) comprise creative and systematic work undertaken to increase knowledge stock.]	Percentage of gross domestic product (GDP)
MF	Material Footprint [The indicator quantifies the worldwide demand for material extractions (biomass, metal ores, non-metallic minerals and fossil energy materials/carriers) triggered by consumption and investment by households, governments and businesses in the EU. Raw material consumption indicator is a measure of material footprints.]	Tons per capita

Source: Author's summary.

The multiple linear regression model for panel data is used to perform the parameter's estimations, as explained below:

$$RP_{it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 MWG_{it} + \beta_3 ERS_{it} + \beta_4 RD_{it} + \beta_5 MF_{it} + \varepsilon_{it} \quad (1)$$

This is a linear model form for panel data, where: RP_{it} = the dependent variable;

GDP_{it}, MWG_{it}, ERS_{it}, RD_{it}, MF_{it} = the independent variables for *i*-countries and *t*-times respectively;

β_i = the model parameters, or coefficients of independent variables in the model, for $i = 1, 2, ..., 13$ (the change of the dependent variable ΔRP_{it} is explained by these coefficients β_i, in "*ceteris paribus*").

ε_{it} = the error term is the only variable that is not predicted and must be stochastic.

The multiple linear regression model for panel data is conducted in this study following basic assumptions of the Gauss-Markov Theorem (Gujarati & Porter, 2009):

First condition: the model must be of linear form related to the parameters β_i.

Second condition: the mathematical expectation of the error term must be $E(\varepsilon_{it}) = 0$.

Third condition: the model must have the error variance constant, i.e., $V(\varepsilon_{it}) = E(\varepsilon_{it}^2)=\sigma$.

Fourth condition: the model must not be correlated between error, $Cov(\varepsilon_{it}; \varepsilon_{jt})= 0, i \neq j$.

Fifth condition: the model must not have multicollinearity, i.e., $Cov(x_{it}; x_{jt}) = 0, i \neq j$.

The parameter estimations are tested according to the fixed and random effects. Following the identification of unit and time effects via the LR test, one should assess whether these impacts are fixed or result from coincidence. Within this context, the Hausman test is commonly conducted to choose among estimators. One of the most emphasized differences between fixed and random effects models is the correlation between unit impacts and independent variables. Random effects can be considered a more appropriate model if no such correlation exists. Hausman statistic is calculated from the formula (Papadopoulos, 2023):

$$H = \left(\hat{\beta}^{RE} - \hat{\beta}^{FE}\right)^{T} \left[Var\left(\hat{\beta}^{RE}\right) - Var\left(\hat{\beta}^{FE}\right)\right]^{-1} \left(\hat{\beta}^{RE} - \hat{\beta}^{FE}\right) \quad (2)$$

Where $\hat{\beta}^{RE}$ are coefficients of the random effects model, $\hat{\beta}^{FE}$ are coefficients of the fixed effects, $\left(\hat{\beta}^{RE} - \hat{\beta}^{FE}\right)^{T}$ is transpose matrix of $\left(\hat{\beta}^{RE} - \hat{\beta}^{FE}\right)$, $Var\left(\hat{\beta}^{RE}\right)$ is variance of $\hat{\beta}^{RE}$, $Var\left(\hat{\beta}^{FE}\right)$ is variance of $\hat{\beta}^{FE}$ and $\left[Var\left(\hat{\beta}^{RE}\right) - Var\left(\hat{\beta}^{FE}\right)\right]^{-1}$ is the

In the Hausman test, H0 = No correlation exists between explanatory variables and unit effects. After applying the Hausman test, the null hypothesis is accepted as related to the time. This implies that a random effect estimator is a better fit for analyzing the phenomena in question. Still, the test figures out evidence to the contrary related to cross-sections, which implies the fixed effect estimator by country.

EMPIRICAL ANALYSIS AND FINDINGS

The analysis would be complete if we analyzed the correlations of the independent variables impacted by the independent variables in a multi-variable regression model. Table 3 below shows the tested model results for each model variable.

Table 3. Pool data model (Dependent variable RP)

Independent variables	Coefficient	Prob. (t-stat.)
β_0	0.1182	0.0003*
RP_{it-1}	0.9284	0.0000*
GDP_{it}	4.28E-06	0.0002*
MWG_{it}	1.82E-09	0.0455*
ERS_{it}	-0.00024	0.7651
RD_{it}	0.0115	0.2836
MF_{it}	-0.0063	0.0000*
AR(1)	-0.2345	0.0013*
Adjusted R^2	0.9886	
Prob. (F-stat.)	2289.63	0000*

Note: "*" $p < 0.05$ (statistical significance), and AR(1) is error lag = 1 to reject autocorrelation from the model.
Source: Authors' calculations in E-views 12.

▲ Table content

As you can see in Table 3, the model is statistically significant (5% significance level) and has a high coefficient of determination of 98.86%. So, 98.86% of the variation in resource productivity is explained by the progress of the values of the factors (independent variables) included in this model. Some factors have a positive and some negative impact on resource productivity (with a statistical significance level of 5%):

- *Resource Productivity of a year ago (RPit-1)*: If the resource productivity value from a year ago increases by one time, it will increase the current resource productivity by 0.92 times. This generally happens as the productivity of an economy does not fluctuate in the short term but in the long term. Thus, an economy with a satisfactory level of efficiency in the use of resources in the creation of GDP is very likely to carry the efficiency of one year to the following years.
- *Real gross domestic product per capita (GDP):* If the real gross domestic product per capita increases by 10000 euros, the resource productivity will increase by 4.3%. The positive correlation between resource productivity and real GDP per capita suggests that improving the efficiency and effectiveness of resource use is conducive to economic growth and higher living standards.
- *Municipal waste generated (MWG)*: If it increases by a million thousand tons (or a billion tons), it will increase the resource productivity by 0.18%. This fact is ambiguous because, in the Circular Economy context, the goal typically focuses on achieving a negative correlation between resource productivity and municipal waste generated by maximizing resource efficiency, promoting reuse and recycling, and improving waste management systems.
- *Material footprint (MF):* If the material footprint increases by an average of 100 tons per capita, it will decrease the resource productivity by 0.63%. The negative correlation between Material Footprint and Resource productivity highlights the importance of adopting sustainable consumption and production practices to achieve efficient resource use and minimize environmental degradation. Increased consumption can lead to greater resource depletion and ecological harm without these measures, ultimately reducing overall resource productivity.

Analyzing the model by time and country, the results show that the time effect is unstable; therefore, over time, variables included in the model have changed resource productivity (i.e., Circular Economy) in EU countries. This means that over time, the importance of this variable has changed (thus, unstable policies are used). Meanwhile, let's analyze the same model by EU countries. The model results show that this territorial effect is stable from one country to another regarding the elasticity of economic factors that impact resource productivity levels. This stable effect by country is statistically significant, as shown in the pool model (Table 3).

CONCLUSIONS

Industries such as Agriculture, Chemical, Construction, Energy, Metal, Paper, Textiles, Water Treatment, Electronics, and Automotive can engage in Industrial Symbiosis. By reusing by-products, waste heat, recycled materials, and treated wastewater, these sectors can optimize resource use, enhance sustainability, and foster collaborative opportunities for a Circular Economy. KPIs in Industrial Symbiosis are vital to ensure sustainable practices, efficient resource use, and long-term sustainability in industrial operations. They assess resource efficiency, waste reduction, and economic gains, highlighting environmental, financial, and social impacts. Key dimensions include legal, regulatory, economic, organizational, technical, social, cultural, and ecological KPIs.

In Industrial Symbiosis, the Circular Economy seeks to maintain the value of products, materials, and resources by minimizing waste and aligning it with climate and biodiversity goals. It promotes prevention, reuse, recycling, and recovery, which is crucial for sustainable development. EU countries prioritize this shift for green recovery, aiming to integrate circular practices by 2050 to foster regenerative growth and mitigate environmental impacts. Challenges include aligning Circular Economy policies with climate strategies, enhancing recycling rates, and managing material use fluctuations, particularly for non-metallic minerals. Municipal waste and material footprint issues remain obstacles to achieving waste reduction targets in the EU. According to this study's findings, based on econometric models, the Circular Economy is represented by resource productivity. Factors such as the previous value of resource productivity (the factor with the highest level of elasticity), the real gross domestic product per capita, and the municipal waste generated have a positive and statistically significant impact on the Circular Economy in the EU.

In contrast, the factor of material footprint has a positive and statistically significant impact. The model suggests that all variables have had a stable territorial impact on resource productivity in each EU country. Meanwhile, this effect is unstable in the time dimension.

Some recommendations from this study are addressed to EU policymakers as follows. EU countries should coordinate more effectively in implementing Circular Economy policies toward climate change requirements and environmental protection. Strategies may be requested to maximize ecological benefits and measure them with concrete targets for each country. EU countries should strengthen more policies promoting circular, including extending producer responsibility with a focus on waste management (efforts should be intensified to increase recycling rates further) and minimization of waste generation. Measures should be implemented to address the stability of the material footprint, mainly focusing on reducing the consumption of non-metallic minerals.

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Industrial symbiosis on the production sectors of cyprus: lessons learned

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ABSTRACT

The economic activity in Cyprus is spread between the services, industry, and agriculture sectors. In 2022, the industry and agriculture sectors contributed 13.47% and 1.65% to Gross Domestic Product (GDP), respectively. However, the industry sector increased its contribution to the GDP by around 35% between 2014 to 2022. This industrial production growth resulted in an increasing stream of wastes and by-products, thus creating a significant challenge for sustainable development. Industries mainly belonging to the construction sector face challenges concerning efficient and environmentally friendly waste management. The lack of holistic waste management schemes resulted in most cases in the deposition of inert materials to open landfills. The lack of mapping and detailed information about those waste streams' characteristics, quality, and quantities introduces difficulties in developing Industrial Symbiosis schemes within the local production ecosystem. This study aims to present a recently developed Industrial Symbiosis scheme between organizations of the construction sector, the overall methodological approach, the identified barriers, and the lessons learned. This scheme includes a cement industry, a quarry company, a manufacturing company, and an academic and research organization that undertakes the development and facilitation of the collaboration. The consortium aims to valorize industrial wastes/ by-products into valuable raw materials and then incorporate them into production processes of innovative and environmentally friendly products. It was identified that an efficient Industrial Symbiosis scheme should be beneficial to all partners. To ensure that, time must be spent establishing trust and developing efficient communication and logistics pathways among the collaborative parties. Moreover, a robust collaboration with experts from academia or outside academia could secure a successful knowledge transfer, a fundamental requirement in those cases. Furthermore, funding schemes or legislative requirements could spark and accelerate the development of more Industrial Symbiosis solutions and partnerships.

KEYWORDS
Industrial Symbiosis; Waste Management; Construction; Innovative products; Barriers; Lessons Learned

INTRODUCTION

The economic activity in Cyprus is spread between the services, industry, and agriculture sectors. In 2022, the industry and agriculture sectors contributed 12.11% and 1.59% to gross domestic product (GDP), respectively (O'Neill, 2022). However, the industry sector increased its contribution to the GDP by around 20% between 2014 and 2022 (O'Neill, 2022).

This industrial production growth resulted in an increasing stream of wastes and by-products, thus creating a significant challenge for sustainable development. Industries mainly belonging to the construction sector face challenges concerning efficient and environmentally friendly waste management. Local construction materials companies, such as cement producers or quarry companies, generate a significant portion of by-products, such as cement kiln dust (CKD) and limestone filler (LF), respectively, with no significant use. Until today, few efforts have been made by local industries to investigate the potential exploitation of these by-products. However, such materials can be used in the manufacturing processes of concrete producers to produce concrete-based materials (Favier et al., 2018; Adesina, 2020; de Brito & Kurda, 2021). Many research studies have identified that using by-products in cement-based mixtures is essential for reducing the built environment's environmental impact (Favier et al., 2018; Adesina, 2020; de Brito & Kurda, 2021). The partial replacement of cement with industrial by-products and the use of locally sourced materials contributes towards producing greener cementitious materials with lower embodied energy yet good physicomechanical properties (Kaish et al., 2021; Al-Harthy, Taha & Al-Maamary, 2003); this is entirely in line with the fundamental principles of Circular Economy (Morsoletto, 2020). Considering the proximity among local industries in Cyprus, a collaboration between these companies can be developed based on an Industrial Symbiosis scheme, where these by-products can be used as raw materials for manufacturing concrete-based materials. However, the lack of holistic waste management schemes resulted in most cases depositing these materials in open landfills. The lack of mapping and detailed information about those waste streams' characteristics, quality, and quantities introduces difficulties in developing Industrial Symbiosis schemes within the local production ecosystem. This study presents a recently developed Industrial Symbiosis scheme between organizations in the construction sector, the overall methodological approach, the identified barriers, and the lessons learned. This scheme includes a cement industry, a quarry company, a manufacturing company, and an academic and research organization. It was developed in the context of two projects. The scope of these projects was the development of sustainable building materials using industrial by-products.

STAKEHOLDERS ANALYSIS

Cement Industry - Vassiliko Cement Works

The demand for cement in Cyprus is solely met by the Vassiliko Cement Works (VCW) company in the Larnaca district. VCW is Cyprus's only cement and clinker provider and is considered one of the most important parties in the local industrial sector. According to Vassiliko Cement Works (2018), in 2017, the company sold 562 thousand tons of clinker and 1,890 thousand tons of cement. The production of clinker involves a complex process that includes the mixing and grinding of raw materials, such as limestone and clay, into a fine powder. This powder is fired in a rotary kiln at high temperatures to produce the clinker. The clinker is mixed with a small percentage of gypsum and grinded into fine particles to make cement. The production process of clinker/cement is responsible for significant CO2 emissions, primarily due to the firing process.

Besides the significant amount of CO2 emissions associated mainly with the firing process, during the production of clinker/cement, a notable amount of dust, known as cement kiln dust (CKD), is produced. This by-product is collected with control devices from the kiln exhaust gas. The composition of this by-product depends on the raw material and the type of fuel used to produce clicker/cement. Thus, it can vary from plant to plant. Some of this material is introduced back into the clicker/cement-making process, while most end up in landfills. According to (Seo et al., 2019), during the production process of one ton of cement, 54-200 kg of CKD are generated. Therefore, notable amounts of this by-product are generated each year. Internationally, many efforts are made to exploit this by-product, such as soil stabilization and cement replacement in cementitious materials. Due to its higher alkali and chloride concentrations, compared to the normative limits for cement, CKD cannot be used in mixtures intended for reinforced concrete (Maslehuddin et al., 2008). Only in Cyprus, significant amounts of CKD are produced each year with no significant use (Vassiliko Cement Works, N/A), primarily due to the lack of data regarding its influence in cementitious mixtures and the strict normative requirements for concrete production. Furthermore, many local concrete companies are unwilling to invest resources to investigate this material's use. As a result, large amounts of CKD are deposited in open old quarries, posing a significant environmental cost to the company.

Quarry Industry - Androlikou Quarry

In Cyprus, several quarries can cover the aggregate demand of the local construction industry. Androlikou

Quarry (AQ) produces limestone aggregate materials in the Paphos district. The production of crushed aggregates includes extracting limestone rocks and crushing them several times into smaller sizes. Afterward, they are sorted into similar sizes and washed to remove the dust produced during crushing. This by-product dust, limestone filler, is collected and disposed of in landfills.

According to the annual report of Cyprus Mines and Quarries Service (2023), more than 10 million tons of aggregates were produced in Cyprus in 2023. As a result, significant quantities of limestone filler were produced and disposed of in landfills. The increasing production of this by-product calls for solutions regarding its proper management. Many researchers investigate its use as cement or aggregate replacement in cementitious materials. As in the case of CKD, in Cyprus, there isn't any significant effort to exploit this material to produce alternative cementitious materials.

Manufacturing Enterprise - Domika Ylika Ledra Group

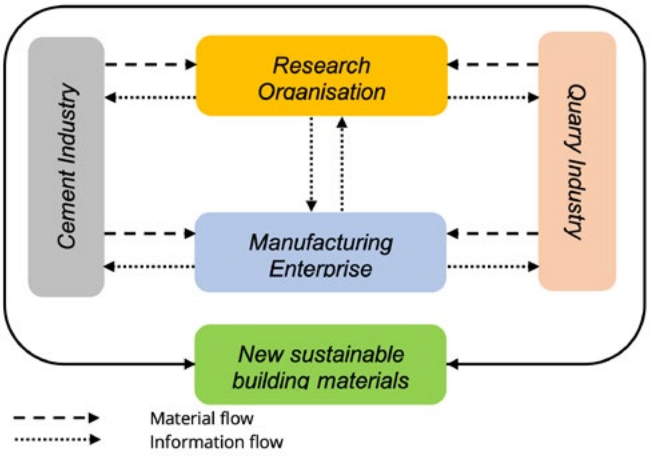
Domika Ylika Ledra Group (DYL) is a local building material enterprise located in the Paphos district and one of Cyprus's constantly growing concrete and concrete material manufacturing companies. More specifically, DYL produces ready-mix concrete of various classes for various structures. DYL's batching plant capacity is 60 m3 of concrete per hour and 150-200 m3 per day. Furthermore, DYL manufactures several concrete components, such as concrete blocks, barriers, pavement slabs, sewage pipes, and inspection chambers. Regarding the concrete blocks, DYL can produce more than 10 m3 of Ledra concrete blocks per day using steel-made molds. DYL's leading suppliers are AQ for aggregates and VCW for cement. DYL concrete plant is 22 km from AQ and 113 km from VCW. The long distance from the VCW increases the transportation cost of cement, putting DYL in a disadvantaged position compared to other concrete companies in Cyprus. Furthermore, according to the Federation of the Building Contractors' Associations of Cyprus (2023), the price of a typical C30 ready-mic concrete has increased by almost 15% at the beginning of 2023 compared to the start of 2022. These facts demonstrate DYL's need to develop new materials at a reduced cost to strengthen its position in Cyprus's local construction and material sector.

Research Organisation - Energy and Environmental Design of Buildings Research Laboratory

The Energy & Environmental Design of Buildings Research Laboratory (EEDB Lab.) was founded in 2014 and is part of the Faculty of Engineering of the University of Cyprus. Its thematic priorities include the energy and environmental design of existing and new buildings, innovative and sustainable construction components and materials, adaptable building envelope design, energy, and ecological and techno-economic analysis of materials, processes, systems and structures. The research team of the EEDB Lab includes engineers from all disciplines, thus promoting a holistic approach to designing and developing new solutions. Regarding building materials, the EEDB Lab., team has conducted many studies to facilitate the use of industrial by-products as cement and aggregate partial replacements to produce sustainable cementitious materials (Kyriadikis et al., 2019; Georigiou, Chousidis & Ioannou, 2022; Dimitriou, Savva & Petrou, 2018).

Analysis and description of the research projects

The primary objective of the projects is to address the stakeholders' problems regarding waste management and increased manufacturing costs via the development of new sustainable building materials, which are products of a sustainable symbiosis process and can be used as alternative solutions to standard building materials. Figure 1 shows a schematic diagram of the Industrial Symbiosis process.



The structure of the proposed Industrial Symbiosis scheme is based on the development of new sustainable building materials. Cement and quarry industries supply the manufacturing enterprise and the research organization with industrial by-products such as CKD and LF. The research organization is responsible for analyzing the raw materials and for the laboratory development of new sustainable building materials. Furthermore, the research organization will share the experimental results regarding the by-products with the cement and quarry industries and the results regarding the materials developed by the manufacturing enterprise. At the same time, the manufacturing enterprise is responsible for the industrial production of the developed materials. Also, the manufacturing enterprise will share information regarding the industrial use of such by-products with the rest of the stakeholders. This scheme was implemented in two different research projects.

EcoSubrick project

This project aimed to advance a prototype masonry brick developed by EEDB Lab., in a laboratory environment to the large-scale production of the proposed product in an industrial environment. The masonry brick consists of a cement-based mixture containing fine aggregates, industrial by-products such as binder additives, and various aggregate replacements in high dosages. The partial replacement of the constituent mixture's cement binder and fine aggregates with waste materials and industrial by-products will reduce the product's overall embodied energy and fully align with the fundamental principles of Industrial Symbiosis. The proposed product can be used for the construction of new buildings or the renovation of existing buildings. In this project, the limestone filler produced from AQ will be used as raw material by DYL to partially replace sand in the mixture used for the industrial production of the proposed masonry brick. EEDB Lab. will perform laboratory tests to evaluate the performance of the industrially produced bricks and compare them against the properties of the prototype masonry bricks made in a laboratory environment. This project facilitated the establishment of a supply chain of limestone filler between DYL and AQ and acted as a basis for the expansion of the Industrial Symbiosis scheme.

GreenBlock project

This project builds on the work performed in the EcoSubrick project and expands the Industrial Symbiosis scheme by including VCW. This work aims to develop a new green block consisting of a sustainable concrete mixture (SCM) as a product of an effective Industrial Symbiosis process. The SCM includes industrial by-products such as CKD and LF from local industries, such as cement and acceptable aggregate partial replacement. EEDB Lab. will analyze the industrial by-products and develop a sustainable concrete mixture. More specifically, a series of alternative cementitious mixtures with different percentages of CKD and LF as cement and aggregate replacements will be designed and produced in a laboratory environment. Each mixture is evaluated using quantitative criteria and compared against pre-defined thresholds to select a suitable mixture. Subsequently, DYL is responsible for industrializing the developed sustainable mixture and proposed concrete block. VCW and AQ will supply the industrial by-products.

The outcomes of the EcoSubrick and GreenBlock project aimed to benefit all the parties involved in the Industrial Symbiosis scheme. The two developed products have excellent prospects for entering the local market, thus resulting in significant economic benefits for DYL. The developed products can be a sustainable alternative to similar materials. More specifically, the proposed products will have lower cement and aggregate content, offering the market a solution with lower cost, higher environmental performance, and lower ecological footprint. Furthermore, the increasing requirements regarding the environmental impact of the built environment will promote the use of such sustainable materials. Therefore, DYL will have the necessary know-how to produce innovative and environmentally friendly materials, establishing the company ahead of the competition. The supply parties (VCW and AQ) will benefit from reducing industrial by-product quantities that must be managed yearly, thus minimizing their overall environmental cost. Also, the rigorous experimental investigation and characterization of their by-products will provide VCW and AW with the necessary information for further exploitation, thus increasing their economic benefits. Regarding the EEDB Lab., the projects' outcomes are expected to promote further research on this topic, creating new funding opportunities and strengthening collaboration with the local industry.

Overall, the project outcomes will attract more companies to include such industrial by-products in their manufacturing process, creating thus new Industrial Symbiosis schemes in the construction sector of Cyprus. The systematic use of materials developed via an effective Industrial Symbiosis scheme can constitute a pioneering measure of energy efficiency and waste management, thus promoting the transition to a Circular Economy model. The following table summarizes each stakeholder's outflows and inflows and the potential benefits of participating in this Industrial Symbiosis scheme.

Table 1. Inflows, outflows and potential benefits for each stakeholder

	Inflows	Outflows	Potential Benefit
VCW	Information from EEDB Lab., and DYL regarding the properties of CKD and its use in cementitious mixtures	CKD to EEDB Lab., and DYL for analysis and development of new sustainable materials	Reduction of CKD Information Regarding CKD properties and potential use
AQ	Information from EEDB Lab., and DYL regarding the properties of LF and its use in cementitious mixtures	LF to EEDB Lab. and DYL for analysis and development of new sustainable materials	Reduction of LF Information Regarding LF properties and potential use
EEDB Lab.	CKD and LF from VCW and AQ, respectively, for analysis Information from DYL regarding the industrial production of sustainable materials	Information to VCW and AQ regarding the CKD and LF properties Laboratory-produced sustainable materials for DYL	Research and innovation development, connecting with industry New funding opportunities
DYL	CKD and LF from VCW and AQ, respectively Information from EEDB Lab. regarding the development of sustainable materials	Information to VCW and AQ regarding the CKD and LF use in cementitious mixtures Information to EEDB Lab., regarding the industrial production of sustainable materials	Boost competitiveness in the local market Introduction of new materials

LESSONS LEARNED

Challenges

The most critical challenge for both projects was developing the proposed products successfully. The development of both products was based on incorporating industrial by-products in the constituent cement-based mixture. Replacing cement and fine aggregates with industrial by-products, such as CKD and LF, resulted in several technical issues that must be addressed. The most critical issue was increasing the water content when using industrial by-products to maintain sufficient flowability. The added water quantity resulted in decreasing the physico-mechanical properties of the mixtures. As a result, a series of alternative mixtures were designed and produced to assess these by-products' impact on the end-product properties. Afterward, minor modifications to the mix design were performed to improve the properties of the mixture.

Another significant challenge was the overall management of the scheme, including the timely supply of the materials, stakeholders' communication, and the provision of essential information regarding each stakeholder's operation. To address this challenge, the EEDB Lab., was responsible for the general management of the scheme. To this end, frequent meetings were arranged to review the progress of the projects and communicate the results to all the stakeholders. These frequent meetings-built trust between the stakeholders, which eased the provision of essential information. Furthermore, each stakeholder appointed a point of contact responsible for these projects to facilitate communication and overall management.

Finally, the local market must accept the developed products to promote and expand the implementation of such Industrial Symbiosis schemes. To this end, a market analysis will be performed to explore the potential of the products to enter the local market, along with various dissemination actions such as seminars, workshops, and articles published in international scientific journals and articles in national and international industry-oriented press.

Barriers

Various barriers were identified during the implementation of the research projects. The most significant barrier was the normative requirements that limit the use of fines, such as LF and materials with high alkali and chloride concentrations, such as CKD, to produce concrete for reinforced concrete structures. As a result, concrete manufacturing companies are discouraged from investigating the potential exploitation of such by-products. However, these materials can produce cementitious mixtures for other concrete components such as concrete blocks, concrete barriers, pavement slabs, sewage pipes, and inspection chambers. Most of these components use a typical concrete mixture without reinforcement steel.

Furthermore, these by-products are not standardized materials; thus, their properties can vary for each batch. Therefore, frequent control checks of their properties are necessary to ensure the quality and consistency of the cementitious mixtures and the final product's properties.

Another critical barrier to implementing such an Industrial Symbiosis scheme is the local industries' lack of knowledge and specialized personnel. Therefore, it is necessary to include a research organization in the scheme to facilitate its implementation and transfer knowledge to the companies' personnel.

Enablers

The most important enabler for the projects and the proposed Industrial Symbiosis scheme is the significant economic benefits potential among the participating companies. The developed sustainable materials will consist of mixtures containing at least 20% of CKD and LF as cement and fine aggregates partial replacement, decreasing thus the manufacturing cost for DYL and the environmental cost for VCW and AQ. Furthermore, several national funding schemes under the Cyprus Recovery and Resilience Plan financed the two projects, thus the development of the proposed Industrial Symbiosis scheme.

The composition and structure of the Industrial Symbiosis scheme could secure its successful implementation and viability. The participation of a research organization can facilitate the development of new solutions based on an Industrial Symbiosis model and transfer knowledge to the rest of the stakeholders. Also, the participation of big companies ensures the engagement of small-medium enterprises in such Industrial Symbiosis schemes. Furthermore, each stakeholder must invest in ambitious and qualified personnel that can ensure the smooth operation of the processes involved.

CONCLUSIONS

This paper describes a recent Industrial Symbiosis scheme developed in Cyprus to produce sustainable building materials. The scheme includes a cement industry, a quarry industry, a manufacturing enterprise, and an academic and research organization. The stakeholders were analyzed, and an Industrial Symbiosis scheme was proposed. The scheme was implemented in two research projects to develop new sustainable materials. Significant lessons were learned through the projects regarding the proposed scheme's challenges, barriers and enablers. It was identified that an efficient Industrial Symbiosis scheme should be beneficial to all partners. To ensure that, time must be spent establishing trust and developing efficient communication and logistics pathways among the collaborative parties.

Furthermore, innovative solutions must be developed to utilize waste streams that have not been significantly used until now. A robust collaboration with experts from academia or outside academia is fundamental to secure the successful development of new products incorporating such wastes. Finally, funding schemes or legislative requirements could spark and accelerate the development of more Industrial Symbiosis solutions and partnerships.

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Methodology to promote, identify, and evaluate industrial symbiosis actions

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ABSTRACT

Industrial Symbiosis (IS) fosters synergies between industries to improve resource efficiency and create new, more sustainable business opportunities. However, there remain challenges in promoting IS due to the lack of adequate management tools to enhance industrial collaborations and communicate its benefits.

The strategy developed has been tested and applied within the iWAYS project, focusing on compiling relevant and critical information from companies, including the demands and needs of resources and the IS initiatives implemented. Additionally, a tool has been proposed to facilitate the self-assessment of the technical and socio-economic viability of implementing each synergy.

The methodology applied has been developed as a step-by-step approach as follows:

STEP 1: Collect information on “Offer and/or Demand Resources” through an ad hoc template by analyzing resource flows and streamlining the exchange process. Understanding the characteristics, limitations, quality, and quantity of a company’s resources is essential in IS. This way, companies can share comprehensive data with other interested parties.

STEP 2: Gather information on current “IS practices” implemented. A template that compiles information regarding the economic, environmental, or social benefits of this current IS practice has been developed. This template is adaptable for future synergies that may be implemented. This document aims to disseminate best practices, provide data for sustainability reports, improve the company’s image, and promote IS in its environment.

STEP 3: Implement a methodology for the self-assessment of the sustainability of identified synergies. A self-assessment tool has been defined and designed to cover the assessment of various dimensions associated with sustainability criteria, including technical, environmental, social, and economic aspects. Each dimension contains multiple established indicators with formulated evaluation questions in an Excel datasheet. With some algorithms applicable to the answers (dropdown menu), it assigns a score that determines the relevance of each indicator. The tool’s results allow users to identify the benefits of IS practices and highlight critical aspects to review their feasibility. The results may be presented in various ways with the help of visual graphics.

During the presentation, practical cases will be provided to improve the understanding of the entire methodology and the results that may be obtained.

KEYWORDS
Industrial Symbiosis; Resources Catalogue; Industrial Symbiosis Practices; Self-assess

INTRODUCTION

Human development has been coupled with the evolution of natural resource extraction, use and disposal. The altering pattern of human growth improved lifestyle conditions in regions such as Europe, but not without compromising resource availability. This context led to a change in development strategies towards a vision of sustainability (Inês Costa, 2010)

An approach to optimizing the use of materials is Industrial Symbiosis (IS), which aims to establish collaborative networks between different organizations and companies to increase the efficiency of those resources that can optimize their use, mainly waste (Artacho-Ramírez et al., 2020).

In practice, IS is applied in industrial parks such as Kalundborg in Denmark, where steam and water exchanges occur, in addition to reusing by-products. These practices have existed since the 1970s (Domenech & Davies, 2011).

Currently, there are policies and regulations such as the Circular Economy Action Plan which includes measures to promote the IS: (a) regulatory such as the revision of the waste directive to incentivize the reuse of materials, (b) financial with funds to support IS projects, such as the Horizon Europe program, (c) research and innovation through support for projects on new methodologies or establishment of clusters, (d) creation of platforms for the exchange of resources or knowledge (European Circular Economy Stakeholder Platform),e) capacity building, (f) creating specific sectoral policies and (g) monitoring through indicators and tools to measure progress.

Another example of IS application in a regional area is the Circular Industry of Bages. This industrial area in Catalonia, Spain, has achieved a) significant improvements in waste recovery and segregation, b) the creation of waste heat networks, c) the use of biomass and biogas production and d) the formation of energy communities. The main drivers are local administrations and the waste agency of Catalonia (d. Bages, N/A).

A series of barriers related to current business models become evident in implementing IS projects. They must be considered if IS is implemented in the industrial sector. The main barrier is profitability; for a model to succeed, the economic benefits of both companies must be considered. Concerning costs, the initial investments in infrastructures are also relevant, as they are usually high and condition their viability. In another sense, legal regulations make it difficult to access the exchange of data on waste, and there are strict and different waste regulations in other territories that make it difficult to reuse waste. Finally, the scarcity of information on available resources and their main characteristics makes data exchange platforms necessary, together with the involvement of all agents, so that all available tools are used (Sommer, 2020).

This document aims to establish a series of steps to facilitate new opportunities to create synergies, promote IS in the territory, and carry out a self-assessment of the measures' sustainability.

OBJECTIVES

- To systematize the application of IS in industrial settings through a methodology to streamline collaboration between stakeholders.
- To facilitate the dissemination of good practices related to IS by compiling implemented synergies and their main features and benefits.
- To promote the sustainability of the synergies implemented utilizing a self-assessment tool that considers technical, social, economic and environmental aspects.

METHODOLOGY

The methodology applied has been developed as a step-by-step approach as follows:

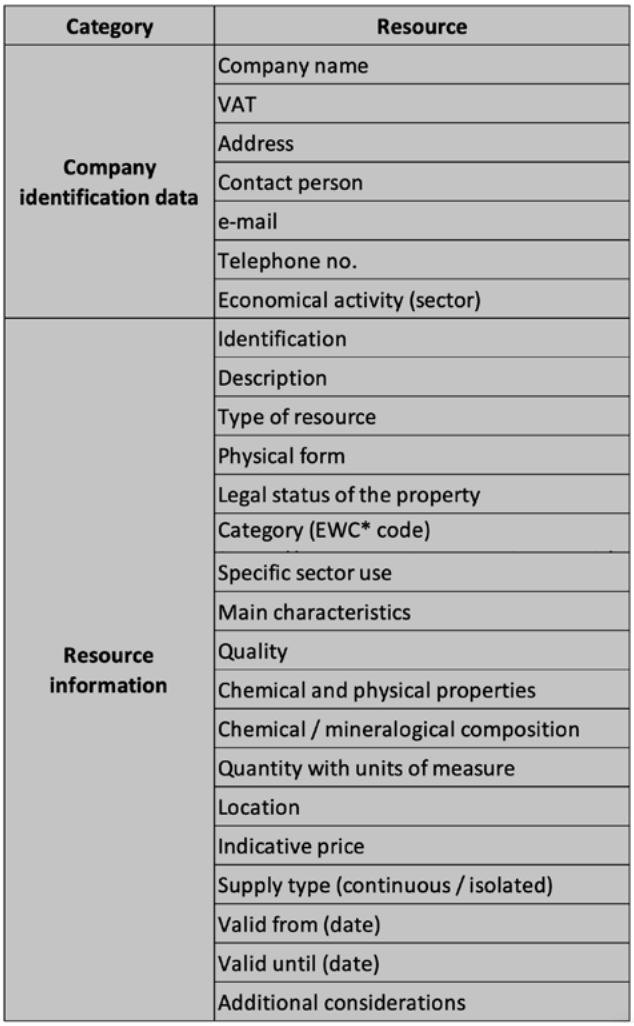
STEP 1: Preparation for Industrial Symbiosis

Collect information on "Offer and/or Demand Resources" through an ad hoc template by identifying resource flows and streamlining the exchange process. For effective implementation and optimization of Industrial Symbiosis actions, companies need to be aware of the following:

- Input and output flows of materials, water and energy.
- Services or infrastructures that can be offered to other companies.

Understanding a company's resources' characteristics, limitations, quality, and quantity is essential for optimizing their exchanges. A template containing the necessary information has been designed to facilitate this process. This enables companies to have comprehensive data available and shareable with other interested parties. Figure 1 shows the information needed to compile the resource catalog.

Figure 1. Resource datasheet



Category	Resource
Company identification data	Company name
	VAT
	Address
	Contact person
	e-mail
	Telephone no.
	Economical activity (sector)
Resource information	Identification
	Description
	Type of resource
	Physical form
	Legal status of the property
	Category (EWC* code)
	Specific sector use
	Main characteristics
	Quality
	Chemical and physical properties
	Chemical / mineralogical composition
	Quantity with units of measure
	Location
	Indicative price
	Supply type (continuous / isolated)
	Valid from (date)
	Valid until (date)
	Additional considerations

The steps taken to develop the Catalogue are as follows:

- Resources identification
- Resource Collection

The types of resources have been grouped according to whether they are material, water, services, infrastructure, or energy. The resource template outlines all the necessary information to be gathered. These templates contain valuable information that could benefit other industries, fostering streamlined data exchange between sectors. Much like a product catalog offers insights into ranges, characteristics, and functionalities, these datasheets could be used as an information tool for surrounding companies regarding available and demanded resources.

With the catalog of resources defined, workshops are organized among the participating companies. At this point, the data on each company's offers and demands are analyzed by attendants to seek potential synergies. The system used in this type of workshop is based on promoting an exchange of information, focusing on the available resources and demands.

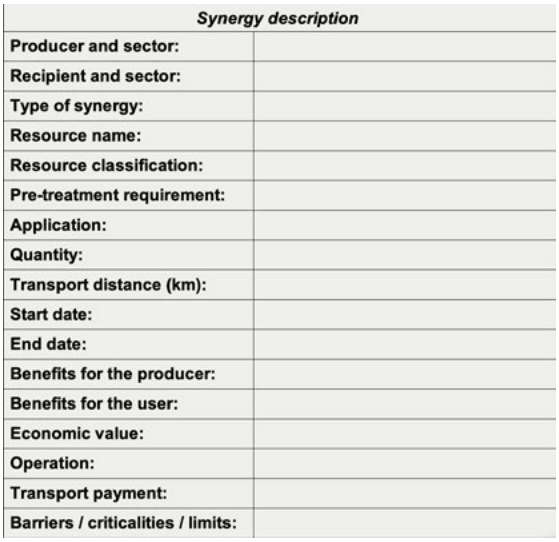
To this effect, the participants are distributed in worktables, following strategic rules to optimize the identification of matchings, for example, avoiding companies from the same industrial sector sitting in the same worktable. The resource datasheets are distributed to pool all the resources requested and offered. With the help of a facilitator at each table, each participant's information is exchanged. If he/she is interested in any of the resources shown in the datasheets, he/she writes it down on specific cards (offers/demands). Finally, the information is shared, and matchings are identified.

Afterward, to identify natural synergies, the information from the matchings is analyzed in more detail, considering aspects such as avoiding tons of waste to landfill, reduction of CO2 emissions, jobs generated, economic savings, reduction of environmental impact or any other relevant impact.

STEP 2: Compilation of Industrial Symbiosis Actions

Gather information on current "IS practices" implemented. A template that compiles information regarding the economic, environmental, or social benefits obtained from this current IS practices has been developed. The utility of this document is to disseminate best practices carried out, provide data for sustainability reports, improve the company's image, attend public authorities requests and promote IS in its environment/region/industrial site/... Figure 2 shows the main characteristics to be considered when collecting IS practices.

Figure 2. Synergy datasheet



Synergy description	
Producer and sector:	
Recipient and sector:	
Type of synergy:	
Resource name:	
Resource classification:	
Pre-treatment requirement:	
Application:	
Quantity:	
Transport distance (km):	
Start date:	
End date:	
Benefits for the producer:	
Benefits for the user:	
Economic value:	
Operation:	
Transport payment:	
Barriers / criticalities / limits:	

The criteria considered for the implementation of Industrial Symbiosis relationships are as follows:

- **Classification of the resource.** The types of resources that can be exchanged between companies are Material, Water, Energy, Services, Logistics, Competence / Information, Space and Infrastructure.
- **Pre-treatment** may be necessary before resource utilization. Circumstances might arise wherein using a resource requires preliminary actions, impacting the synergy's technical, economic, or environmental viability.
- **Quantity.** Regarding quantifiable resources, estimating the required waste quantity and determining the continuity of the flow are essential factors.
- **Distance between producer and recipient.** Proximity between producers and recipients is pivotal in Industrial Symbiosis, reducing transport costs and carbon dioxide emissions, fostering stronger relationships among involved companies, and enhancing resilience.
- **Benefits.** Benefits encompass various aspects that contribute to the success of the symbiotic relationship. These advantages extend beyond economic gains and may encompass social or environmental benefits for both the resource producer and user.
- **Barriers**. Barriers refer to critical aspects or limitations that may impede the success of the symbiotic relationship.

STEP 3: Self-Assessment of synergies

The last step would involve the assessment of synergy from a sustainability perspective. A self-assessment tool has been defined and designed to cover the evaluation of various dimensions associated with sustainability criteria, including technical, environmental, social, and economic aspects. Each dimension contains multiple established indicators with formulated evaluation questions (Table 1).

Table 1. Indicators considered for the self-assessment tool

Technical	Economic	Environmental	Social
Quantity available	Transformation needs	Transport	New jobs /positions
Supply constancy	Synergy implementation effort	Reduction of virgin raw materials	Workplace safety
Constancy with quality	Complexity and innovation	Type of virgin raw material substituted	Use of PPE
Production process	Profitability	Type of secondary resource	Local supplier
Resource functionality	Planning certainty	Water reduction	Fair trade relations with your partners/suppliers
Absence of contamination	Costs	Generation of waste or wastewater	Sustainable opportunities
Legislation	Economic benefit	Energy reduction	Value creation and opportunities
R+D	Savings from resource reduction	Atmospheric emissions	Social media
		End-of-life impacts	Risks for users
		Carbon Footprint	Information to the user
		Environmental Communication	

Table 2. Scale of colors for interpretation of results

Combination of possible answers		Results depending on the combination of answers	
Status answers	Relevance answers	Colour assigned	Meaning
Partially meets my needs	!!! (high relevance)	🟥	Very relevant
Non-compliant	!!! (high relevance)		
Non-compliant	!! (medium relevance)		
Partially meets my needs	!! (medium relevance)	🟧	Relevant
Non-compliant	! (low relevance)		
Partially meets my needs	! (low relevance)	🟦	To be reviewed
Fully meets my needs.	All answers	🟩	Positive or neutral
Mostly meets my needs.	All answers		

CASE STUDY

This section describes the application of this methodology in a Spanish territory. Specifically, it was implemented in the province of Castellón within a consortium of municipalities hosting several industrial sites. The workshop took place in 2023 and was divided into two parts: the first focused on explaining basic concepts related to the Circular Economy and Industrial Symbiosis, and the second practical part involved applying the methodology to identify synergies among the various companies attending the workshop.

During the practical part, the workshop began by introducing all the participants, indicating their company of origin and position, and briefly describing some of the resources they offered and required. Each introduction was followed by a short discussion to explore the possibilities of identifying potential synergies.

While the introductions and discussions were taking place, the potential synergies discussed were noted down so that, after all participants had presented, a provisional list of possible synergies was available. This list was reviewed collectively to clarify any doubts and to expand on the aspects that were considered most attractive. After the second round, all participants finalized and agreed upon a concrete list of potential synergies.

Companies involved

The list of attending companies can be seen in Table 3.

Table 3. Information about attendees of the IS-Workshop

Sector	Activity
Building materials	Building products specialized in insulation and energy savings.
Logistics	Transport of goods.
Waste management	Separation and classification of waste and materials for recovery. Collection and transport of any non-hazardous waste. Collection of non-hazardous products. Treatment and disposal of non-hazardous waste.
Furniture Manufacturer	Manufacturer of retail displays for ceramics and point of sales marketing.
Waste management	Hazardous and non-hazardous waste transfer center.
Furniture Manufacturer	Home furniture manufacturer.
Administration and management services	Itinerant assistance in employment, tourism and industry. Obtaining funding and subsidies for municipalities.
Research	Research and service center for the entire value chain of the ceramics and related industries.

Synergies achieved

Table 4 shows the synergies identified during the IS Workshop.

Table 4. Synergies identified during the IS-Workshop

Sinergy	Comments	Solution
Sharing the surplus generated by photovoltaic panels	Some companies on the same industrial site would be interested in sharing with neighboring companies. It has not been carried out due to bureaucratic issues.	Create an access point in the company or an energy community within the industrial park.
Recovering mattress fillings		Recovery of the material for use as a composition in the manufacture of insulation bricks.
Animal skin waste		Recovery of the material for use as a composition in the manufacture of insulation bricks.
Animal skin waste	The feasibility would have to be studied.	Manufacture of new furniture collection.
Use strapping for the manufacture of swimming costumes or bags.	Strapping cannot be reused because it cannot be fed into the packaging machine. They are not shredded due to faults in the shredding machine. Study feasibility	The strapping would be sent to the company that manufactures the thread for swimwear. A company in the province manufactures bags with strapping and is looking for certified suppliers.
Setting up of a management and modernization entity in the industrial park.		The entity offering management services offers itself for advice.
Use of cellulose waste from nearby companies.	They have not participated in the workshop but might be interested.	Recovery of the material for use as a composition in the manufacture of insulation bricks.
Decanting and separating the mineral part and the water in sludge from the manufacturing process of the participating company.	The company needs the know-how to dewater sludge and reintroduce it into its process.	The research organization can provide technical advice.
Revaluing fiberglass	The research organization has been involved in fiberglass utilization projects and offers expertise in this field.	Introduction of glass fiber in ceramic compositions.
Revaluation of ceramic or marble pieces (with and without defects) for use in furniture manufacture.	The measurements you need are determined as we manufacture as standard.	The research entity could provide information on nearby companies that may be interested.

Recommended actions for the facilitator

This section includes the recommendations given to the facilitator to implement the IS and give continuity to the synergies workshop:

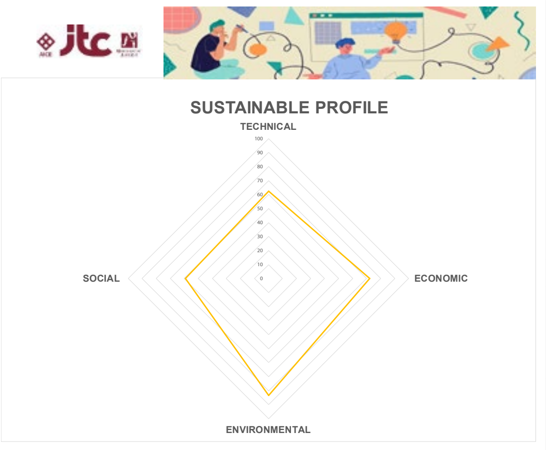
1. Conduct an in-depth analysis of the synergies found, considering aspects such as the amount avoided in landfills, reduction of carbon dioxide emissions, creation of new jobs, and economic savings.
2. Prioritize the synergies considering different criteria such as required investment, return on environmental benefit, and legal documentary needs.
3. Develop a plan for implementation and follow-up by the facilitator.

Status

Currently, the entity that organized the workshops in the county is following up on the synergies detected during the workshops. To this end, it is arranging meetings with the participating companies to discuss the progress of implementing the synergies.

Once these synergies are in place, each company will use the tool described in step three. For example, the results from applying the self-assessment tool to one of the synergies detected during the workshop (STEP 1) are presented below: Synergy_ Recovering mattress fillings.

Figure 3. Sustainability profile of the mattress filler recovery synergy



The above graphic represents the results of applying the self-assessment tool to the Synergy_ Recovering mattress fillings. For simplification, the results from the questionnaire are not included in this document. It can be observed that the economic and environmental indicators have a higher valuation since these indicators show more positive results. This is because synergies are not implemented unless they are economically viable, and regarding the environmental aspect, regulations mandate compliance with specific standards.

Upon a more detailed analysis in the social section, it is necessary to consider workplace risks, personal protective equipment use and improving fair relations with suppliers. Finally, in the technical section, it is essential to ensure the supply of resources and maintain consistency in their quality. The assessment of the indicators can be seen in the Annex of the present report.

RESULTS

The tool's results allow users to identify the benefits of IS practices to see strengths and areas for improvement according to the user's importance. The self-assessment tool serves multiple purposes:

- Identify weak points and obtain guidance to enhance relations among involved stakeholders.
- Prioritizing actions that yield the most significant sustainability impact in Industrial Symbiosis.
- Generating ideas and opportunities for immediate improvement through self-assessment and reflection on the indicators presented within each tool category.
- Showcasing the benefits and strengths of identified synergies.

CONCLUSIONS

To find more potential synergies within the territory, it would also be of interest to have a roadmap with specific actions to be carried out by Town Councils, the management of industrial estates, and the companies themselves. The aim is to improve the relationship between companies, industrial sites, and territorial public bodies to promote Industrial Symbiosis.

To follow up on the progress of the roadmap, it is advisable to dedicate human resources who would act as Industrial Symbiosis Facilitators. This new job profile aims to boost the implementation of any synergies identified during the workshops, organize meetings or training activities to raise awareness about the benefits of Industrial Symbiosis practices, bridge the gap between public authorities and engaged companies, seek funding programs for implementing the synergies, and manage the overall process.

It is essential to convey the message that Industrial Symbiosis actions are here to stay, and it is crucial to establish measures to maintain these practices if we are to realize all the benefits derived from their application.

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ANNEX I. RESULTS FROM THE SELF-ASSESSMENT TOOL

DIMENSION	INDICATOR	ASSESSMENT QUESTION Residual steam and compressed air purchasing	PLEASE, INDICATE YOUR STATUS FROM THE DROP-DOWN LIST	IMPORTANCE FOR THE APPLICANT'S ACTIVITY Please, indicate !!!, !! or ! depending on how important
TECHNICAL	Quantity available	Is the resource provided in sufficient quantity to meet your needs?	Mostly meets my needs	!!!
	Supply constancy	Is the resource offered with enough constancy to meet your needs?	Partially meets my needs	!!
	Constancy with quality	Is the resource provided with a consistent quality to meet your needs?	Partially meets my needs	!!
	Production process	In general, do the characteristics of the exchanged resource meet the requirements of the company's production process?	Fully meets my needs	!!!
	Resource functionality	Does the exchanged resource satisfy the functionality that will be required of it? In other words, is it technically feasible?	Largely satisfies the required function	!!
	Absence of contamination	Is there a guarantee of absence of contamination of the shared resource (waste/surplus raw material)? Applicable when this aspect is critical	Fully guaranteed	!
	Legislation	Is the new industrial symbiosis project likely to be affected by legislation?	No changes in the associated legal implications are detected.	!!!
	R+D	Has this symbiosis led to R&D investments or actions, whether or not related to the symbiosis project?	It has not motivated any R&D investment or action.	!
ECONOMIC	Transformation needs	Can the resource be used directly without having to undergo further processing other than the usual practice?	Requires slight further processing	!!!
	Synergy implementation effort	Is it necessary to integrate new processes and/or technologies in order to use the exchanged resource?	A few new processes need to be integrated	!!
	Complexity and innovation	What is the effort to implement this synergy with respect to the novelty of the necessary changes?	Not applicable	!
	Profitability	What is the profitability of investments in industrial symbiosis compared to traditional investments?	Higher or equal to traditional ones	!!
	Planning certainty	The environmental conditions during the planning period are....	Stable or changes can be foreseen with certainty	!
	Costs	How many costs are involved in incorporating this resource (transport + processing + transactions/bureaucracy...)?	Costs involved but not relevant	!!
	Economic benefit	Does this transaction generate additional economic benefits?	Generates significant economic benefits	!!!
	Savings from resource reduction	What are the cost savings of incorporating these resources?	Significant savings	!!
ENVIRONMENTAL	Transports	Is additional transport required that increases fuel consumption, (either because it travels more distance or because it has higher requirements on the type of vehicle)?	Additional low-demand transport is required	!!
	Reduction of virgin raw materials	What is the reduction of virgin raw materials compared to one unit of (mass) production?	It implies a substitution of part of the virgin raw materials.	!!!
	Type of virgin raw material substituted	What type of virgin raw material replaces this resource?	It is a non-fossil/renewable raw material.	!!
	Type of secondary resource	What type of material is the waste or surplus raw material to be incorporated?	It is an inert, non-hazardous material.	!!
	Water reduction	Does the incorporation of this resource lead to savings in water consumption at any stage of the life cycle?	Total or very significant savings in water consumption	!
	Generation of waste or waste water	Does the incorporation of this resource generate new waste (solid or liquid) at any stage of the life cycle?	It does not generate new waste, in fact, it prevents new waste in my company or at some other stage of the life cycle.	!!
	Energy reduction	Does the incorporation of this resource lead to savings in energy consumption at any stage of the life cycle?	Total or very significant savings in energy consumption	!!
	Atmospheric emissions	Does the incorporation of this resource generate new air emissions at any stage of the life cycle?	It does not generate new emissions in my company or at any other stage of the life cycle.	!
	End-of-life impacts	Does the incorporation of this product generate harmful effects at the end of the product' service life?	Not applicable	!
	Carbon Footprint	Does this symbiosis reduce the carbon footprint of the product/service or organisation?	Yes, the carbon footprint is reduced	!!
	Environmental Communication	Does this industrial symbiosis allow you to obtain any kind of eco-label or environmental certification for the product/business?	Not applicable	!
SOCIAL	New jobs /positions	Does this new product lead to the creation of new/different jobs positions in the company? (capacity building for employees)	Does not create new jobs	!
	Workplace safety	Does this symbiosis involve occupational hazards or accidents at work?	May involve additional risks that can be minimized through training and/or use of PPE and/or additional on-site measures	!!
	Use of PPE	Does this symbiosis require the use of additional PPE?	The use of new PPE is necessary, but they are available	!!
	Local supplier	To what extent does this symbiosis contribute to have local suppliers?	In general, we give priority to local suppliers where possible	!!!
	Fair trade relations with your partners/suppliers	Does this symbiosis foster fair business relations with your partners/suppliers (e.g. fair financial conditions, being informed about the working conditions of your partners, including staff)?	This has not been and will not be a priority at the moment.	!
	Sustainable opportunities	Do you identify opportunities related to industrial symbiosis to attract new partners, shareholders and customers, enter new untapped markets and strengthen your business?	Industrial symbiosis offers us some opportunities	!!
	Value creation and opportunities	Does this symbiosis create value and opportunities for partners and communities in your region (e.g. local employees, opening of related businesses, etc.)?	It allows to generate new values and opportunities	!!
	Social media	Could this symbiosis influence the company's social media activities?	The number of followers is the same	!
	Risks for users	Could the incorporation of this resource lead to health and safety effects of the product in the use phase (toxins, emissions, spills, etc.)?	Not applicable	!
	Information to the user	Could you provide information to the end-user on this industrial symbiosis?	Not applicable	!

Table content

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ABSTRACT

Industrial Symbiosis is crucial in advancing the Circular Economy by promoting efficient industry resource-sharing. This research explores the potential for implementing Industrial Symbiosis across 12 industrial zones in Alicante, Spain, over six months using the SYNERGie® resource matching platform by International Synergies Limited (ISL) and facilitated support activities. With over 20 years of experience, ISL has facilitated significant environmental and economic impacts, including avoiding 42 million tons of CO2 emissions and generating over £2B in economic benefits through their NISP® network in England.

This project aims to evaluate the applicability of ISL's NISP® methodologies and the SYNERGie® platform in Alicante to enhance resource efficiency, reduce waste, and improve economic productivity. The research employs a mixed-methods approach encompassing:

1. We will identify principal manufacturing companies and stakeholders for resource-matching workshops where we will locate each companies have and wants and generate initial ideas for matching companies based on these resources.
2. Use the SYNERGie® platform for resource mapping and synergy identification among local industries with the workshop results and direct company interactions. The platform's history of aiding industries in utilizing undervalued resources is crucial for decarbonization, especially in tackling Scope 3 emissions. The Advisor function within SYNERGie® uses advanced algorithms and global successes to find solutions.
3. Interviews with industrial participants to gather quantitative and qualitative data to gauge their readiness for symbiotic relationships and overcome potential barriers.
4. Development of viable synergies that participants are committed to implementing with the support of our solution-provider network.

While results are pending, the project aims to identify over 100 potential synergies from workshops, advance at least 10% of these synergies to the under-development stage, where companies actively seek solutions, and resolve at least one synergy as a case study. The study will also assess the carbon footprint and tonnage impact and update literature on technical and non-technical barriers to Industrial Symbiosis.

In summary, this project tests the feasibility of replicating ISL's successful model in Alicante, adapting proven practices to local industrial contexts to replicate similar sustainable and economic benefits. This initiative aims to promote global adoption of these practices, contributing to broader sustainability and net-zero objectives.

KEYWORDS
Industrial Symbiosis; Resource Matching Platform; Facilitation;
Circular Economy; Efficient Resource Sharing; Decarbonization; Implementation

INTRODUCTION

Like much of Europe, Spain lacks a dedicated legal framework exclusively for Industrial Symbiosis (IS). However, IS is gradually gaining traction as part of broader Circular Economy strategies across various countries, supported indirectly by waste framework directives that promote resource reuse (Lander Svendsen, Claësson Kaarsberg & Watson, 2022). In Spain, regional and local initiatives are beginning to incorporate IS. For instance, Castilla-La Mancha stands out with its Circular Economy Strategy for 2030 (Gobierno de Castilla-La Mancha, 2021), explicitly including IS as one of four strategic sectors with clear objectives for implementing circular models.

Regionally, IS is aligned with the strategies of the Generalitat Valenciana and the goals of innovation and sustainability set out in the Valencian Strategy for Reconstruction (EVR). The Ministry of Sustainable Economy, Productive Sectors, Trade, and Labor supports these efforts through the Valencian Industrial Strategic Plan (PEIV), which backs the EVR and the European strategy for reindustrializing the Valencian region. The key focus areas here are Circular Economy practices in production processes and preventing air, water, and soil pollution. In addition to these regional strategies, specific actions are being implemented to meet the objectives of the Comprehensive Waste Plan of the Valencian Community and new regional laws: LAW 6/2022 on climate change and ecological transition and LAW 5/2022 on waste and contaminated soils. These laws are designed to promote the Circular Economy within the Valencian Community.

Across Spain, over 17 IS initiatives have been identified. These include local initiatives led by research centers, specific projects for industrial parks such as the ASLE (Basque Association of Labour Companies), and IS projects within funded programs like LIFE Rewaincer, LIFE Replay, and LIFE Hypobrick. These projects primarily focus on reusing specific industrial materials rather than implementing a comprehensive IS program. Examples of successful IS initiatives in Spain include the SYMBI project in Extremadura and the Bufalvent industrial park in Catalonia.

This paper examines explicitly the application of the English methodology called NISP® (National Industrial Symbiosis Programme) in the Province of Alicante (Valencian Community), Spain, comparing it with the previous methods used for IS implementation in the region. The focus is on the first stages of IS implementation, the recruitment of companies and resource-mapping / synergy identification phases. The aim is to guide local government agencies on effectively overcoming barriers and obstacles to developing IS within their regions using the correct approach.

METHODOLOGY

This comparative research paper analyzes two approaches to developing Industrial Symbiosis (IS) in the Alicante Province of Spain. It is important to note that other methods, such as the clustering method, exist in Alicante and allow for defining standard symbiotic features among stakeholders, classifying them with similar IS potential. This method involves isolated IS workshops, typically employed by research centers focused on materials from a specific industry. The two methods compared in this paper are those used by the Spanish consulting company REDECOEC, which specializes in Circular Economy, in the development of IS in Alicante Province:

- The first approach maps resources and flows within an individual industrial park as part of the municipal Circular Economy Plan. This project aims to identify resources and synergies at the municipal level. Funded by the municipality and developed by REDECOEC with support from the local business association, resources are mapped through site visits, surveys, and Circular Economy diagnoses. Data from the Circular Economy Plans of San Vicente del Raspeig and Callosa de Segura will be compiled for comparison.
- The second approach uses the NISP® methodology, a comprehensive national program for developing Industrial Symbiosis, supported by the SYNERGie® resource-matching platform. Funded by the Province of Alicante and coordinated by FEPEVAL (Valencian Community Industrial Parks Federation, or park managers), in collaboration with REDECOEC consultancy, this project spans 12 industrial parks. It aims to map resources, flows, and synergies across the Alicante Province through dynamic workshops. The results presented in this paper are from one workshop (Elche Industrial Park) and represent an initial assessment as the project is ongoing.
- For each approach, we compared both quantitative and qualitative information. We identified the benefits and barriers encountered during company recruitment and individual interviews or workshops for qualitative results. For quantitative results, we compared:
- Number of companies contacted for the project

- The number of participants in the project
- Main participating sectors (NACE codes grouped by sector)
- Industry Mix (number of sectors represented, as the presence of a variety of industries within the park, with potential for various by-product exchanges, is essential for IS implementation (Neves et al., 2020))
- The types of participating companies are categorized as associations, SMEs or large enterprises (with over 250 employees and over 50 million in annual revenue).
- Percentage of manufacturers in an industrial park
- The participation rate of manufacturers
- Percentage of participating companies represented by manufacturers
- The number of resources mapped
- The type of resources mapped
- The number of potential synergies (ideas generated) identified
- The types of potential synergies (ideas generated) identified
- The types of resources were categorized according to the NISP® methodology into infrastructure, material (including water and energy), knowledge, capacity, and logistics. The types of potential synergies were categorized based on the elements that link or generate synergy between different industrial entities (Castellet-Viciano et al., 2023):
- Mutuality synergies: there is no flow of materials or products, but these synergies involve sharing services, facilities, or infrastructures. (e.g., energy supply or waste treatment, emergency planning, training, logistics, and transport).
- Substitution synergies: these are transfers of products where the waste of one company or industrial process is part of the resource flow of another (e.g., exchange of by-products, waste, waste heat, etc.).
- Genesis synergies involve creating an original activity to satisfy the reuse requirement of any flow (including expertise) or company.
- These categories are not mutually exclusive; a synergy can encompass all three. For example, underutilized space can be used to recycle solar panels (mutuality), creating a new business opportunity (genesis), and the resulting materials can then be reused by local industries (substitution).

RESULTS

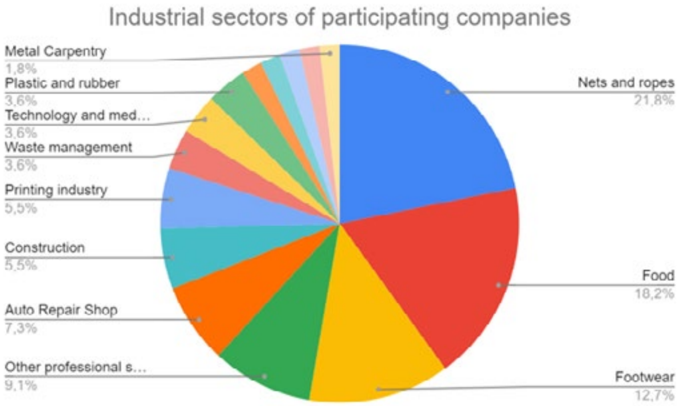
Approach 1: Individual approach in a municipal Circular Economy plan

This project unfolds in four phases: collecting databases of existing companies in the industrial park, recruiting companies, conducting individual visits to each participating company, and analyzing material and energy flows. During the company visits, a Circular Economy diagnosis is performed to determine their current stage, along with a subsidy and energy analysis to identify potential benefits from ongoing funding for Circular Economy initiatives or opportunities to save on energy costs. REDECOEC collects electricity bills and other inputs and outputs from the companies to map the quantity and cost of electricity, water, raw materials, and waste flows. This data is then compiled into an individual report for each company and a general report for the municipality. The report includes the results of the Circular Economy diagnosis, potential subsidies they can apply for, and the total energy savings. The general report maps resource flows at a territorial level and identifies potential synergies for implementation

Quantitative results - Participation

For the Circular Economy Plans in San Vicente del Raspeig and Callosa de Segura, we contacted 242 and 56 companies, respectively. On average, 55.3% were manufacturing companies, and 91.5% were SMEs. In Callosa, 85% of the companies were manufacturers, with 46% participating in the project, representing 66% of the total participants. In San Vicente, only 25.6% were manufacturers, with 11% participating, representing 31.8% of participants. On average, manufacturers had a participation rate of 28.5% and represented 49% of participants. In San Vicente, 9% of participating companies were large enterprises; in Callosa, it was 8%, averaging 8.5%. The rest were SMEs, and no business associations were present. On average, 27.5 companies participated in the projects, representing an 18.4% participation rate. Participating companies came from an average of 10 sectors.

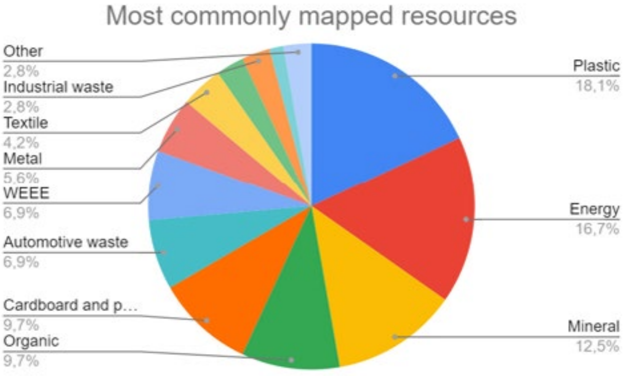
Figure 1. Industrial sectors to which belong the participating companies (results averaged from sectors found in Callosa de Segura and San Vicente del Raspeig).



Quantitative results - Resource-mapping

In Callosa de Segura, 11 companies (33.3% of participants) shared their information. All provided data on energy consumption (electricity, 45.5% of the resources mapped). The remaining resources shared were 40.9% raw materials and 13.6% waste, with 30.8% being plastics. Six companies (27.2% of participants) shared their information in San Vicente. The resources mapped were equally divided between raw materials and waste, with the most common being mineral (18%), plastic (12%), and organic (12%) materials. On average, only 30.9% of participating companies provided information about their inputs and outputs, exclusively concerning material resources. The following graphic summarizes the total amount of resources. The most common resources are plastics (18.1% for packaging and raw materials) and energy (16.7% electricity), followed by mineral resources (12.5%, primarily from construction sites).

Figure 2. Most mapped resources in Approach 1 (averaged from individual results in San Vicente and Callosa).

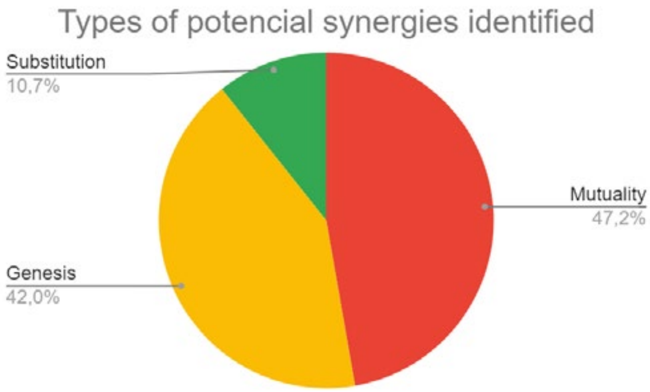


Unfortunately, we collected only limited information regarding material quantities, which hindered our ability to generate synergies. However, we could still identify opportunities through the EC diagnosis and site visits.

Quantitative results - Identification of synergies

The ideas generated were primarily mutuality and genesis synergies (47,2% and 42%, respectively). In contrast, substitution synergies represented 10,7%, involving shared knowledge for new business opportunities, logistics for managing standard waste streams or producing electricity through a Local Energy Community (CEL, Comunidad Energética Local). On average, about 8,5 ideas were generated that can later become concrete synergies.

Figure 3. Types of synergies identified in Approach 1 are mostly mutuality (47,2%) and genesis synergies (42%).



Qualitative results - Benefits of the approach:

1. Targeted recruitment: companies are recruited or invited to participate, ensuring that interested and relevant businesses are engaged.
2. Assessment of Circular Economy advancement within the territory
3. Individual assessment for each participating company: tailored recommendations for each company.
4. Site visits: Identify specific opportunities for improvement.
5. Engaging SMEs in sustainable practices with energy-saving tips to implement right away and access to subsidies for sustainable projects
6. 6. Individual reports: each company receives a customized report detailing the results of their Circular Economy diagnosis, potential subsidies, and total energy savings.
7. Creation of a consolidated database for the town hall or managing entity like the local business association (if existing)
8. Raising awareness of Circular Economy and Industrial Symbiosis and encouraging collaboration on resource efficiency.
9. Municipality-level insights: a general report for the municipality maps resource flows at a territorial level and identifies potential synergies, offering a broader perspective for regional planning.

10. Facilitates synergy identification: the detailed analysis and reports help pinpoint opportunities for Industrial Symbiosis within the industrial park.

Qualitative results - Barriers Detected:

Lack of initial information

- Absence of a consolidated database by the city council and local business association.
- Difficulty obtaining information about companies' inputs and outputs, as well as precise details like quantity, continuity of production, current management, and costs.

Difficulties in synergy identification

- Failure to identify specific non-material resources such as infrastructure, logistics, and knowledge.
- Failure to precisely identify the needs of companies necessary for identifying synergies.
- Reports only communicated potential synergies at a territorial level, not at the company level.
- Synergies are primarily based on shared resources or logistics (mutualization) rather than specific collaborations based on one material (genesis symbiosis or substitution synergies), where materials can be reinjected into a new business model.
- Deindustrialization: The lack of manufacturing companies in one of our industrial parks led to a low number of detected synergies.

Lack of Coordination

- Lack of solid presence and persuasive power from the local business association to encourage company participation.
- There is an absence of a central facilitator to identify symbiosis opportunities, mediate dialogue, and help overcome technical or logistical barriers.

Lack of trust

- The company is reluctant to share sensitive data on material and energy flows and processes due to fear of leaked information from competitors.
- Lack of stable public-private relationships: municipal neglect of industrial parks and misaligned project goals (not business-oriented).
- Inconsistent follow-through with municipal events and pilot projects, discouraging business participation in city council initiatives (inconsistent commitments due to political changes).

Lack of knowledge of IS:

- Companies are overwhelmed by the numerous events and projects organized by the municipality and local agencies (chamber of commerce, specialized resource institutes, local business associations, etc.), making it difficult for them to recognize the value of an IS project when it is introduced.
- The lack of funding and difficulty in executing IS projects and following up on identified synergies are possibly due to a lack of knowledge about IS and its benefits.

Approach 2: Regional or collective approach using the NISP® methodology, accompanied by the resource-matching platform SYNERGie®

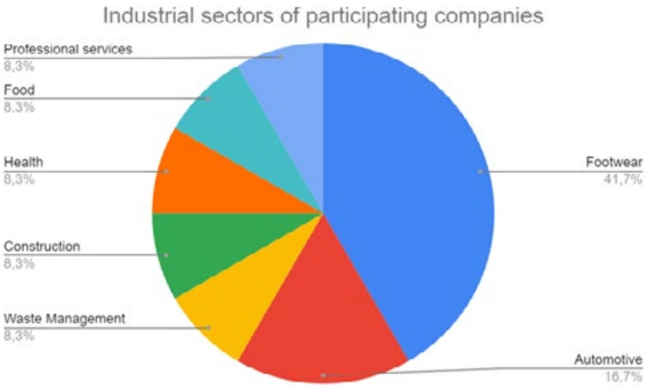
This approach follows a four-step process, beginning with data collection about companies and industrial parks to recruit them for the project, like Approach 1. From there, instead of focusing on individual companies, the NISP® method uses "business opportunity workshops" where companies come together to share their resources and needs. The workshop was held in a training room at one of the largest companies in the industrial park. During these workshops, dynamic tables identify and rotate resources and needs, ensuring all participants are exposed to the same information. Companies identify opportunities for synergies with the help of facilitators. The results are then input into the SYNERGie® resource-matching platform. This platform allows IS facilitators to send personalized reports to companies, helping them develop synergies and identify new matches within the same industrial park or region, thanks to the platform's algorithmic function. Facilitators actively assist companies in developing their synergies by making necessary connections and guiding the process.

Quantitative results - Participation

Elche Industrial Park, one of the largest in Alicante Province, is home to approximately 750 companies. For the Business Opportunity Workshop, facilitators selected 193 companies of particular interest, including manufacturers, large enterprises, and companies in the food and construction sectors. Ultimately, 12 companies participated in the event, with 18 attendees, resulting in a participation rate of 6.2%. Among the participants, 5 were large enterprises with 2 or 3 representatives each, making up 41.7% of the participating companies, 33.3% were SMEs, and the remaining 25% were business associations. Manufacturers comprised 65.8% of the initial 193 companies, but only 4 attended the event, accounting for 33.3% of the total participants and a general participation rate of 3.1%.

The following graphic divides the participating companies by NACE code:

Figure 4. Industrial sectors which belong to the 12 participating companies from approach 2.



In total, seven different sectors participated. The primary sectors represented in participating companies are the footwear sector (41,7%) and the automotive sector (16,7%).

Quantitative results - Resource-mapping

With the workshop method, companies detected 73 resources in total, and we can distinguish between what companies have (55 resources identified) and what companies want (16 needs identified). Additionally, the exchanges between companies identified 37 and 18 more potential haves and wants (55). All types of resources were mapped, but the primary type of resources was material resources, with 72,6%.

Figure 5. Type of resources mapped in total for Approach 2

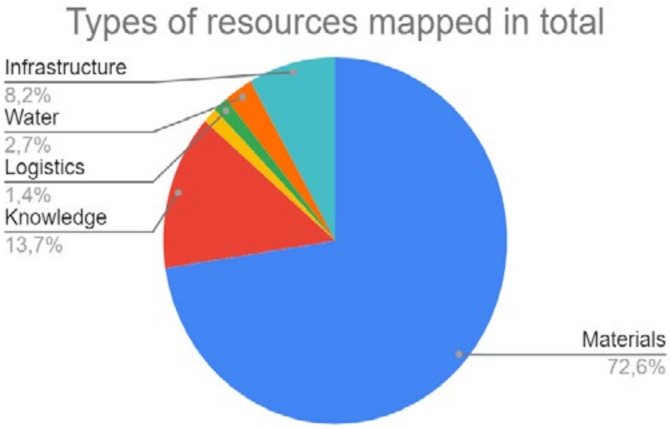


Figure 6. Most mapped material resources for Approach 2, classified by quantity incidence of each resource

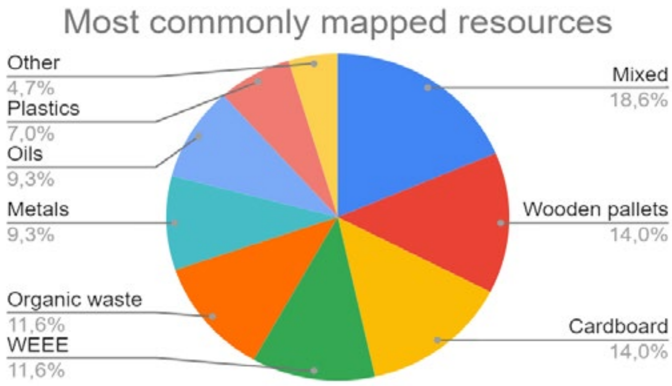
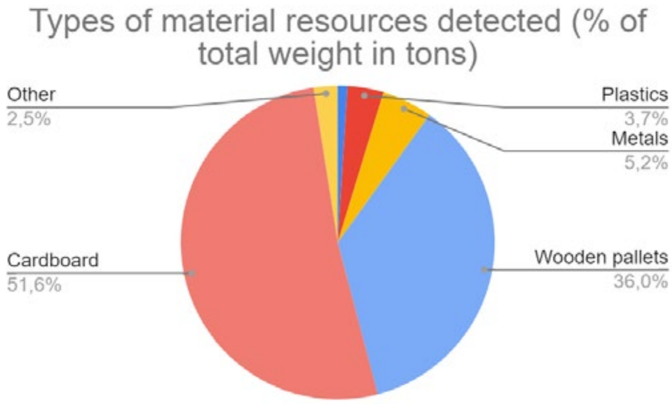


Figure 7. Most mapped resources for approach 2 (classified by resource weight).



Some resources, such as WEEE, oils, organic waste, and mixed materials, have such a low weight that they do not appear on the graphic.

Quantitative results - Identification of Synergies

During the workshop, 50 ideas were generated that could be resolved into concrete synergies between companies. The synergies identified were primarily substitution synergies (70,21%), where one company was interested in reusing the resource of another, and mutuality synergies (29,8%) for shared logistics, infrastructure and knowledge.

Quantitative results - Benefits of the approach

- Targeted recruitment: companies are recruited or invited to participate, ensuring that interested and relevant businesses are engaged.
- Creation of a consolidated database for the town hall or managing entity like the local park manager.
- Raising awareness of Circular Economy and Industrial Symbiosis and encouraging collaboration on resource efficiency.
- Collaborative environment: business opportunity workshops foster a collaborative environment where

companies can share resources and needs.
- Efficient resource sharing: dynamic tables used in workshops expose all participants to the same information, streamlining the identification of opportunities.
- Identification and quantification of the companies' specific problematic resources and needs.
- Facilitator assistance: facilitators help companies identify synergies, providing expert guidance.
- Personalized reports: facilitators use the platform to send customized reports to companies, detailing possible synergies and opportunities.
- Facilitates synergy identification: the SYNERGie® resource-matching platform automates the matching process, making it easier to identify potential synergies.
- Algorithmic matching: the platform's algorithmic function enhances the identification of new matches within the same industrial park or region.
- Active facilitation: facilitators actively assist companies in developing synergies, ensuring follow-through and implementation.
- Broader network: the platform allows for the discovery of synergies within the industrial park and across the region, expanding potential opportunities.

Quantitative results - Barriers detected:

Lack of initial information
- Absence of a consolidated database by the city council and local park manager.
- Complex regulatory environments or inadequate policy frameworks can limit opportunities for companies to collaborate or reuse waste products due to fears of poor waste management and potential legal consequences.

Difficulties in synergy identification
- Deindustrialization: lack of manufacturing companies in industrial parks that lead to low detected synergies.
- The most identified resource was municipal waste, such as cardboard, paper, and plastic film, which everyone wanted to dispose of, but few were willing to take.
- There was difficulty in identifying resources and needs by attendees who were heads of departments.
- Varying information among attendees from different departments of large companies

Lack of knowledge of IS:
- Companies are overwhelmed by the numerous events and projects organized by the municipality and local agencies (chamber of commerce, specialized resource institutes, local business associations, etc.), making it difficult for them to recognize the value of an IS project when it is introduced.

CONCLUSIONS

This study is indicative, based on only three workshops in Alicante Province. More seminars and methodologies are needed for reliable conclusions and steady indicators for IS implementation. However, we observe a clear distinction between the two methods: despite the lowest participation rate (6.2% in Elche), Approach 2 achieved the highest and most qualitative results, mapping 73 resources (plus 55 potential ones discovered through matches) and detecting 50 synergies, compared to 38.5 resources and 8.5 synergies on average in Approach 1. In Callosa, 85% of the 56 companies were manufacturers, leading to a 59% participation rate. Manufacturing stood out as the sector with the highest potential for establishing symbiosis relationships (Neves et al., 2019). However, only eight synergies were identified, primarily based on shared infrastructure and waste logistics. With the most companies (242) and highest sector representation (12 sectors), San Vicente mapped 50 resources. Still, it identified only nine synergies due to a lack of detailed information on resource quantity, quality, and frequency.

While density, type and nature of industrial activities (manufacturer presence and sector representation) suggestively influence the inclinations toward IS (Ruiz-Puente et al., 2015), the results highlight the importance of companies identifying their resources and needs, as in Approach 2. Here, facilitators help companies identify resources and opportunities rather than doing the matching themselves. This approach provides precise information on company problems, identifies likely synergies due to direct company interest, and includes all resource types (infrastructure, materials, knowledge, capacity, and logistics). As a result, Approach 2 shows a higher occurrence of substitution synergies (70.2% compared to 10.7% in Approach 1), significantly impacting the supply chain by promoting efficient resource use in a Circular Economy. With the 20-year-old NISP® methodology and dynamic table setup, it was easy to convince companies to set aside their competitive concerns and share more information on their inputs and outputs. Workshops also built trust, offering opportunities for companies to meet and collaborate, aligning with their interests as business opportunity workshops.

In contrast, Approach 1 identified only material resources and relied on Circular Economy diagnosis to identify feasible synergies due to a lack of specific information. Further work could explore whether different approaches inherently favor other types of synergies, as the NISP method predominantly favors substitution synergies. Therefore, when starting an IS project, the choice of method could be tailored based on the desired synergies outcome.

The workshop in Elche (Approach 2) also showed the importance of extensive company participation (41.7% versus 8.5% in Approach 1) and support from the local park manager for recruiting influential companies. While a mix of company sizes is beneficial, a critical mass of larger companies with significant resource needs or waste generation can provide a strong foundation for IS (World Bank, 2019). According to Akhtar et al. (2022), these types of synergistic collaborations are more prevalent in developed regions and are linked to larger-sized industries. Large enterprises brought significant material resources, and the park manager's involvement ensured visibility and participation from both large and smaller companies. Without their help, the event might have been lost among the many local activities organized by the town hall, chamber of commerce, business associations, and research institutes. This role helps stabilize public-private relationships and address misaligned project goals and issues, such as industrial park waste management and maintenance, providing further reassurance and support to the participants. These entities can identify new partners for infrastructure sharing and joint provision of services, provide training, facilitate information exchange, foster cooperation, and coordinate potential symbiosis relationships. What's more, in places where no synergy networks have been established, the role of these facilitators can be highly relevant (Neves et al., 2019).

Beyond better quantitative results, the NISP® methodology overcomes several other barriers in Approach 1. Approach 2, regional or national, combats deindustrialization more effectively as a multi-industrial park project with the SYNERGie® resource-mapping platform, which can automatically match resources as the project progresses. Approach 2's regional/national collaborative approach ensures consistent follow-through, overcoming the inconsistent commitments due to political changes that discourage business participation in municipal initiatives. More companies are expected to participate as the program develops, gaining trust and interest. The SYNERGie® platform's algorithm will further enhance match detection. Companies expressing interest in improving their processes are more likely to finance the synergies they want to implement.

To ensure Approach 2's success, it's essential to involve manufacturers and solution providers (recyclers) who are vital to transforming waste into new materials. This is not necessarily a barrier to the process but a necessary step for the approach to succeed. Each company has a vital role in the IS network: recovering produced wastes and saving required inputs. Firms achieve this by exchanging wastes for inputs, with high resource consumption and generation (water, energy, raw materials), suggesting reuse potential for others (World Bank, 2019). It is essential to select company representatives with technical expertise who understand their resources and needs and can creatively identify collaboration opportunities. Additionally, having prior knowledge of waste and safety regulations will reassure participants and facilitate match formation. Overall, Approach 2 fosters a collaborative environment through workshops, using the SYNERGie® platform for automated resource matching and dynamic tables for efficient resource sharing, providing ongoing support and broader network opportunities compared to Approach 1's individualized support.

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Opportunities, challenges and barriers found in industrial symbiosis implementation in the Basque Country

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ABSTRACT

Industrial Symbiosis can be a powerful tool to facilitate the transition towards the Circular Economy for industries of all types and sectors. The Basque Country, located in the north of Spain, has industrial solid roots and density, primarily SMEs, and a significant metal sector presence. In this industrial ecosystem, the technical consultancy Onurak ecosolutions, together with jurist partners and researchers from the University of the Basque Country, has so far carried out three Industrial Symbiosis projects in the region: two of them within the framework of a business association, and a third one in an industrial estate.

The three projects have been carried out using a similar method: 1) mapping stage by presenting the project to the companies and issuing a questionnaire for data collection (primary raw materials consumed, main waste streams generated and main interests in sharing services/infrastructures), 2) stage of identification of synergy opportunities and 3) stage of technical-legal and economic feasibility study.

The results show great opportunities arising from Industrial Symbiosis and challenges and barriers to its implementation. The main opportunities identified early in the Industrial Symbiosis between companies in an industrial ecosystem focus on mutuality or sharing synergies. In all three projects, companies are highly interested in primarily sharing the management and transport of their waste streams and generating renewable energy self-consumption communities. The challenges and barriers identified are related to the need to overcome the operational inertia of the companies, especially in smaller SMEs.

Based on this experience, it is concluded that Industrial Symbiosis requires awareness raising and should be implemented gradually, starting with small, simple and effective synergies. This will generate a climate of trust in companies towards this tool and thus lead progressively to behavioral changes towards greater openness and acceptance of Industrial Symbiosis.

KEYWORDS
Industrial Symbiosis; Implementation; Basque Country; Opportunities; Challenges; Mutuality

INTRODUCTION

The Basque Country, located in the north of Spain, has industrial solid roots and density, primarily SMEs, and a significant metal sector presence (Orkestra - Instituto Vasco de Competitividad, 2023). Companies in the region increasingly take Circular Economy and sustainability into account, which is mainly driven by legislation and, more recently, the market, especially as a decarbonization strategy. However, smaller SMEs find it more challenging to adopt circular measures (Iheba, 2019). Industrial Symbiosis can be a powerful tool to facilitate the transition towards the Circular Economy for industries of all types and sectors. However, few Industrial Symbiosis experiences have been carried out in the Basque region (Gobierno Vasco, 2022).

In this industrial ecosystem, the technical consultancy Onurak Ecosolutions S.L. and jurist partners and researchers from the University of the Basque Country developed four Industrial Symbiosis projects in the region during the last three years. Three of the projects were performed within the framework of ASLE companies (Asociación de Sociedades Laborales de Euskadi), a business association located in the Basque Country, where each project was focused in a different territory inside Basque Country (Gipuzkoa, Bizkaia and Araba). The fourth project is being performed in an industrial estate called Apattaerreka Industrialdea (Gipuzkoa), where around 60 companies (primarily industrial) are established.

METHODOLOGY

The Industrial Symbiosis processes materialized through the development of four consecutive activities: a first stage of initiation and mapping, a second stage of diagnosis and identification of synergies, a third stage of evaluating the viability of the identified synergies, and a final stage of execution of selected projects. The four projects were carried out using a similar method, although different stages were reached in each one.

1) Mapping. The projects began by presenting to all the companies located in the industrial ecosystem the main goals, steps and benefits for participants, as well as issuing a questionnaire for data collection (general company data -sector, activity, location-, primary raw materials consumed - description, annual amount, criticality-, main waste streams generated - description, yearly amount, destination, criticality - and main interests in sharing services/infrastructures –shared water treatment or reuse, shared waste management, shared transport for employees or materials, shared storage/parking spaces, shared machinery, renewable energy self-consumption communities, shared process heat-). At this stage, monitoring and assistance were required to encourage as many companies as possible to participate and complete the necessary data.

2) Identification of synergy opportunities. It involved processing all collected data, particularly considering those waste or raw materials deemed critical by companies. Synergies between companies were classified according to their typology as substitution or exchange synergies (use of waste as raw materials) or mutuality synergies (based on sharing services or infrastructure). Aspects such as proximity between potentially synergistic companies and the existence of previous experiences based on one's own expert knowledge or specialized databases [4, 5] were considered when establishing potential synergies or opportunities.

3) Technical-legal and economic feasibility study, which could lead to a final stage of implementation and monitoring of selected projects, also called "activation of synergies". Two of the four projects that were carried out reached this stage (one is currently being implemented). However, the disparity in the synergies' complexity required very different time schedules and resources. Therefore, this stage initially required prioritization of opportunities to identify those that may be more feasible and have more significant economic, social and environmental impacts, focusing on the strategic areas for the companies involved to promote the Circular Economy in the project's ecosystem. This prioritization and the available time and budget in these last stages of the projects determined the specific opportunities to be developed.

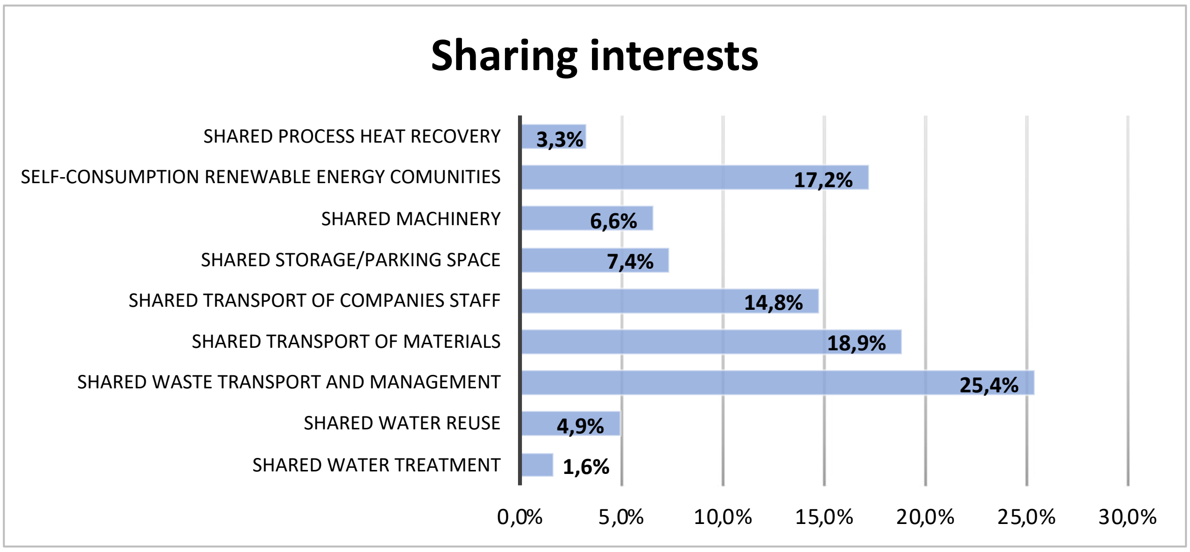
4) Execution and monitoring of selected projects. In the final stage, activating the synergies evaluated as viable in the previous stage could be carried out.

RESULTS

The main opportunities identified early in the Industrial Symbiosis between companies in an industrial ecosystem focused on mutuality or sharing synergies. In all four projects, companies showed a high level of interest in primarily sharing the transport and management of their waste streams, sharing transport of materials and generating renewable energy self-consumption communities. Figure 1 shows the main sharing interests indicated by the companies participating in the four projects, where 122 interests in sharing services or infrastructures were collected.

Figure 1. Main sharing interests by companies parti-

cipating in the four developed Industrial Symbiosis projects.



In mutuality synergies, proximity played a key role. Thus, the symbiosis processes developed in an industrial estate, such as the Apattaerreka project, significantly facilitate the activation of opportunities related to sharing services and infrastructure, such as energy communities (limited by law to a maximum distance of 2km between companies) [6], shared waste management, shared transport of staff or materials, shared use of machinery, shared spaces, etc. For this reason, in the Apattaerreka project, 14 of the 20 opportunities identified corresponded to mutuality synergies, with great activation potential in the creation of an energy community (with eight interested companies), the shared management of lubricant oil waste (4 interested companies) or shared transport of staff (5 interested companies).

On the other hand, mutuality synergies presented significant matching difficulties in the ASLE symbiosis processes, in which the companies were located and dispersed in each territory. In this case, exchange synergies (waste as raw material) were not so limited by proximity, allowing synergies -depending on the case and the criticality of the material- in companies located more than 50 km away. The most common exchange synergies in the four developed projects referred to using cardboard packaging waste as filling material for new packaging and wood waste for new product manufacturing.

The challenges and barriers identified were related to the need to overcome the operational inertia of the companies, especially in smaller SMEs. Starting with the data collection stage, larger SMEs usually have specialized staff in the environmental area and could, therefore, be more proactive in getting involved. On the other hand, smaller SMEs require more effort to get involved, often due to their lack of human resources. This is why symbiosis projects also require prior awareness-raising work to trigger interest and encourage participation in small industries.

The activation or implementation of synergies can vary widely in terms of time and resources, depending on their complexity, from easily activatable synergies, such as shared waste management, to more technically complex synergies, such as energy communities, the sharing of water treatment or process heat facilities, or exchange synergies that require prior waste transformation. In the four projects, the successfully activated synergies were simple symbioses based on sharing waste management (e.g., lubricant oils), leading to direct economic savings for the companies. These types of synergies were welcomed by companies, allowing them to establish a basis to start collaboration habits and work on new synergy opportunities. Boosting participation in workshops for the companies is also essential, as it makes them aware of project results so they can see their participation's direct benefits. This way, debate and exchange spaces are opened where companies can contribute their needs and proposals, creating in-situ links and emerging new opportunities that could not be identified through the questionnaire.

CONCLUSIONS

The results showed great opportunities arising from Industrial Symbiosis but challenges and barriers in its implementation. The materialization of synergies can be very uneven in time and resources, depending on the complexity, from easily activatable synergies, such as shared waste management, to more technically complex synergies, such as energy communities, the sharing of water treatment or process heat facilities, or exchange synergies requiring prior waste transformation. The four Industrial Symbiosis projects referred to in this study showed the need to overcome the operational inertia of the companies, especially in smaller SMEs. Based on this experience, it is concluded that Industrial Symbiosis requires awareness raising and should be implemented gradually, starting with small, simple and effective synergies. This will generate a climate of trust in companies towards this tool and thus lead progressively to behavioral changes towards greater openness and acceptance of Industrial Symbiosis.

ACKNOWLEDGEMENTS

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Opportunities for industrial symbiosis between the agroindustrial and furniture sectors: R&D projects

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ABSTRACT

The agricultural sector is the most critical industry in the Region of Murcia (Spain), dedicating 50% of its entire surface to crops. This high production is associated with huge waste derived from vegetal transformation and processing. In this context, research and development have played a crucial role in exploring the feasibility of converting these underutilized resources into high-value compounds for synthesizing materials applicable to the furniture sector. This integrated approach seeks to reduce waste, minimize environmental impact, diversify raw material sources in the furniture sector and promote circularity in the supply chain. In recent years, CETEM has worked on three main lines related to the identification, extraction and application of compounds derived from vegetal by-products in the production of innovative and sustainable materials, replacing conventional ones, which can commonly be toxic: 1. Lignin extraction from lignocellulosic waste materials using physical, chemicals and biologicals methods for application in the synthesis of adhesives; 2. The production of bio pigments from the citrus waste fermentation to develop dyes and colorants for coatings; and 3. The processing and functionalization of vegetal fibers for the manufacture of agglomerated composites. This research found a lignin-based adhesive used as a binder in fiber composites, an orange dye used to color wood coatings and particle boards made from 100% vegetable by-products fiber (artichoke, rice husk and vine stem).

KEYWORDS
Sustainable Materials; Valorization; Furniture; Adhesives; Bio-pigments; Composites

INTRODUCTION

The high amount of waste in the agrifood industry

In the food industry, the sector dedicated to processing fruits and vegetables generates a substantial quantity of plant waste (bark, leaves, stems, peels), which contains components of interest, such as fiber, antioxidants, sugars, and vitamins, despite lacking commercial value. The food industry can extract and utilize these materials or serve as raw materials in developing products and applications in other fields, including cosmetics, biomaterials, biofuels, and pharmaceuticals. Waste valorization addresses numerous environmental issues, including pollution prevention and reducing demand for virgin resources and raw materials. This process facilitates the development of sustainable, biodegradable, and renewable products.

To establish synergies between the agrifood and the furni-

Table content

ture sectors, this plant waste has been analyzed to identify its potential for developing sustainable materials that can replace traditional ones in the habitat sector.

Valorizing waste fibers

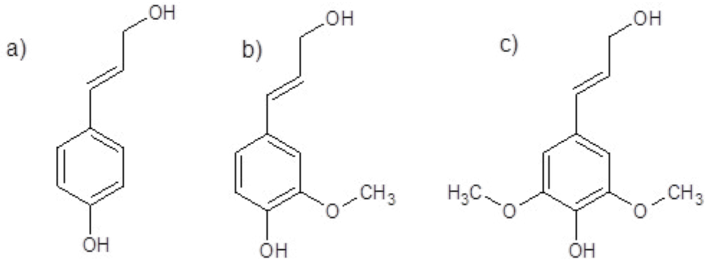
Wood-based panels and fiberboards represent the most used composite materials in the furniture industry. These boards are manufactured aggregating wood fibers with adhesive resins or binders. During manufacturing, the resin-impregnated fibers are compacted under pressure and high temperature (Rocco et al., 2015). The worldwide availability and biodegradability of lignocellulosic fibers and their good specific mechanical properties have increased interest in the industrial use of waste fibers in producing composite materials (Petar et al., 2017). In the furniture sector, raw fiberboard materials are low-grade virgin wood, which is also used in other products. This high demand for low-grade wood leads to an increase in the cost of wood chips, which can lead to instability in the supply of particleboard and an increase in market prices. That is the reason that agro-industrial fibers of various origins, such as flax, hemp, kenaf, sisal, jute, and coconut, have been used in the production of wood-like composites (Galle, 2017; Kettser et al., 2011). In this sense, the research of alternative and renewable raw materials for fiberboards is gaining interest in producing wood composites (Klimek & Wimmer, 2017).

The potential of lignocellulosic biomass: lignin

The industry advocates for developing sustainable alternatives to traditional fossil-based products. For adhesives and fiberboards, essential materials in the furniture sector, a necessity for alternative raw materials and manufacturing processes that can replace traditional ones is detected. Among these are phenol-formaldehyde adhesives, which are considerably toxic and present significant limitations. The European Commission has classified PF as a Category 1B carcinogen and a Category 2 mutagen, leading to substantial restrictions on marketing products. Consequently, the research for alternatives for total or partial reduction of formaldehyde-based adhesives in fiberboards is currently a key challenge in this industry.

The management of lignocellulosic waste in the agro-industrial sector has traditionally involved burning. However, lignocellulosic biomass contains different valuable components, such as lignin. Lignin is the most abundant natural source of phenols and typically constitutes 15-30% of the weight of lignocellulosic biomass (Li et al., 2018). A noteworthy property of lignin is its high potential to replace phenol in the synthesis of phenolic resins and to formulate wood adhesives. This is due to the structural units of lignin, which are mono- and di-substituted phenylpropenol in the aromatic ring (Figure 1).

Figure 1. Main monomers in lignin



Lignin exists in a complex and recalcitrant form, embedded in the wall of plant cells, which makes it challenging to work with (van NIeuwenhove et al., 2020). It is necessary to break the lignocellulosic structure and separate it from cellulose and holocellulose to isolate lignin. Several strategies have been developed to extract and obtain lignin from woody plant sources, including physicochemical and biological tools.

A colorful world of possibilities

Another raw material commonly used in the furniture sector is wood coatings or finishing products that contain pigments in their formulation, such as stains and varnishes. The pigments currently used in these formulations are typically of synthetic origin, and their composition sometimes includes chemical elements of considerable toxicity, such as cadmium-based yellow pigments.

The search for alternatives to synthetic pigments in various applications has led to the evaluation of the use of pigments of natural origin. Carotenoids are one of nature's most critical and widespread pigments, providing colors ranging from yellow to deep red in vegetables and fruits. Citrus fruits have higher levels of carotenoids in the outer layer of the peel, making waste from the citrus processing industry an excellent alternative source of this compound.

Various techniques are used to extract pigments, the most common being extraction with organic solvents. Other research has shown that using enzymes and microorganisms is an alternative and advantageous method. Among the organisms, the fungus of the Monascus species is one of the most promising due to its good yields (Kongruang, 2011). Numerous studies have used this fungus to produce bio pigments from rice, maize and cassava residues (Carvalho et al., 2007).

METHODOLOGY

Waste characterization and pretreatments

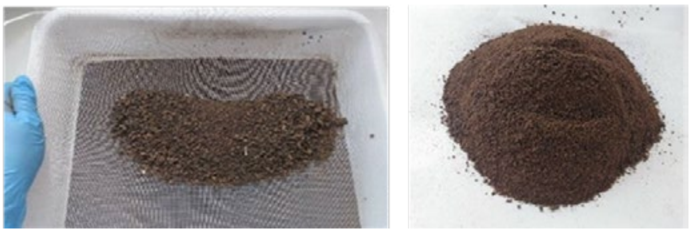
Considering that the waste and by-products with the potential to produce valuable materials in the furniture sector include plant fibers, lignocellulosic waste, and pigments, local products generating these wastes were selected for evaluation. Artichoke, rice and vine shoots were selected for fibers, orange peels for pigments, and stems for lignocellulosic material for lignin extraction.

These wastes originate from the food industry's processing of fruits and vegetables in the Region of Murcia, specifically to produce canned food, frozen vegetables, and juices. They were provided by the CTNC (National Technological Centre for Food and Canning) with the necessary pretreatment and stabilization according to intended applications (Figure 2).

Upon receipt, the physical and chemical properties of the waste were evaluated. The lignocellulosic fibers intended for board production were characterized through humidity content analysis using the oven weight loss test. Vine stems and shoots for lignin extraction were analyzed to determine their lignin concentration. Three types of orange peel waste (O1, O2, O3) were analyzed for various characteristics that could affect fungal growth, such as moisture, pH, nitrogen and sugar content. Then, it was ground and sieved through a 1.5mm pore size to provide a uniform and accessible substrate for the fungus (Figure 3). The moisture content was adjusted by evaluating different media such as water, phosphate buffer or PDB (potato dextrose broth).

Figure 2. Vine shoot (left) and vine steam (right)

Figure 3. Sieving the orange peel waste



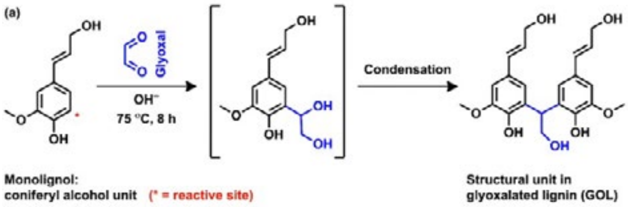
Lignin extraction and adhesive development

Once the biomass composition was known, the most appropriate experimental protocols were designed to optimize the fractionation and delignification of lignocellulosic biomass to valorize its structural components. The synergy between microwave and ultrasound technologies, alkaline treatments and fungal delignification was tested. For the physical-chemical pathway, parameters such as alkali concentration or time and temperature of the processes were analyzed. For biological delignification, critical aspects such as fungal strain, humidity, supplemented media, time and temperature of incubation and inoculum concentration were studied.

After the biomass delignification, the fraction called black liquor was acidified to precipitate lignin, which was characterized using different analytical techniques (Fourier Transformer Infrared Spectroscopy FTIR, Gel Permeation Chromatography GPC) to determine the cross-linking capacity, chemical structure and molecular weight. The remaining delignified biomass was also characterized and treated like vegetable waste fiber for fiberboard production.

The adhesive was developed through modification and functionalization with glyoxal of experimental lignin, and commercial lignin was used as a control.

Figure 4. Reaction scheme between lignin and glyoxal



Fiberboards production

Fibers of vegetable waste origin were impregnated with a water-based adhesive at a concentration of 17% w/w. The adhesive, previously diluted to 80% w/w in water, was sprayed under 4 bar pressure while mixing with blades (Figure 4). Fir tree fiber was chosen as a control to produce reference fiberboards and compare properties with the experimental boards.

Once impregnated with the adhesive, the fibers were placed in a 20 cm² mold and pressed in two phases: a cold phase (80 bars, 5 minutes), which gave the board its shape, and a hot phase (80 bars, 190°C, 20 minutes), which promoted the cross-linking of the adhesive and imparting rigidity and strength to the board.

Figure 5. Fiberboard development process: left, mixing system using blades while the adhesive is applied by pressurized spray; center, fibers impregned with adhesive in the mold; right, hot plate pressing.

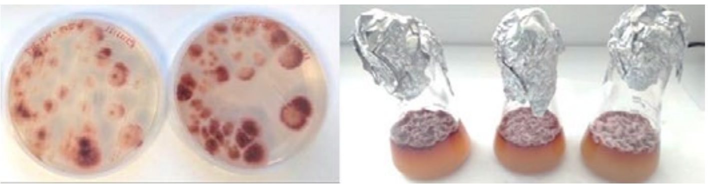
When cold, the fiberboards were evaluated through physical-mechanical characterization, including density, tensile strength, internal cohesion and swelling tests, following the specifications of the relevant standard (UNE-EN 312:2010).

Production of bio-pigments and coloring of wood coatings

The fungus Monascus purpureus was selected for its robustness in various media and conditions and its proven ability to grow and produce pigments from orange waste. The fungus was characterized at both morphological and biochemical levels to understand its growth development and the pigment production process, among other aspects.

The previously sterilized orange waste was inoculated with a spore suspension from a seven-day culture in PDA (Figure 5) and incubated at 30ºC with orbital shaking (180 rpm). Different parameters were studied to determine the most suitable conditions to maximize the yield in the production of biopigments.

Figure 6. Monascus purpureus culture after seven days of incubation in Petri dishes for characterization (left) and in flasks to obtain thigh biomass for orange waste inoculation (right).



After appropriate incubation periods, extraction processes were carried out to obtain pigments from the fungal biomass and the orange waste. This process involved several steps, including suspending the fungal and orange biomass in ethanol using ultrasonic agitation, followed by centrifugation and filtration. To estimate the concentration of pigment, the ethanol solutions were analyzed by visible light spectrophotometry at the wavelengths corresponding to yellow (400 nm), orange (475 nm), and red (500 nm), which are indicative of the carotenoids from orange and biopigments of Monascus purpureus.

After rotary evaporation (94ºC, 180 rpm) and concentration processes, pigments were isolated and incorporated as an additive in formulations for wood coatings. A commercial water-based resin was used and formulated according to previously developed protocols. Once a homogeneous mixture was obtained, it was applied to different wooden panels (pine, oak, beech, fir) using a universal resin applicator (thickness 250 µm).

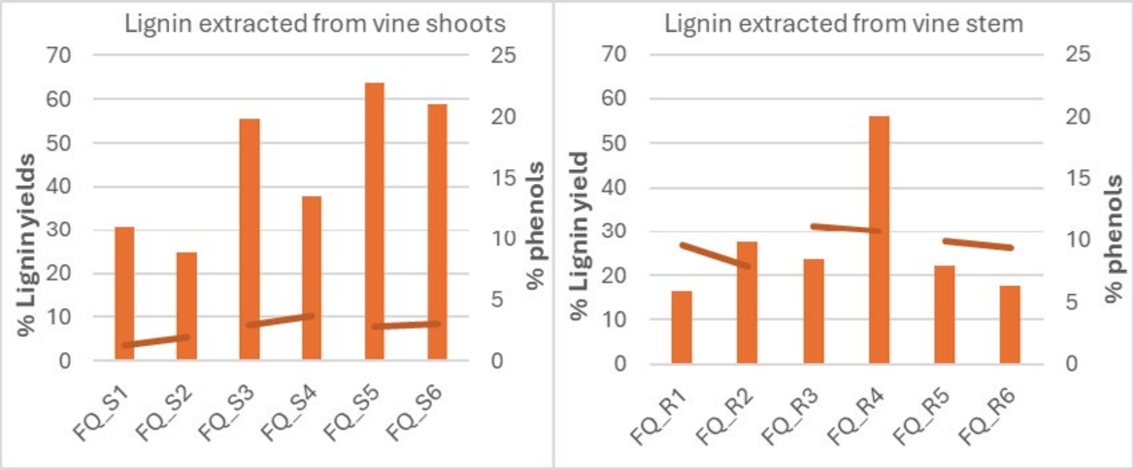
RESULTS

According to a structural analysis of lignocellulose-containing grapevine waste, vine stems have a higher lignin content than vine shoots (Table 1).

Lignocellulosic waste	% Cellulose	% Hemicellulose	% Lignin	% Ashes
Vine shoot	32,32	22,11	30,32	6,74
Vine stems	22,82	15,07	42,53	1,89

In the physicochemical pathway for lignin obtention, vine stems demonstrated a higher extraction yield and a better quality in lignin polyphenol content than lignin from vine shoots, reaching up to 19%. These results were obtained under conditions of 0.5 N NaOH and microwave treatment. Figure 7 graphically shows the results of the tests, expressed in terms of quantity (% lignin yield) and quality (% phenols) of the lignin. Higher concentrations of NaOH increased the lignin yield. Applying ultrasonic (US) treatment only slightly improved the phenolic content of lignin in vine shoots but had the opposite effect in vine stems.

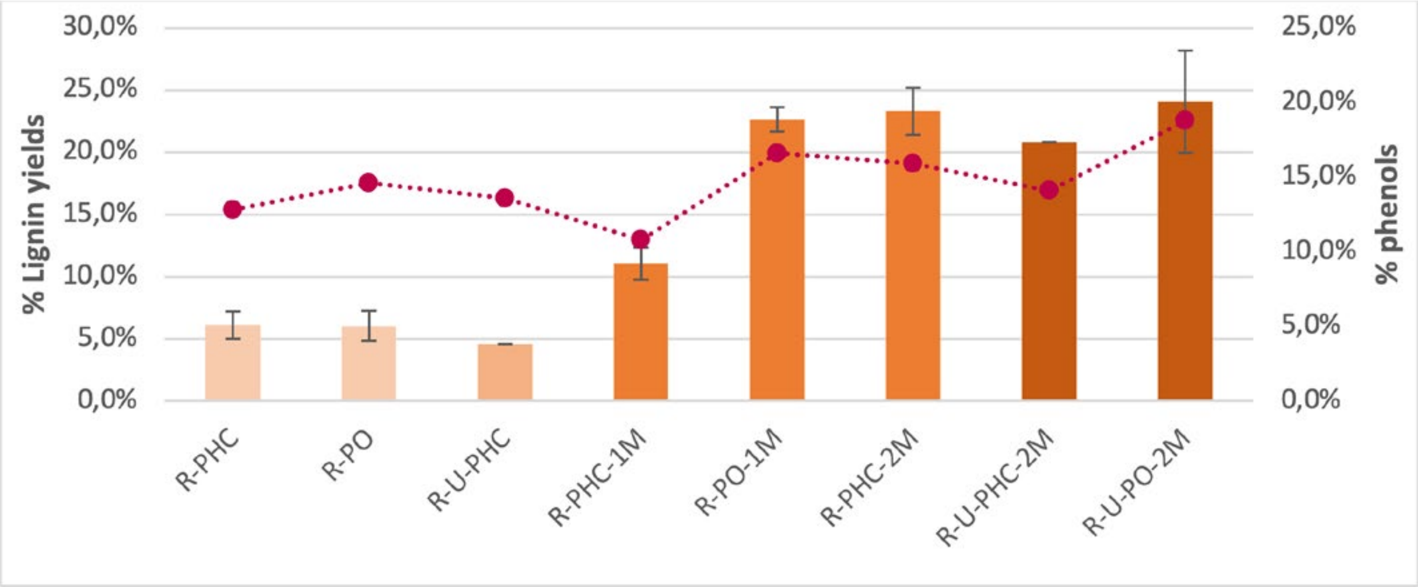
Figure 7. Results of extracted lignin yield in concentration relative to lignin in biomass (%, bars) and phenols relative to lignin weight (%, lines) for physico-chemical pathway.



The numbers indicate increasing concentrations of NaOH (0.8M, 1M, 2M for vine shoots, S, and 0.1M, 0.5M, 1M for vine stems, R), with the samples paired so that the odd number indicates alkaline treatment + microwaves and the even number alkaline treatment + microwaves + ultrasound.

On the other hand, for the biological treatment in vine waste delignification, the fungal strains *Phanerochaete chrysosporium* (PHC) and *Pleurotus ostreatus* (PO) were selected. The optimal conditions for lignin extraction were lignocellulosic biomass incubated for 12 days at 28ºC supplemented with saline solution in a 1:2 ratio (biomass: medium) for vine stem. The most efficient combined treatments for vine stem fractionation were alkaline treatment for PO strain (22.7% lignin yield and 16.6% phenols) and PHC fungus (lignin yield of 24.1%, phenols of 15.9%).

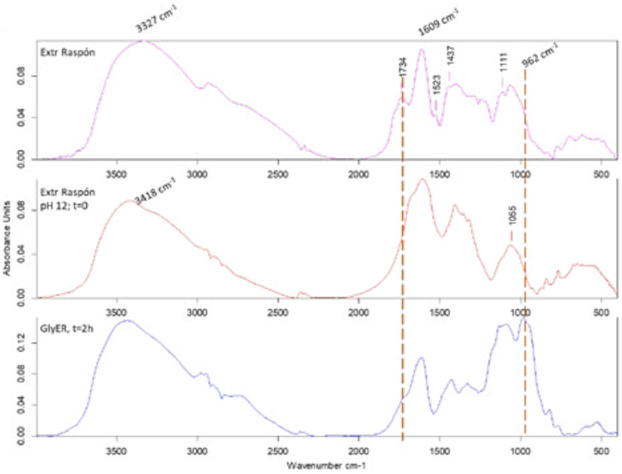
Figure 8. Results of extracted lignin yield in concentration relative to lignin in biomass (%, bars) and phenols relative to lignin weight (%, lines) for vine stem (R) through the biological pathway.



The references show the waste (R), fungal strain (PHC or PO) and auxiliary treatments (U for ultrasounds, 1M for NaOH 1M and 2M for NaOH 2M).

The phenolic content of the lignin extracted from the stems using biological treatments exceeds the values obtained in physical-chemical fractionation (14.15% and 19.07% maximum). It comes very close to the phenol concentration in commercial lignin (24.6%).

Figure 9. FTIR absorption spectra during the study of glyoxylation: unmodified vine stem lignin (pink), vine stem + glyoxal + alkaline catalyzer at time 0 of reaction (red), and vine stem + glyoxal after 2 hours of reaction.



Evidence of lignin modification was obtained from FTIR analysis, where new bands and changes in the intensity ratio between the 1515 cm^{-1} and 1215 cm^{-1} bands were observed. One of the most significant changes was the increased intensity in the 1212 cm^{-1} band, which corresponds to C-C, C-O and C=O bonds of the glyoxal introduced into the molecule, thereby confirming the reaction between lignin and glyoxal. From the adhesive derived from alkali-catalyzed glyoxylation of lignin, fiberboards were produced by agglomerating the delignified stem and vine fibers.

Research into developing fiberboard from plant waste has identified a minimum moisture content of 9% for good adhesive-fiber homogenization. Below this, the fiber absorbs the adhesive, causing a negative effect on its cohesive strength. For this reason, artichoke fibers, rice husks and vine shoots were selected (Table 2).

Table 2. Humidity content of vegetal waste fiber destined for fibreboards

Waste	Humidity content (%)
Artichoke fibers	10,58 ± 1,0
Rice husk	16,66 ± 2,4
Vine shoot	11,8 ± 0,9

Figure 10 shows samples of each type of fibreboard obtained using the process described in the methodology section.

Figure 10. Experimental fiberboards developed from (left to right) fir (control), artichoke, vine shoot and rice husk fibers.

The results of the characterization tests were satisfactory, with the boards meeting all the requirements of the relevant specifications and regulations, except for rice husk fiberboards. Vine shoot and artichoke fiberboards were classified as P2 boards for interior applications (including furniture) used in dry environments. It is worth noting that the fiber that behaved most like fir fiber (reference board) was vine shoots, which showed better internal cohesion than the others. The table shows the results of the characterization tests for each type of board.

Table 3. Results in characterization tests for reference and experimental fiberboards (data for rice husk fiberboards is not shown)

Test	Reference fiberboard (fir)	Artichoke fiberboard	Vine shoot fibreboard
Density	561 ± 15	555 ± 14	560 ± 20
% humidity	5 ± 1	5 ± 1	5 ± 1
Swelling	26,3 ± 4	-	33,1 ± 0,3
Internal cohesion	1,4 ± 0,5	0,6 ± 0,1	1,1 ± 0,4

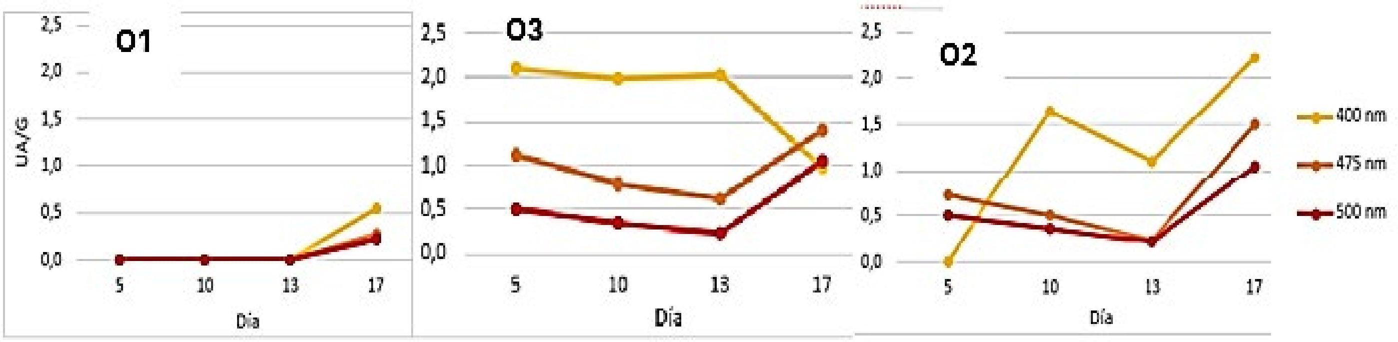
Regarding the characterization of orange peel waste for biopigments production, Table 4 shows the results. O1 presented the lowest humidity and total sugar content, while the nitrogen content was the highest. The pH values are similar in the three types of waste.

Table 4. Orange peel waste characterization results

	O1	O2	O3
Humidity content (%)	6.1	12.1	9.1
pH	3.48	3.72	3.72
Total nitrogen (%)	1.15	0.62	0.62
Total sugars (g/100g)	22.5	47.7	52.7
Fructose (g/100g)	11.1	23.4	25
Glucose (g/100g)	7.4	22.1	24.1
Sucrose (g/100g)	4	2.2	3.6

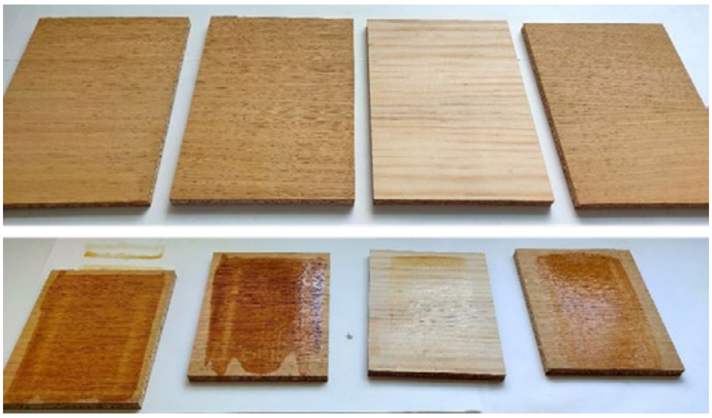
When comparing the performance of the different color pigments, it was observed that O2 and O3 yielded better results than O1 (Figure 8). This outcome aligns with the sugar content determined in the waste characterization.

Figure 11. Results of pigment yield expressed in absorbance units (UA) per gram of residue over the days of the incubation period with the fungus.



After evaporation and concentration of the pigment solution, the result is a highly viscous product of dark ochre color. Adding 0.5% of this product to the resin formulation imparts an orange-beige tone to the wood coating.

Figure 12. Samples of wood panels before and after pigmented coating.



CONCLUSIONS

Lignin extracted through physicochemical and biological methods exhibits a high phenolic content that is suitable for adhesives. In the first one, vine stems showed superior extraction yield and higher quality lignin than

Table content

vine shoots. Biological delignification using two fungal strains proved effective, achieving notable phenolic content in vine stem lignin. These findings facilitated the production of fiberboards using adhesive derived from alkali-catalyzed glyoxylation of lignin and delignified vine fibers.

After studying the potential of producing fiberboards from waste fibers derived from plant food processing, it is evident that fiberboards can be manufactured using a water-based adhesive without significant differences in their main properties compared to commercial counterparts. Although some characteristics have had lower values, further research will focus on optimization to enhance these properties.

Monascus purpureus is the most suitable fungus for producing biopigments from agro-industrial orange waste, which can be incorporated into wood finishes. Future research will explore concentrated pigment powders for varnishes, paints, and textile dyeing.

In conclusion, the findings demonstrate that two seemingly disparate sectors, the agro-industrial and furniture industries, have numerous synergies. These synergies pave the way for research aimed at facilitating the establishment of Industrial Symbiosis.

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Portuguese footwear cluster - industrial symbiosis, innovative green materials, processes and products

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ABSTRACT

Fashion businesses, including footwear, need to decarbonize and help minimize the depletion of the planet's resources and greenhouse gas emissions. Realizing this transition is fundamental and will not happen spontaneously. It requires planning and collaborative efforts involving private and public sectors across value chains. While some businesses have immediate opportunities, namely e-commerce platforms, others will benefit from research and innovation, such as Industrial Symbiosis, biological and biobased materials, man-made material-to-material recycling, and circular processes.

Firm steps are being accomplished within BioShoes4All, a Portugal PRR, Next Generation EU cofounded project aiming to support the transition of the footwear and allied trade sectors to a circular and sustainable bioeconomy. It is promoted by 50 companies covering the whole footwear value chain. It includes leather, soles, chemicals, software, production equipment, leather goods and footwear, representation and leadership, plus 20 R&D bodies with complementary capabilities coordinated by CTCP.

The project promotes industrial symmetry between footwear value chain companies and agri-food, agro-industrial, forest biomass, and pre- and post-consumer waste businesses.

The global approach pursued in the project will be shared, along with examples of the new and "next generation" of materials and processes resulting from Industrial Symbiosis, including:

- Leathers valorizing hides from the meat industry and tanned with pine tree bark.
- Coated textiles embed bio polyurethanes and chestnut shells or olive stones with over 70% biogenic carbon globally.
- Soling materials incorporating up to 80% bio content, namely bio rubber, rise, and mussel shell.
- Polymeric materials for soles or whole shoes incorporate over 50% pre- and post-consumer waste.
- New concepts of functional, durable, or circular footwear.

A critical step towards sustainability in footwear is doing a materials and product life cycle assessment (LCA). Results and strategies to reduce the carbon footprint by applying LCA and Industrial Symbiosis approaches will be presented.

KEYWORDS
Bioeconomy; Footwear; Industrial Symbiosis; Leather; Polymers

INTRODUCTION

Fashion businesses, including footwear, need to decarbonize and help minimize the depletion of the planet's resources and greenhouse gas emissions. Realizing this transition is fundamental and will not happen spontaneously. It requires planning and collaborative efforts involving private and public sectors across value chains. While there are immediate opportunities for some businesses, footwear and allied trade value chain need and benefit from research, innovation and industrial symbiosis to deploy the next generation of biological and biobased materials, men-made material-to-material recycling, bio footwear and leather goods and circular processes.

Firm steps are being accomplished within BioShoes4All, a Portugal PRR, Recovery and Resilience Plan, and Next Generation EU cofounded an integrated Project to support the transition of the footwear and allied trade sectors to a more circular and sustainable bioeconomy. The project comprises 50 companies covering the whole footwear value chain, including leather, soles, chemicals, software, production equipment, leather goods and footwear production and retail, representation and leadership, plus 20 R&D bodies with complementary capabilities. It is coordinated by CTCP and is divided into five parts: Biomaterials, Ecological Footwear, Circular Economy, Advanced Production Technologies, Capacitation and Promotion (Figure 1).

BioShoes4All supports footwear and allied trade sectors to embrace circularity, bioeconomy and digital transition. It promotes industrial symbiosis (IS) between the footwear value chain and agri-food, agro-industrial, and forest biomass industries.

Figure 1. BioSoes4All main I&I areas

DEVELOPMENT: STARTING OBJECTIVES, METHODOLOGY, DATA OBTAINED AND MAIN RESULTS

New leathers tanned with pine tree bark extracts and EcoLightLeathers

Leather production valorizes animal hides, a subproduct of the meat industry, and enables the creation of durable, comfortable, high-added-value footwear. It has high resistance to repeated flexion, tearing and abrasion, resistance to water penetration, good sweat absorption and desorption, and even resistance to heat and fire. From a sustainability point of view, it deserves to be highlighted that leather is durable, repairable and "ages" well.

Hides are biological per se but must be chemically stabilized (covalent or other chemical bonds) to be used in footwear. The stabilization process involves several steps; the tanning phase is the most important. Tanning is done mainly using metals, especially chromium, fossil derivatives, namely glutaraldehyde, and, to a lesser extent, vegetable tannins, which, in many cases, are imported to Europe.

BioShoes4All is defined as a target to develop and deploy up to 100% biological leathers tanned using local forest wastes or subproducts adding economical value to these sectors while contributing to preventing forest fires. IS protocols were established with agroforest raw material suppliers and BioShoes4All chemicals, leather and research partners. The project partners develop processes to extract tannings, produce modified tanning agents, and tan hides to obtain, namely Pinus pinaster pine tree bark tanned leather (Figure 2). These vegetable-tanned leathers may be used in footwear and leather goods and present tear resistance and retraction temperature values of over 100 N and 70° C, respectively.

Figure 2. Leather tanned with pine tree bark extracts (example)

Vegetable extracts of tanned leather tend to have higher density. For applications where lightness is appreciated, project partner Dias Ruivo developed EcoLightLeather. EcoLightLeather is a soft, lightweight, metal-free material with a contraction temperature of around 80°C and good physical properties that can be used in footwear (Table 1). Leathers using this method can take different finishes, such as aniline and colors and be in various thicknesses, and they are being presented at international events and fairs.

Table 1. EcoLightLeather physical properties

Parameter	Specification	Results
Thickness (mm) Contraction temperature (°C)	- > 70	1.8 80
Surface charge resistance (N)	> 350	436
Tear strength (N)	> 100	182
Apparent volumetric mass (kg/m3)	-	651

Bio-based coated textiles

The sustainability of materials has achieved unprecedented importance, particularly in the search for biobased approaches that favor raw materials of biological origin and thus offer alternatives with a lower carbon footprint. However, many coated textile products are still made from raw materials of fossil origin. It is now possible to synthesize polyurethanes partly from raw materials of plant origin, such as vegetable oils modified into polyols, which are then polymerized with reagents of fossil origin known as BioTPU. These can, therefore, be considered a more sustainable alternative to fossil-based polymer coatings.

A complementary approach to increasing the proportion of bio-based content is incorporating biocharges and fibers into the coating and reducing the fossil-based content.

Portugal is one of the largest producers of olive oil, and the olive stone represents an abundant biomass estimated to be 60,000 tons per year. It is currently not used for anything other than burning to create energy. This has contributed to its being chosen by Monteiro Fabrics as bio-waste to be incorporated into bio-coating formulations. The ORIGIN material produced within the BioShoes4All project results from developing a BioTPU and water-based formulation containing olive stones applied to a cotton fiber textile base. Some relevant physical and mechanical characteristics are shown in Table 2 and fulfill the specifications for shoe uppers. It also has a proven 72% bio-based carbon content following ASTM D6866-22 Method B.

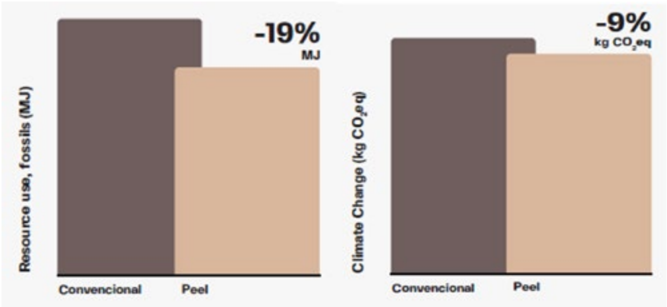
Table 2. ORIGIN olive composite physic-mechanical properties

Parameter	Specifications fashion shoes	Results
Tensile Strength (N/mm)	T> 10	11.3
	TR> 5	6.6
Elongation at break (%)	T> 50	62.7
	TR> 100	115.6
Tear strength (N)	T> 25	29.4
	TR> 20	26.2
Adhesion to the coating (N/5cm)	T> 1	1.19
	TR> 1	1.32

T- Warp; TR- Weft

Chestnuts are traditionally used for human and animal consumption, given their nutritional properties, and Portugal is, again, a significant producer. Processing generates various byproducts, such as shells, flowers, leaves and wood. Monteiro Ribas, together with local partners, collects these biomaterials. They are crushed and ground into a fine powder, then turned into an innovative product. Faced with the challenge of developing planet-friendly solutions, the company has created its PEEL collection incorporating 60% plant-based materials, including chestnut waste, organic cotton and natural oils, and 40% PVC. Making these solutions available attractively and efficiently reinforces its commitment to best environmental practices. The material is offered in eight colors, allowing customers to create innovative products without choosing between cost, performance, aesthetics or sustainability. It is a technologically viable product, ready to be produced on a large scale without compromising performance. Technical requirements for use in cemented footwear are all met, including high Bally flex resistance (150000 cycles), Martindale abrasion (400000 cycles), and resistance to friction (Crockmeter), among others. Peel's 65% bio-based carbon content has been verified following ASTM D6866-22 Method B. Additionally, the material Life Cycle Assessment (LCA) made by CTCP based on the EU footwear draft Product Environmental Footprint (PEF) methodology indicates a reduction of 19% in fossil resources used and a reduction of 9% of its carbon footprint (Figure 3).

Figure 3. PEEL fossils resources and carbon footprint reduction (LCA from raw material extraction to PEEL production)



Bio soles

Nowadays, consumers' desire for appellative and bio-based footwear has motivated BioShoes4All industrial partners to rethink the production value chain and processes and establish partnerships to deliver innovative performing components and products.

BioShoes4All partners Atlanta, Aloft and Procalçado and research teams, including CTCP, are developing materials for use in flexible and durable soles. New formulations, processes and advanced additives have been studied to create high-quality bio rubbers embedding certified natural rubber (Hevea brasiliensis) and additives derived from waste rise or mussel shells, with biobased content of around 80%. Test results confirm the optimized materials and soles meet the specifications required by fashion and more demanding casual footwear, including high Benewart flex resistance (150000 cycles) and abrasion according to ISO 20871 (< 250 mm3).

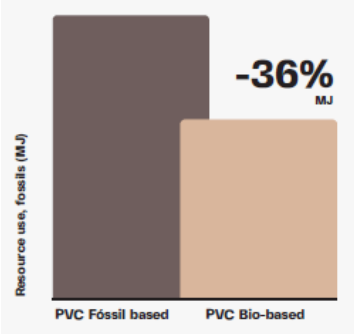
Project partners are also developing thermoplastic materials with high biobased content that can be processed to produce flexible and recyclable soles and complete footwear by injection molding. One example is Coblex bioPVC, claiming up to 97% biobased content and the same level of performance as conventional materials in hardness, density, flexion, and abrasion resistances (Table 3).

Table 3. BioPVC physical properties

Parameter	Specification	Results
Hardness (ISO 868, Shore (A))	60 - 65	63 - 64
Density (ISO 2781-met A, g/cm3)	1.18 - 1.22	1.19-1.2
Abrasion resistance (ISO 20871, mm3)	<250	106 - 115
Ross flex resistance (BS5131-Part 2.1, mm)	<0.4	0.0

Additionally, the material LCA made by CTCP indicates a reduction of 36% in fossil resources used (Figure 4, LCA from raw material extraction to BioPVC pellets).

Figure 4. BioPVC fossil resources reduction



RESULTS AND MAIN CONCLUSIONS

IS protocols and works were established to (1) obtain forest and agro-industrial byproducts, including pine bark, cereals, chestnuts, olives, and fruit parts that cannot be used in human or animal food; (2) pre-treat and prepare the biomaterials; (3) produce or obtain biochemicals and additives; and (4) develop innovative bio leathers, coated textiles and soles and their respective making process.

BioShoes4All partners are using these materials and components by developing concepts of footwear based on eco-design approaches to reduce product footprints based on the EU draft footwear PEF methodology.

The PEF method assesses 16 impact categories (Table 4), covering climate change, acid rain, human toxicity, particulate matter, and impacts due to water, land, and resources. Table 5 shows the characterized, normalized, and weighted results obtained.

Table 4. Footwear environmental footprint impact categories assessed

EF Impact Category	Impact category Indicator	Unit
Climate change, total + fossil + biogenic + land use and land use change	Radiative forcing as global warming potential (GWP100)	kg CO2-eq
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11-eq
Human toxicity, cancer	Comparative Toxic Units for Humans (CTUh)	CTUh
Human toxicity, non-cancer	Comparative Toxic Units for Humans (CTUh)	CTUh
Particulate matter	Impact on human health	disease incidence
Ionizing radiation, human health	Human exposure efficiency relative to U235	kBq U235-eq
Photochemical ozone formation, human health	Tropospheric ozone concentration increase	kg NMVOC-eq
Acidification	Accumulated Exceedance (AE)	mol H+-eq
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N -eq
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P-eq
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N-eq
Ecotoxicity, freshwater	Comparative Toxic Unit for Ecosystems (CTUe)	CTUe
Land use	Soil quality index and others	Dimensionless (pt)
Water use	User deprivation potential (deprivation-weighted water consumption)	m3 world eq
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq
Resource use, fossils	Abiotic resource depletion – fossil fuels, ADP	MJ

Table 5. PEF example of results: characterized, normalized and weighted results

Impact category	Characterised results		Normalized	Weighted
	Reference unit	Total impacts	Total impacts (Person-years)	Total impacts (Points)
Acidification	mol H+ eq	4,46E-02	8,02E-04	4,97E-05
Climate change	kg CO2 eq	8,7	1,07E-03	2,26E-04
Ecotoxicity, freshwater	CTUe	1,60E+02	3,74E-03	7,19E-05
Eutrophication, freshwater	kg P eq	3,54E-03	2,20E-03	6,17E-05
Eutrophication, marine	kg N eq	9,57E-03	4,90E-04	1,45E-05
Eutrophication, terrestrial	mol N eq	7,98E-02	4,51E-04	1,67E-05
Human toxicity, cancer	CTUh	3,85E-09	2,28E-04	4,86E-06
Human toxicity, non-cancer	CTUh	1,12E-07	4,87E-04	8,96E-06
Ionizing radiation	kBq U-235 eq	6,42E-01	1,52E-04	7,62E-06
Land use	Pt	7,81E+01	9,53E-05	7,56E-06
Ozone depletion	kg CFC11 eq	4,59E-06	8,56E-05	5,40E-06
Particulate matter	disease inc.	4,04E-07	6,79E-04	6,08E-05
Photochemical ozone formation	kg NMVOC eq	2,89E-02	7,11E-04	3,40E-05
Resource use, fossils	MJ	1,24E+02	1,90E-03	1,58E-04
Resource use, minerals and metals	kg Sb eq	1,28E-04	2,01E-03	1,52E-04
Water use	m3 depriv.	8,20E+00	7,15E-04	6,08E-05
Total (single score)	n/a	n/a	n/a	9,41E-04

Table 6 details the results for 3 of the seven most relevant impact categories. These three categories, “Climate change,”; “Fossil resources use,”; and “Minerals/metals resources use”, represent about 57% of the total impact.

Table 6. Footwear’s most relevant impact categories, stages and process (example)

Impact category	% Contribution	Life cycle stage	% Contribution	Material/component / process	% Contribution
Climate change	24,0%	Raw materials in the final product	55,5%	Outsole	22,3%
				Insole	8,0%
				Interlayer	7,8%
				Insock	6,9%
				Upper	3,5%
		Raw materials that go to waste	3,0%	Interlayer	1,4%
		Waste	19,8%	Urban waste	15,7%
		End of Life	7,3%	Transport passenger car	3,8%
				Municipal solid waste	3,2%

Resource use, fossils	16,8%	Raw materials in the final product	68,0%	Outsole	35,1%
				Insole	9,9%
				Insock	7,5%
				Interlayer	5,6%
		Waste	15,4%	Urban waste	12,0%
		Raw materials that go to waste	2,8%	Interlayer	1,3%
Resource use, minerals and metals	16,1%	Waste	90,9%	Urban waste	84,0%

Table 6 also details the environmental impact associated with the product's "Life cycle stage" and "Materials, components and/or processes", indicating changes to reduce the product's PEF/environmental impact. Among these, "Climate Change" is one of the most relevant impact categories, and it was chosen to present and discuss the ecological impact of the shoe models. Figure 5 presents the results of the Climate Change impact category, Global Warming Potential indicator (GWP100), in kg CO2 eq, calculated for, for example, each pair of footwear before and after redesign (sustainable). Within this study, it was possible to reduce the selected model's carbon footprint (kg CO2 eq) by up to 36%, considering the more sustainable version.

Figure 5. BioPVC fossil resources reduction

ACKNOWLEDGEMENTS

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Table content

Textile and wood industries symbiosis

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ABSTRACT

One of the biggest challenges for textiles is the increasing amount of waste from textile production and second-hand textiles, much of which ends up in landfills or is incinerated, polluting soil and water and emitting greenhouse gases. Recently, attempts have been made to find appropriate technical measures for environmental protection and sustainable recycling. The study focuses on new ways of using textile waste in the wood industry, specifically incorporating textile waste into particleboard. Manufacturing is the industrial sector with the most significant potential for symbiotic relationships. Directly reusing waste as raw materials between companies is an Industrial Symbiosis. Reusing one company's waste as a raw material by another company supports sustainable development and provides social and economic benefits. As a result of this Industrial Symbiosis, the paper proposes an idea and a technological pathway for converting textile waste into raw material in the particle board industry. This could be an innovative idea for applying the Circular Economy principles.

KEYWORDS
Wood Industry; Textile Waste; Circular Economy

INTRODUCTION

The textile industry has contributed significantly to the economic development of many countries. Global textile production has recently increased due to population growth and higher living standards. The Circular Economy is significant in the European Commission (N/A-1) textile industry. The EU produces 12.6 million tons of textile waste every year. Specifically, clothing and footwear account for 5.2 million tons of this waste, equivalent to 12 kilograms per person. The introduction and enforcement of appropriate regulations could significantly improve recycling in the textile sector. Only 22% of textile waste is collected separately for reuse or recycling after consumption, but unfortunately, most of the remaining waste is incinerated or thrown away European Commission, N/A-1; Ortega & Mouazan, 2018).

A staggering 10 million tons of unused furniture from the European Union is in landfills yearly (Ortega & Mouazan, 2018). 80-90% is incinerated there, and the remaining 10-20% is recycled. However, the high hazardous waste of textile-related industries is a significant concern. Improper management and irregular disposal of textile waste pollute the environment (water, air and landfill) and directly impact human health (Shirvanimoghaddam et al., 2020). Recently, environmental sustainability has been nominated as one of the most critical factors for the modernization of modern industrialization. The European Green Deal Action Plan targets reducing the energy sector's dependence on fossil fuels, currently more than 75%. Textile waste refers to discarded or recycled clothing and textile products. Textile waste is a major environmental problem, occupying much landfill space and causing pollution and greenhouse gas emissions (European Commission, N/A-2). Textile waste can be reduced by reusing or recycling materials and fibers into new products or using them as raw materials in other industries (Shirvanimoghaddam et al., 2020). There is a need for greater exchange of materials between different industries and sectors. Potential industrial partnerships could arise between the forest industry, agriculture and food, engineering, construction and automotive sectors. EU CO2 emissions come from the production and use of energy, while European industry uses only 12% recycled materials (European Commission, N/A-3). It is very popular in various sustainability concepts and activities and has an essential place in recycling. Recycling is processing waste and its use as a raw material in new or reused products (European Commission, N/A-4).

In Europe, timber production accounts for 25% of total industrial output, and wood-based panel production accounts for 9% of total wood production. Wood has been gaining increasing attention in the construction industry for several years (Ortega & Mouazan, 2018). Concerns about sustainability and the carbon footprint of buildings have led to the rapid development of new construction methods and innovative use of wood. Wood is cut in recycling, and the product is wood panels. Recycling non-hazardous solid textile waste may be an alternative for wood and furniture industries (Maier, 2021).

Incorporating textile waste into new production processes can help to ensure sustainable waste management and increase the value of new goods. In other words, waste management can be addressed by recycling and reusing textile residues in industry (European Commission, N/A-4). In addition to producing new textiles, various textile wastes can be used for other purposes, such as composites for multiple applications and particle boards for furniture (Patricio et al., 2022). The research aims to develop the optimal composition structure, forming wood boards of wood and textile waste, which are characterized by new functional characteristics. Particle boards made from renewable resources such as wood and textile waste play an essential role in the sustainable development of society (Circle Economy Foundation, N/A).

METHODOLOGY

Wood panel board is made from compressed wood particles, including wood residues, logging and textile recycling waste. It is an inexpensive and tightly bonded general-purpose panel used for various applications, including furniture, cabinets, flooring and construction. For wood-based products such as particleboard for interior applications, virtually only UF adhesives are used due to their cheap raw materials, fast curing, muscular dry adhesion and colorless glue line (Merli, Bolloni & Buratti, 2021).

Shredded textile waste produced the wood-based panels AsWood 7502 hardener and AsWood 7000 resin. For the experiment, different combinations of particleboard panels with different textile waste ratios were created and tested for their mechanical properties (Figure 1).

Figure 1. Wood waste and textile mix fiber waste.

RESULTS

The global situation is worsening yearly, driven by the increasing extraction and use of materials. Statistics from the “Circle Economy Foundation” show that more than 90% of materials are wasted, lost or locked up in long-term inventories such as buildings and machinery (Ortega & Mouazan, 2018). This gap is. Therefore, it is a significant challenge as our planet mainly depends on new materials, leading to environmental degradation and resource depletion (Schuber, Panzarasa & Burgert, 2023). The Circular Economy is an alternative to our current linear economy based on growth and the principle of take-make-waste (Ortega & Mouazan, 2018). Every industry, including the timber industry, uses vast resources to produce products, which we consume and discard. This system consumes limited raw materials and generates huge waste (Araújo et al., 2019).

By 2050, we will consume as many resources as the three planets on Earth. To avoid this, attempts are being made to find alternative raw materials, such as waste textiles, by reusing them and incorporating them as an ingredient in particleboard (European Commission, N/A-2; European Commission, N/A-3).

Wood panels were produced using textile waste and developed using the Joos-Laboratory-Press LAP 40 (Gottfried Joos Maschinenfabrik GmbH & Co., Germany). The press has a maximum temperature of 250 °C and a pressing surface of 500 x 500 mm. The press can apply a force of up to 400 kN.

Two different groups of samples were produced to produce particleboards. The composition of the particleboards produced is given in Table 1.

Table 1. Wood panel board composition

Wood panels group	Composition
Panel 80/20	80 % wood sawdust, 20 % textile waste
Panel 80/10	90 % wood sawdust, 10 % textile waste

Two different groups of samples (Figure 2) were produced during the production of the wood panel boards and were subjected to moisture determination.

Figure 2. Wood panel boards with textile and wood waste

The screening, crushing, sorting, mixing and molding of the primary raw materials was carried out with a change in the material content ratio. Producing such panels is an excellent way to introduce and maintain the principles of the Circular Economy, bringing already-used materials into the industry (Schuber, Panzarasa & Bzrgert, 2023).

In addition to reducing the amount of waste, using textile waste in creating wood panel boards produces a material that does not differ in appearance from traditional wood panel boards (Araújo et al., 2019).

Companies increasingly recognize the dual benefits of Industrial Symbiosis - the synthesis of environmental protection and economic opportunities. Innovations in materials, production processes and business models, such as using textile waste in the wood industry, are paving the way (Papamichael et al., 2023).

CONCLUSIONS

Using textile waste to produce wood panel boards is a potential strategy for creating environmentally friendly and sustainable materials. Recycling wood and textile waste positively impacts the environment by reducing resource consumption in particleboard production. Recycling wood and textile waste positively impacts the environment by reducing resource consumption in particleboard production. Waste and residues from the production process are converted into raw materials for reuse in the Circular Economy, thus reducing waste and the need for new raw materials. This technology, which uses waste wood and textiles, will create a technological and business environment, allowing recycled wood and textiles to be incorporated into a wider product portfolio.

Future research:

- Comparative studies of the mechanical properties of manufactured chipboards.
- Comparative studies on the structure and physical-mechanical properties of wood panel boards with textile waste, depending on the additive content, particle size, mixing with binders and molding technology used.
- Recyclability of particleboards with textile waste and their natural degradation period and natural conditions.

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▲ Table content

The significance of livestock wastes in the context of industrial symbiosis and the reuse of these wastes

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ABSTRACT

Industrial Symbiosis is a concept that enables the integration of waste and by-products between different industries. This approach ensures more efficient use of resources by utilizing or reusing waste generated in one sector in another sector. The Industrial Symbiosis of livestock waste enables cooperation between various industries, promoting the utilization and reuse of these wastes.

Nowadays, issues such as environmental sustainability and resource efficiency, inter-industry cooperation and reuse of resources are becoming increasingly important. In this context, ensuring Industrial Symbiosis of livestock waste and reusing it in animal nutrition has become a significant environmental and economic issue.

Livestock waste generally consists of various sources such as animal manure, animal residues and animal by-products, which are rich in organic matter and nutrients. Correctly managing these wastes is critical for reducing environmental pollution, efficiently using resources, and providing economic benefits. Among these wastes, especially blood and bone meal, are rich sources of protein and minerals essential for animal nutrition. A blood meal is a waste of animal origin rich in protein. In meat processing plants, the blood obtained after slaughtering animals is processed, dried and ground into powder. The blood meal obtained in this way is an important protein source for animal feed. It contains amino acids necessary for young animals' growth and development, as well as some components supporting their immune system and improving digestive health. Bone meal is obtained from the bones of animals in meat processing plants. It supports animals' skeletal health and can enhance eggshell quality. First, using these wastes meets animals' nutritional needs by increasing animal feed's protein and mineral content.

As a result, Industrial Symbiosis of animal waste is an essential strategy for environmental sustainability and resource efficiency. This approach lays the foundation for a more sustainable future by increasing cooperation between industries and encouraging the evaluation and reuse of waste. In this way, a comprehensive win-win situation can be created that benefits both the environment and the economy.

KEYWORDS
Livestock Wastes; Industrial Symbiosis; Waste Reuse; Sustainable Agriculture;
Waste Management; Environmental Sustainability

INTRODUCTION

Industrial Symbiosis is a concept that enables the integration of waste and by-products between different industries. This approach allows for more efficient use of resources through the utilization or reuse of wastes generated in one industry in another. Industrial Symbiosis of livestock wastes encourages the utilization and reuse of these wastes by providing cooperation between various industries (Arvanitoyannis & Ladas, 2008; Delgado et al., 1999; Leinonen et al., 2013; Merriam-Webster, N/A; Kellems & Church, 2010; Ayachit, 2015).

Nowadays, issues such as environmental sustainability and resource efficiency, cooperation between industries and resource reuse are becoming increasingly important (Gerber et al., 2011; Meeker & Hamilton, 2006; Mirabella, Castelani & Sala, 2014; FAO, 2006; Kellems & Church, 2010). In this context, the Industrial Symbiosis of livestock wastes and their reuse in animal nutrition has become a significant environmental and economic issue (Steinfeld et al., 2006; EPA, 2004).

Livestock wastes consist of various sources such as animal manure, animal wastes and animal by-products, which are generally rich in organic matter and nutrients (Delgado et al., 1999; Ockerman & Hansen, 2001; Steinfeld et al., 2006; Pandey et al., 2000). Proper management of these wastes is critical to reducing environmental pollution, utilizing resources efficiently, and providing economic benefits. Among these wastes, blood and bone meals are wealthy sources of protein and minerals essential for animal nutrition. This article will provide information on the use of blood and bone meals in animal nutrition and highlight the potential of these wastes. Blood meal is a protein-rich waste of animal origin (Mirabella, Castellani & Stela, 2014; FAO, 2006; Ramirez-Ramirez et al., 2020; Steinfeld et al., 2006; EPA, 2004). The blood obtained after the slaughter of animals in meat processing plants is processed, dried and pulverized. The blood meal obtained in this way is an important protein source for animal feeds. It contains amino acids, which are especially necessary for the growth and development of young animals. In addition, blood meal may include some components that support the immune system of animals and improve digestive health.

Bone meal is a rich source of calcium, phosphorus and other minerals (FAO, 2006; Ramirez-Ramirez et al., 2020). It is obtained from the bones of animals in meat processing plants. Bone meal contains minerals that are especially necessary for bone development and healthy teeth. It also supports the skeletal health of animals and can improve eggshell quality. Bone meal is often used in the diet of different animal species, such as chicken, cattle and pigs (Ockerman & Hansen, 2001; Woodgate, 2006).

Blood meal and bone meal provide several advantages when used in animal nutrition. Firstly, using these wastes fulfills animals' nutritional needs by increasing animal feed's protein and mineral content. It also helps to provide a balanced diet by diversifying the formulation of animal feeds. This results in better animal health, growth and productivity (Karayazı & Balcı, 2014).

However, there are some important considerations regarding the use of blood meal and bone meal in animal nutrition. Hygienic conditions and quality control are essential while processing these wastes. In addition, regulations and standards regarding utilizing these wastes should be complied with (Levis & Barlaz, 2011; FAO, 2006; Kellems & Church, 2010; Ramirez-Ramirez et al., 2020; Mirabella, Castellani & Sala, 2014).

In conclusion, the Industrial Symbiosis of livestock waste is essential for environmental sustainability and resource efficiency. This approach provides the basis for a more sustainable future by increasing cooperation between industries while promoting the valorization and reuse of waste. In this way, it can create a comprehensive win-win situation, benefiting the environment and the economy (Figure 1) (Chadd, Davies & Koivisto, 2002). Animal wastes can be utilized in agriculture, energy production, chemical industry, construction, automotive, textile, food and leather/footwear industries. In this way, Industrial Symbiosis can be realized by cooperation between different sectors and the reuse of wastes (Table 1) (EPA, 2004).

Table 1. Livestock Wastes in Industrial Symbiosis and Reuse

Livestock Waste Type	Industrial Symbiosis Potential	Reuse Applications
Animal Manure	• Biogas production (energy source) • Compost production (soil amendment)	• Agriculture • Energy Production
Blood Meal	• Animal feed component (protein source)	• Animal Nutrition
Bone Meal	• Animal feed component (mineral source) • Fertilizer (phosphorus source)	• Animal Nutrition • Agriculture
Animal Fats	• Biodiesel production • Soap and cosmetic products	• Energy Production • Chemical Industry
Feathers and Hair	• Plastic and composite materials • Fiber and felt production	• Construction and Automotive Industry • Textile Industry
Animal Bones	• Animal feed component (calcium source) • Gelatin production	• Animal Nutrition • Food and Pharmaceutical Industry
Animal Hides	• Leather processing industry	• Leather and Footwear Industry

Source: adapted from EPA, 2004

ADVANTAGES OF USE OF ANIMAL WASTE IN ANIMAL NUTRITION

The utilization of animal waste in animal nutrition offers a multitude of advantages. These wastes, particularly blood and bone meal, are rich sources of protein, calcium, phosphorus and other minerals, supporting animal growth, development and productivity (Ayachit, 2015; Ramirez-Ramirez et al., 2020). Furthermore, animal wastes are incorporated into feed formulations, diversifying the nutritional composition of animal feeds and creating more balanced rations (Ayachit, 2015; Salminen & Rintala, 2002). Using animal waste as feed also facilitates the evaluation of these wastes and the prevention of resource waste. Consequently, pressures on the environment can be reduced (Mirabella, Castellani & Sala, 2014). From an economic perspective, animal waste can reduce feed costs by providing alternative protein and mineral sources (Ockerman & Hansen, 2001). Furthermore, sharing and reusing animal waste among different sectors with an Industrial Symbiosis approach contributes to a more sustainable environmental and economic system (Meriam-Webster, N/A). Nevertheless, ensuring hygiene and quality control throughout animal waste processing produces safe, high-quality feed (Salminen & Rintala, 2002).

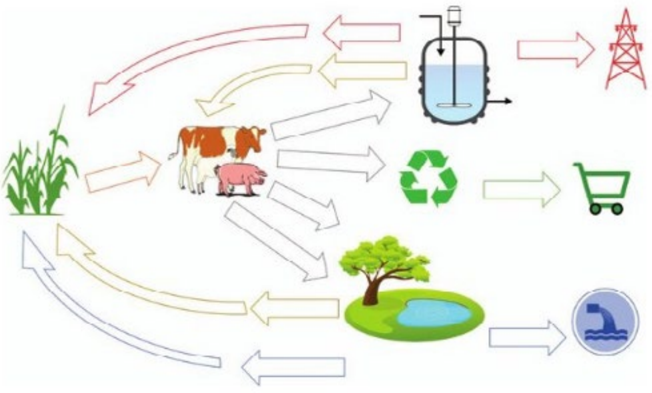
DISADVANTAGES OF USE OF ANIMAL WASTE IN ANIMAL NUTRITION

The utilization of animal waste in animal nutrition is not without its disadvantages. There is health risks associated with the consumption of this waste, as well as the risk of animals contracting diseases transmitted by it. This threatens animal and human health, mainly if adequate hygiene and quality control are not ensured during processing (Arvanitoyannis & Ladas, 2008; Pandey et al., 2000). Additionally, feeding some animal waste to animals may be legally restricted (Smith, 1998; Ramire-Ramirez et al., 2020).

The processing and storage of animal waste can give rise to environmental problems, including the generation of odorous emissions and contamination of water and soil. In the absence of appropriate processing and waste management, these can have adverse effects on the environment (Müller, 2001).

The costs associated with collecting, processing and distributing animal waste can be considerable, particularly regarding infrastructure and labor. This may result in an economic disadvantage, increasing feed costs (National Research Council, 2003; Sapkota et al., 2007).

Figure 1. Circular Economy approach to livestock industry wastes.



CONCLUSIONS

In conclusion, the Industrial Symbiosis of livestock waste presents a promising environmental sustainability and resource efficiency strategy, fostering cooperation between industries while promoting waste valorization and reuse. This approach can create a comprehensive win-win situation, benefiting the environment and the economy.

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▲ Table content

Understanding the industrial symbiosis through a waste-to-energy approach

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ABSTRACT

Valorization of waste via repurposing it into resilient raw feedstock for consumer goods, energy, or materials is an urgent need today. In addition, promoting the Circular Economy accelerates the transition to these processes and develops opportunities for establishing and flourishing new businesses. This necessitates a better understanding among the research community, stakeholders, and policymakers, a multidisciplinary approach, and a constructive dialogue at a theoretical and practical level. The latter discusses technological, financial and legislative limitations of repurposing wastes for further use and how to overcome existing constraints. We must not waste our waste anymore and enhance the wider public awareness of opportunities for raw material innovation, knowledge transfer, and entrepreneurship. Results indicate the advantages of waste minimization and their improved management, the efficiency of resources, avoidance of dependence on fossil fuels during times of uncertainty, fewer logistics implications, integration of more Renewable Energy Sources (RES) and increase of performance in the industrial sector. In that way, our waste sources can be transformed into the most valuable feedstock for industries for cheap and environmentally friendly energy, fuels or materials. In conclusion, all may be the critical link to the chain of several industries, small and medium size to considerable, to be advantaged by a realistic Industrial Symbiosis future.

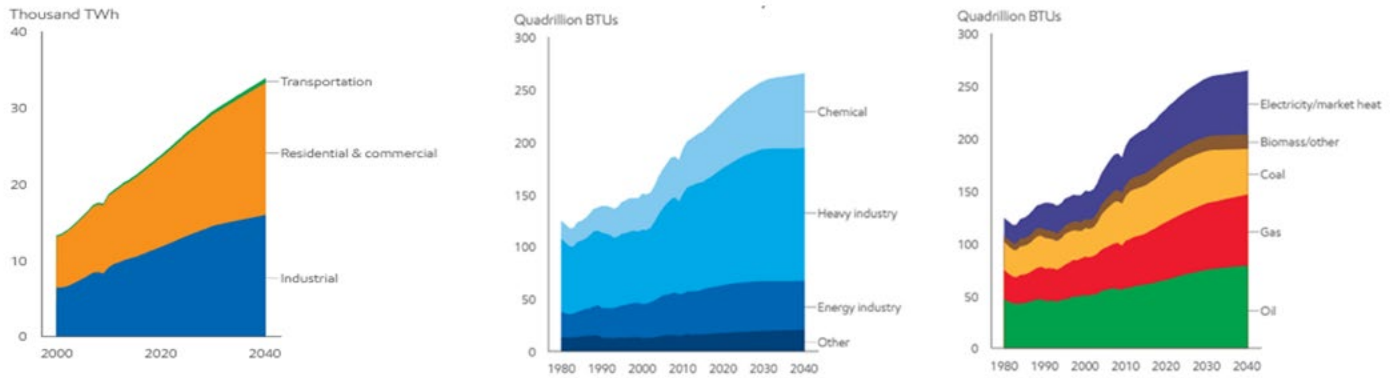
KEYWORDS
Wastes; Energy; Materials; Fuels; Chemicals; Innovative Processes

INTRODUCTION

The global energy and materials market is transitioning to more resilient and sustainable solutions to adjust to the societal demand of de-fossilizing. This is extremely important in an era of unstable economic environments imposed by unprecedented geopolitical incidents and unforeseen natural disasters due to climate change. Figure 1 showcases the global increasing energy demand (Figure 1a), indicating that too much energy is needed for the residential and commercial sectors, followed by industry and chemical production to cover the consumers' goods and energy (Figure 1b). In contrast, industry still relies on oil, gas and coal (Figure 1c).

Nowadays, the energy demand is driven by three (3) pillars: policy, consumer preferences, and technology. Shifting from traditional economies to a Circular Economy (CE) requires investing in eco-innovations, such as materials that last longer, a ban on single-use plastics, and resilient and sustainable engineering solutions. As a result, any innovative low-to-net carbon engineering solution should aim to close the loop of the materials and energy cycle. In that direction, any waste-to-materials and energy must be developed (Vaskalis et al., 2019). Transitioning to CE, though, might seem easy as a theoretical concept; however, hands-on experience indicates that it requires not only substantial changes in the mode of materials production, consumption, users' and consumers' behavior and new legislation (Jaca et al., 2012) but also an understanding of new modes of operation of all processes in terms of 'engineering' our waste upgrading technologies.

Figure 1. Future projections of global energy demands: a) per sector, b) industrial energy demands, and c) fuel demands by sector



a) b) c)

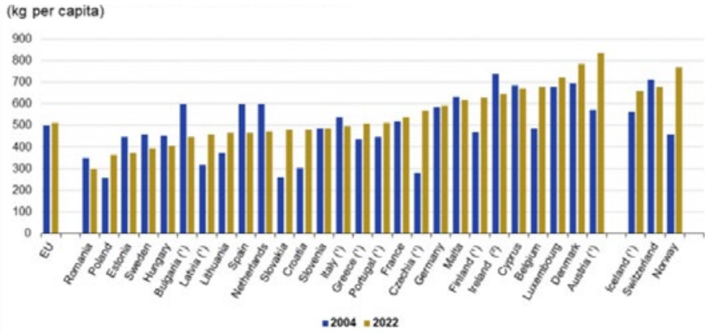
Source: Exxomobil, 2024

It is also widely known that we are a global society that generates too much waste, from biodegradable wastes such as wood waste to all types of plastics. The latest global amount of plastic production is estimated to reach 391 million tons in 2021 (Statista, 2024), while estimations indicate that it will get more than 2 billion tons in 2030. From this amount, only 9% of plastic waste is recycled (~ 35 million tons), while at least 22% is mismanaged (~ 86 million tons). Other prevailing ways of managing plastic waste are mainly sending it to landfills and incinerating it. The remaining 270 million tons/y presents a challenge due to the physicochemical characteristics of the wastes (plastics or biomass) plus logistic issues. However, there is a considerable potential to use them as alternative fuels or feedstock for new materials, establish new businesses in repurposing waste, train new engineers on adaptation to RES processes, and integrate RES processes with fossil fuel industrial practices and low carbon processes. The main reason for the missing opportunity to use all waste is not only the inability to collect from the source when it comes to residential mainly consumers but also improper disposal methods, such as depositing waste in landfills or discarding to the environment (Padmanabhan et al., 2022).

Concerning municipal solid waste generation in the European Union (EU), Figure 2 indicates that we still produce too much waste in the EU, with an average of ~513 kg/capita (Eurostat, 2022). However, it seems that, as a society, we still have much to achieve in successfully applying circularity. For example, the flow of materials in practice in 2022 in the EU was 11.3% and only up 3.3 points in 18 years (from 2004) (Eurostat, 2022). Huge amounts of fossil fuels (parent material of plastics) while biomass (fossil fuels parent material) is extracted from the environment to produce materials or energy. When products, by-products or wastes, which are not competing with food in the case of biomass, from such industries reach the end of their life, they may be combusted-incinerated, recycled, or still discarded in landfills.

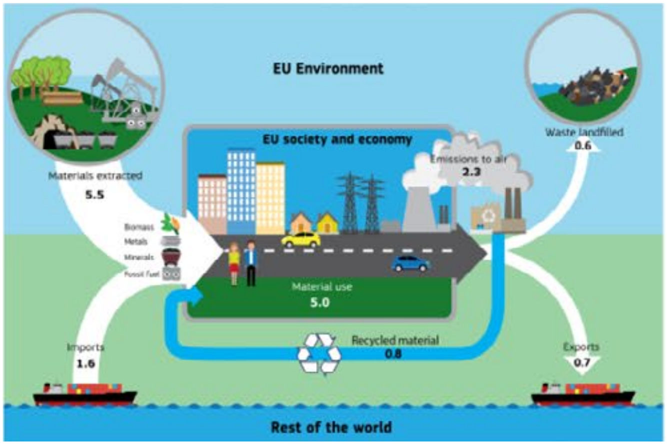
It is evident then that all these wasted materials have a great potential to be incorporated into CE concepts; however, the question from a technical point of view is whether that is always possible when we receive such wastes in their raw form. The answer is not always, not for all waste and pretreatment of them is very often needed.

Figure 2. Change of municipal solid waste (MSW) generation per capita in European Union (EU) member states during a 15-year timeslot



Source: Eurostat, 2022.

Figure 3 represents the status of circularity of, among other fossil fuels, the parent material of plastics and biomass in the EU (Eurostat, 2023a).



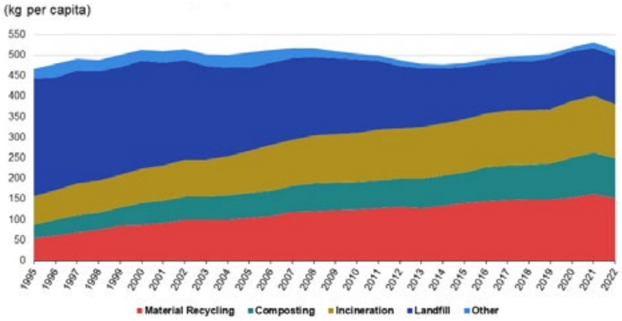
Source: Eurostat, 2023a

At that point, one must say that nowadays, Industrial Symbiosis (IS) can be translated as the process, steps of actions by which any by-products and/or waste of any kind of industry, small to medium size (SMS) and or large enterprises can be used either raw or after special pretreatments as the new raw repurposed feedstock for other industrial processes. Those processes must have been identified to improve their environmental impact while at the same time achieving not only their economic benefits but also sustainability.

From Figure 4, though, and for the case of the EU, it is apparent that we still rely heavily on managing MSW mainly by un-sustainable processes such as landfills and incineration, which are estimated as the discarded ~ 250 kg/capita of waste (Eurostat, 2023a).

The two (2) broad sources of plastic and biomass wastes are those ending up in Municipal Solid Wastes (MSW) and those emerging from the industrial sector. The usual suspects for plastics pollution are mainly low-density and high-density polyethylene (LDPE and HDPE, respectively), polystyrene (PS), polyethylene (PE) and rubber, as well as many contaminated plastics with, i.e., paints, food residues etc. All those with inappropriate management at source may be the hardest to control.

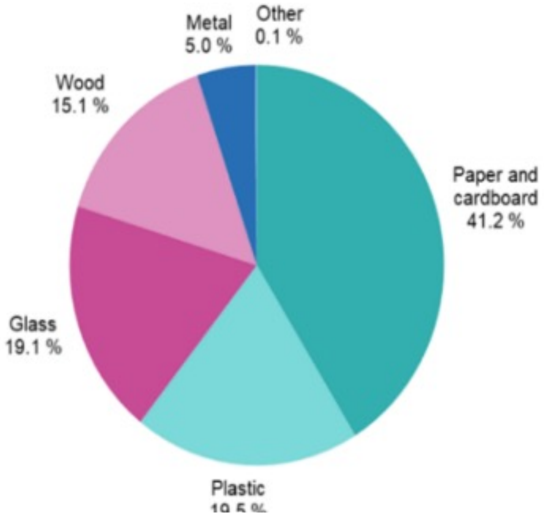
Figure 4. Main of municipal solid wastes (MSW) management in EU member states during a 15-year timeslot



Source: Eurostat, 2017

Plastic waste also represented a high fraction ranging between 30-35 wt.% of Municipal Solid Waste (MSW) and generated on an annual basis in industrialized countries (Tencati et al., 2016), while wood and food waste still a high percentage (~15%). Plastic wastes are known to have a high calorific value, somewhere between 14-42 MJ/kg (Wasilewski & Siudyga, 2013), indicating that it would be a good substitute for imported solid fuels (calorific value of 15-35 MJ/kg) while wood equally can reach a calorific value of ~ 3-4 MJ/kg. Figure 5 shows that all packaging waste, plastics and wood waste are generated at a percentage of 34.5%, with this amount slightly increased compared to 2013 estimations (Eurostat, 2023b; European Commission, 2020).

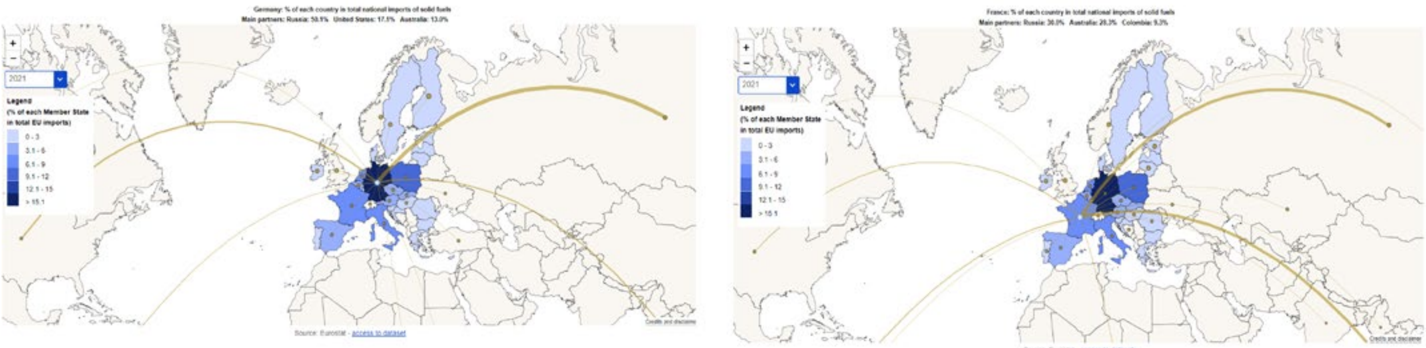
Figure 5. Estimation of percentages of packaging types of waste produced in the EU



Source: Eurostat, 2023b

In addition, and from Figures 6 – 8a, b, it is evident that at an EU level and for the short- and medium-term future, all EU countries rely heavily on solid, gaseous and liquid fuels imports from all around the world for cover their continually increasing energy consumption needs.

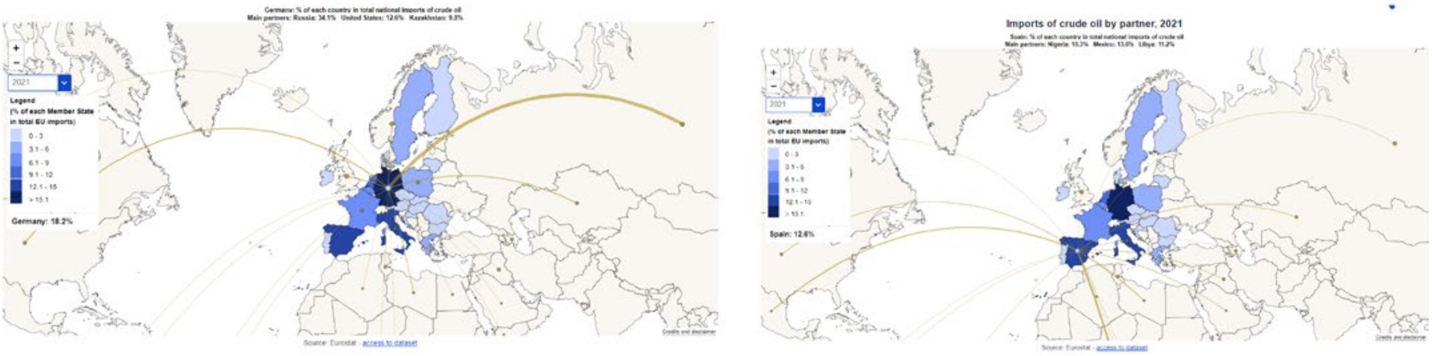
Figure 6. Imports of solid fuels in EU countries 2021: a) in Germany, b) in France



a) b)

Source: Eurostat, 2024

Figure 7. Imports of crude oil in EU countries 2021: a) in Germany, b) in Spain



a) b)

Source: Eurostat, 2024

As a result of all the above, to cover our energy needs and move towards less fossilized energy and material dependence, as well as solve our environmental problems of waste and carbon emissions and repurposing our waste to new types of more sustainable energy/fuels and materials is highly important.

Figure 8. Imports of gaseous fuels in EU countries 2021: a) in Germany, b) in Italy

a) b)

Source: Eurostat, 2024

METHODOLOGY

The present work can be classified as a short semi-systematic review designed for the CE and IS theme in the plastic waste-to-energy applicability of engineering solutions. This methodology and literature review are suitable for multidisciplinary works, among others, in the engineering sciences (Snyder, 2019). The method on which the present work is based is the semi-systematic review, which is composed of three (3) steps:

a) database selection, b) keywords, and c) the final articles screening and reviewing. The research works found were further narrowed down to the chemistry, mechanical, and chemical engineering aspects of plastic waste for energy, valuable materials, and chemicals from the side of engineering science.

RESULTS AND DISCUSSION

In the UK, the waste or refuse-derived fuels (RDF) mainly come from their solid combustible portion with the main interest in plastics, but also another combustible part of MSW such as wood biomass and paper etc. and are increasingly recognized as a renewable energy source. There are indeed cases where the production of RDF in either existing or repurposed or new Waste-to-Energy (WtE) plants led to an incredible 50% diversion of MSW from the landfills over the past ten (10) years (Hobbs, 2018).

Characterization of wastes

Before suggesting any waste-to-energy solutions, the physicochemical properties of plastic wastes must be studied. The chemical and qualitative analysis of the most common plastic waste species found in our MSW is shown in Table 1 below. Any alternative solid fuel to be used for energy generation must have low moisture content, low ash content, low sulfur and nitrogen, and from Table 2, it can be seen that plastics ending up nowadays in the environment as waste tick all the boxes as their suitability to be repurposed as waste-to -solid fuels while in the case of biomass special pretreatment, to remove ash prior repurposing might be needed (Taylor, Alabdrabalameer & Skoulou, 2019) and or any other pretreatment creating new business opportunities as they key rings in the chain of IS on waste to energy models.

Table 1. Comparison between the chemical composition of different plastic wastes with woody wastes

	Carbon (wt.%)	Hydrogen (wt.%)	Nitrogen (wt.%)	Sulphur (wt.%)	Oxygen by difference (wt.%)
Polyethylene (PE)	86	11.2	0.2	0.2	2.4
Polypropylene (PP)	87	12.5	0.3	0.03	0.3
Polystyrene (PS)	86.1	6.3	0.3	0.2	1.7
Polyethylene Terephthalate (PET)	63	4.3	0.04	0.1	32.6
High-density polyethylene (HDPE)	85.4	14.2	0.1	0.0	0.1
Low-density polyethylene (LDPE)	86.3	13.6	0.0	0.0	0.0
Agricultural residues (rice husks	46.6	7.5	2.5	0.3	43.1
Forest residues (birch wood)	50.4	5.6	0.1	0.0	43.9

Source: Addapted from Taylor, Alabdrabalameer & Skoulou, 2019; Chen et al., 2016; Singh & Ruj, 2016; Özsin & Pütün, 2017; Zhou et al., 2015; Zhao et al., 2022; Sarker & Nilson, 2015; Chen & Wu, 2009

Table 2. Comparison between the quality of different plastic wastes with woody wastes

	Moisture (wt.%)	Volatiles (wt.%)	Fixed Carbon (wt.%)	Ash (wt.%)	Calorific Value (MJ/Kg)
Polyethylene (PE)	0.17	99.78	0.02	0.13	46.3
Polypropylene (PP)	0.1	99.60	0.10	0.04	46.4
Polystyrene (PS)		99.10	0.39	0.04	41.4
Polyethylene Terephthalate (PET)	0.38	90.10	9.43	0.09	45.7
High-density polyethylene (HDPE)	0.01	99.99	0.0	0.0	n.a
Low-density polyethylene (LDPE)	0	99.1	0	0.9	46.1
Polyvinylchloride (PVC)	0.2	94.8	5.1	5.1	18
Agricultural residues (rice husks)	dry	78.9	13.4	7.7	15.8
Forest residues (birch wood)	dry	82.2	n.a	0.5	20

Source: Addapted from Taylor, Alabdrabalameer & Skoulou, 2019; Chen et al., 2016; Singh & Ruj, 2016; Özsin & Pütün, 2017; Zhou et al., 2015; Zhao et al., 2022; Sarker & Nilson, 2015; Chen & Wu, 2009

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Engineering processes for energy and materials chemicals production

Combustion and incineration processes are the most common energy generation technologies applied worldwide. However, concerns about carbon (CO2) and other harmful emissions to the atmosphere and climate change are shifting our energy generation technologies to lower carbon ones. On the other hand, plastics pollution, degradation during recycling cycles, non-recyclability of all products and by-products of industrial processes, and difficulty in changing consumers' habits in terms of recycling present a group of challenges that though lead to continuous efforts for the development of low carbon alternate technologies for solid, liquid and gaseous fuels and or energy (heat/electricity). Some of those developed today at different technology readiness levels (TRLs) are the upcycling technologies like pyrolysis (TRL 5) for pyrolysis oil production to partly substitute oil, gasification (TRL 8) for syngas (H2+CO) for not only energy generation but also a wide range of helpful commodity chemicals, transportation fuels and many others. These low-carbon engineering technologies can convert, for example, plastic waste or woody biomass waste into secondary materials and/or recover energy. As a result, they have lately gained much attention from multidisciplinary teams of engineers as there is a continually increasing need for energy and materials.

Moreover, as we move fast from the long-established linear economy to the applicability of Circular Economy at a very high rate (Srivastava & Sowmya, 2017), where efficient supply chains are a must, towards that direction pyrolysis and gasification are two exciting technologies to turn our waste into low carbon energy which come with their advantages and disadvantages such as pyrolysis need a continuous input of heat energy to operate while gasification can be auto thermal, pyrolysis is still in research and development or small scale while gasification operates at industrial scale, directives for pyrolysis of waste still obscure while gasification often misunderstands with the two staged combustion process. Pyrolysis oil can be produced from a single species of clean plastics but not from a mixture, while syngas emerging from steam, especially gasification, are enriched in H2, the latter beneficial molecule for chemicals and waste-to-fuels and chemicals production. Many other processes under R&D and development, from lab scale to pilot applications, are not mature enough for the markets.

Pyrolysis for liquid fuels and gasification for syngas- H2 production

Pyrolysis remains one of the emerging low-carbon, innovative technologies for upgrading plastics into valuable feedstock to produce secondary beneficial chemicals and fuels (Sharma et al., 2021; Miskolczi et al., 2009). Pyrolysis as a process involves the heating, under an inert atmosphere, of the solid wastes (plastics or woody biomass) at temperatures ranging between 300–700°C and ambient pressure, while with the aid of catalysts, less energy-intensive environments and higher efficiencies can be achieved. Depending on the modification of the engineering process itself, such as the use of a catalyst or not, the reactor type and scale, heating rate, and slow or fast- flash then the pyrolysis leads to useful pyrolysis chars (solids) (via the slow process), the non-condensable pyrolysis gas with substantial calorific value, and the liquid fraction which is the pyrolysis oil (produced via the fast pyrolysis process). All those are useful feedstocks that emerge for the upgrading of either plastic wastes or woody wastes to value-added new materials, fuels and chemicals for many other industries, such as hydrogen (H2), drop-in fuels, carbonaceous materials and many others (Kaimal & Vijayabalan, 2016; Chen & Chen, 2020). Pyrolysis is an advanced thermal process producing low carbon emissions compared to combustion and incineration. Still, it requires continuous heat (energy) to run, and this is one of its' main disadvantages (Chen, Wang & Zhang, 2021), along with some other operational problems keeping the process still at a relatively low TRL. That is the reason why the science of catalysis (applied chemistry) is also developing in parallel with engineering advances to run any low-to-net carbon process, such as pyrolysis at considerably lower temperatures but with a selectivity towards the desired pyrolysis products needed from the national and international markets such as pyrolysis oil (Kaimal & Vijayabalan, 2016; Uekert et al., 2021). An indicative only example of the sustainable prospects of pyrolysis oil from waste streams such as plastics is that it has even the potential to be upgraded to sustainable aviation fuels (SAF) (Zhao et al., 2022; Chen, Wang & Zhan, 2021), while woody biomass gives a wealth of valuable chemicals for industries such as carboxylic acids, non-aromatic esters, non- aromatic aldehydes, non-aromatic ketones, furans, pyrans, benzenes, catechols, phenols, aldehydes, methoxyphenols and many others (Kantarelis, Yang & Blasiak, 2013). Pyrolysis oil, depending on the quality of feed plastics and the upgrading process, is composed of chemicals such as motor oil

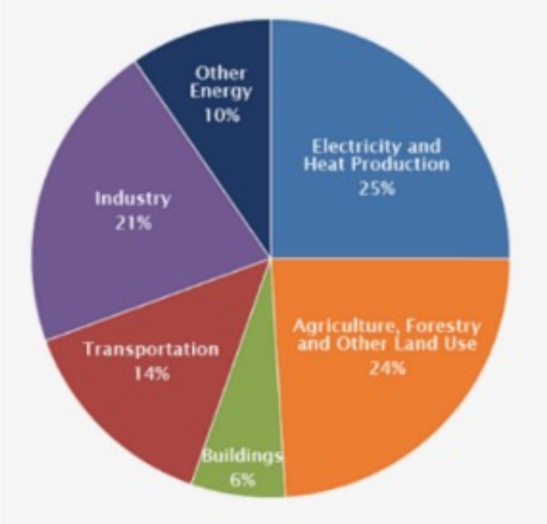
(C23–C40), diesel (C12–C23), kerosene (C10–C18), and gasoline (C4–C12) (Arabiourrutia et al., 2012; Wang et al., 2021). Many researchers also work on pyrolysis oil produced from different types of plastic wastes, indicating that the quality of the oil presents similar properties to diesel (Zhao et al., 2022; Kalargaris, Tian & Gu, 2017).

Moving quickly towards a hydrogen economy and electrolysis being very expensive, waste gasification is a transformative solution in the battle against plastic waste, heralding a paradigm shift in waste management. Plastic waste is metamorphosed into versatile syngas, predominantly composed of hydrogen (H2) and carbon monoxide (CO), through a meticulously controlled process devoid of oxygen or steam. The syngas emerging from waste, plastics, biomass or mixtures serve as a valuable resource, offering avenues for power generation, chemical synthesis, fuel production, and H2.

trategies for CO2 reduction

Finally, the latest outlook of the economic sectors contributes the most to carbon emissions in the atmosphere. From Figure 9, it is evident that in the heat and power generation industry, transportation is via liquid fuels. Industries such as steel and cement are the most significant carbon footprint suspects, contributing to 60% of carbon emissions (EPA, 2020).

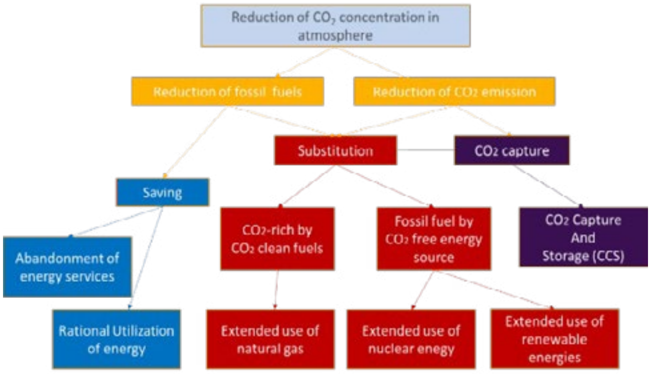
Figure 9. Comparison of the impact of carbon emissions on different sectors of the economy.



Source: EPA, 2012.

Nowadays, engineering developing technologies serve the three main strategies of CO2 reduction (Spliethof, 2012), namely by either substituting fossil fuels or carbon capture and storage (CCS) and carbon capture and utilization (CCU) substituting high carbon fuels with low carbon fuels (H2) offering many business opportunities, similar with repurposing our waste to value-added feedstock and developing innovative energy and fuels generation processes of low carbon footprint and or even 'decarbonizing' our old know heat and power generation processes of incineration of our waste. Bioenergy with Carbon Capture and Storage (BECCS) has been developing projects running at an industrial scale in the UK (International Energy Agency, 2024).

Figure 10. Possible routes of decarbonizing in the future include maintaining our energy security needs.



Source: adapted from Spliethof, 2012

CONCLUSIONS

Innovation, such as low-carbon engineering processes for energy and or materials from wastes, offers a wide range of opportunities to increase the productivity of any relevant industrial sectors for the benefit of society. This is remarkably achievable by sharing wastes and establishing the appropriate engineering technologies that ensure efficient valorization of wastes between, for example, agriculture (i.e., biomass wastes), local authorities and councils (i.e., plastic waste management) and the industrial sector (energy – materials security).

Any CE and IS solutions in the field of waste to energy and materials address a range of productivity, management and, above all, suitability of waste for valorization as well as processing challenges, which, however, rely on technical solutions. Those engineering solutions are far beyond the theoretical concepts and, when efficient, realistic and cheap, align with current environmental targets such as low-carbon energy solutions to ensure the immediate embodiment in our industrial sectors.

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Utilization of processed chicken manure in fish feed production: a sustainable approach

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ABSTRACT

This study examines the potential of using processed chicken manure in fish feed production. Chicken manure can be a valuable resource for fish feed production due to its high protein and mineral content. However, direct use poses pathogenic risks, necessitating appropriate processing methods.

The research investigated the processing of chicken manure through fermentation and heat treatment. The processed manure was incorporated into tilapia feeds at 10%, 20%, and 30% inclusion rates. After a 12-week feeding trial, tilapia with 20% processed chicken manure showed growth performance and feed conversion ratios comparable to the control group.

Results indicate that properly processed chicken manure can be a partial protein source in fish feed formulations. This approach presents significant potential for waste management and sustainable aquaculture practices.

KEYWORDS
Chicken Manure; Fish Feed; Sustainable Aquaculture; Waste Management; Sustainability.

INTRODUCTION

The aquaculture industry has experienced significant growth in recent decades, becoming a crucial source of protein for the global population. However, this rapid expansion has increased demand for fish feed, particularly protein sources, which has raised concerns about traditional feed ingredients' sustainability and environmental impact (Jonhson, 2023; FAO, 2022). As the industry seeks more sustainable alternatives, researchers have focused on unconventional protein sources, including processed animal manure (Jonhson, 2023; Yamamoto, 2022).

Chicken manure, a byproduct of the poultry industry, has emerged as a potential candidate for inclusion in fish feed formulations. This waste product is rich in nutrients, particularly nitrogen, phosphorus, and potassium, making it a valuable resource often underutilized (William, 2021). Using chicken manure in fish feed aligns with the principles of circular economy and industrial symbiosis, where waste from one industry becomes a resource for another.

However, the direct use of raw chicken manure in aquaculture poses significant challenges, including potential pathogen transmission, water quality degradation, and consumer acceptance issues (Jonhson, 2023). Various processing methods have been developed to transform chicken manure into a safe and nutritious feed ingredient to address these concerns.

Recent studies have explored fermentation, heat treatment, and chemical processing as potential methods for converting chicken manure into a suitable fish feed component (Anderson, 2022). These processes aim to eliminate pathogens, reduce harmful bacteria, and enhance the nutritional profile of the manure. For instance, demonstrated that a combination of anaerobic fermentation followed by heat treatment could effectively reduce pathogen loads while preserving valuable nutrients (Patel, 2021).

The potential benefits of incorporating processed chicken manure into fish feed are multifaceted. From an environmental perspective, it offers a solution to the waste management challenges faced by the poultry industry while reducing the aquaculture sector's relian-

Table content

ce on fishmeal and other unsustainable protein sources (Chem, Y., 2024). Economically, it presents an opportunity to reduce feed costs, which typically account for a significant portion of aquaculture production expenses (Thompson, 2023).

However, integrating processed chicken manure into commercial fish feed formulations is challenging. Palatability, digestibility, and potential impacts on fish growth and health must be carefully evaluated (Li, 2022; Zhang, 2024). Additionally, regulatory frameworks and consumer perceptions regarding using processed animal waste in food production systems must be addressed.

This paper aims to comprehensively review the current research on using processed chicken manure in fish feed production. It will examine processing methods, nutritional profiles, feeding trial performance, and the implications for sustainable aquaculture practices (Patel, 2021; Chen, 2024). By synthesizing existing knowledge and identifying areas for further research, this study seeks to contribute to the ongoing dialogue on innovative and sustainable approaches to fish feed production in the rapidly evolving aquaculture industry (Rodriguez, 2023; Yamamoto, 2022).

Table 1: Macronutrient Composition of Typical Chicken Feed

Nutrient	Starter (0-6 weeks)	Grower (6-18 weeks)	Layer (18+ weeks)
Crude Protein (%)	20-22	16-18	16-18
Metabolizable Energy (kcal/kg)	2900-3000	2800-2900	2700-2800
Crude Fat (%)	4-5	3-4	3-5
Crude Fiber (%)	3-4	3-5	3-5

Source: Zhao, 2023

Table 2: Mineral Content of Typical Chicken Feed

Mineral	Starter (%)	Grower (%)	Layer (%)
Calcium	0.9-1.0	0.9-1.0	3.5-4.0
Phosphorus	0.45-0.50	0.40-0.45	0.35-0.40
Sodium	0.15-0.20	0.15-0.20	0.15-0.20
Magnesium	0.05-0.06	0.05-0.06	0.05-0.06

Source: Zhao, 2023

Table 3: Amino Acid Profile of Typical Chicken Feed (% of diet)

Vitamin	Starter	Grower	Layer
Vitamin A (IU)	11,000	9,000	8,000
Vitamin D3 (IU)	3,000	2,500	2,500
Vitamin E (IU)	50	40	30
Vitamin K (mg)	3	3	3
Riboflavin (mg)	8	6	4
Pantothenic Acid (mg)	15	12	10

Source: Zhao, X., 2023

These tables provide a general overview of the nutrient content in chicken feed for different growth stages. Actual compositions may vary based on specific formulations, regional differences, and the needs of the flock. Always consult with a poultry nutritionist or refer to up-to-date feed standards when formulating chicken diets (Anderson, 2022; Williams, 2021).

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CONCLUSIONS

Exploring processed chicken manure as a component in fish feed formulations represents a significant step towards more sustainable and circular aquaculture practices. This innovative approach offers a multifaceted solution to several pressing challenges in the poultry and aquaculture industries.

The potential benefits of this strategy are manifold. It addresses the issue of waste management in poultry farming, provides a partial alternative to unsustainable fishmeal in aquaculture, and aligns with circular economy principles. Studies have shown promising results regarding fish growth performance and feed conversion ratios when using properly processed chicken manure, indicating its viability as a partial protein source in fish diets (Anderson, 2022; Jonhson, 2023; Thompson, 2023).

However, the path to widespread adoption is not without obstacles. Concerns regarding processing methods, consistency in nutrient content, potential pathogen risks, and regulatory compliance must be thoroughly addressed (William, 2021; FAO, 2022). Moreover, consumer perception and acceptance of this practice will be crucial to its commercial success.

Despite these challenges, the potential environmental and economic benefits make this an area worthy of continued research and development. By reducing reliance on fishmeal and utilizing a waste product, this approach could significantly decrease the ecological footprint of aquaculture while potentially lowering production costs.

In conclusion, while using processed chicken manure in fish feed is not a panacea for all sustainability issues in aquaculture, it represents a promising step towards more environmentally friendly and economically viable practices (Chen, Y., 2024). As the global demand for fish protein continues to rise, such innovative approaches will be crucial in ensuring the sustainable growth of the aquaculture industry. With continued research, development, and careful implementation, this strategy can contribute significantly to sustainable aquaculture's future.

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▲ Table content

What is the potential of the total site process integration in promoting industrial symbiosis?

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ABSTRACT

Pinch technology and total site integration have an enormous potential to facilitate Industrial symbiosis. They are primarily invented for minimization of waste heat, but later is developed for mass flows in production systems. The use of Pinch technology, as methodology for analysis of material and energy flows and process optimization, can lead to significant cost savings and maximal use of resource inside the company, but also the possibility to share with others in industrial parks. Pinch technology identifies opportunities in resource sharing and process optimization within the integration between all interested sites. It helps to companies in minimization of waste generation and improve overall efficiency. This approach identifies areas where resources can be shared, and waste can be exchanged. Later, this methodology was extended to reduction of gas emissions, optimization of green hydrogen production, minimization of footprint and optimization of Supply Chain. The principles of Pinch technology are the same or remarkably similar for all these extended uses. Selection of streams (heat, mass, items, etc.) is based on the need for use of utilities for their heating/cooling or component supply. Minimization of the use of utilities increase the efficiency and minimize the cost. Selected streams are divided on rich (sources) and poor (sinks) by their content. The quality of each stream is determined by the driving force of process of exchange heat, mass or items. The analysis can be done with table algorithm or graphical approach. In this paper is used Problem Table Algorithm and graphical determination of composite curves as simplest way to compare all uses. In analogy to heat and mass Pinch technology is shown the generalized approach to the Water Pinch, Footprint Pinch, Hydrogen Pinch, and Supply Chain Pinch. Finaly, economic analysis must be done to all generated alternatives as solutions of integration problems. The solution with minimum total cost and optimal driving force is ranged as the best. This methodology can be applied to the production process inside the company, or there can be created solutions as opportunities in exchange heat, mass, water, wastewater, byproducts and many more types of streams between companies inside industrial parks with aim to create industrial symbiosis. The existence of companies interested in exchange of resources in near neighbourhood increase the efficiency of the whole integration and symbiotic process.

KEYWORDS
Pinch Technology; Industrial Symbiosis; Industrial Park; Waste Exchange; Process Integration; Resource Sharing

INTRODUCTION

Industrial symbiosis (IS) has considerable attention in recent years because of its potential to reduce production expenses and increase sustainability. This concept, which support industrial ecology, involves companies within an industrial park (IP) to collaborate and share resources to maximize the utilization of available resources prior to seeking external resources (Sharpe & Agarwal, 2014). Implementing IS allowing the establishment of sustainable and mutually beneficial relationships between industries, resulting in increased resource efficiency and reduced waste generation. This approach involves identifying and utilizing opportunities for symbiosis, such as the use of waste products from one company as input for other companies' manufacturing processes. By employing IS, resource depletion can be minimized, and environmental consequences can be mitigated by optimizing resource allocation within the surrounding region. In addition, IS supports sustainable development of the industrial sector by promoting the adoption of circular economy principles, decreasing dependence on primary resources, and stimulating economic growth through cost savings and improved competitiveness.

The implementation of waste exchange program and encouragement the cooperation among industries can result with creation of a closed-loop system in which resources are continuously repurposed and recycled. That reduce the need for new raw material extraction in nature and minimizing the amount of generated waste (Fraccascia & Giannoccaro, 2020). This closed-loop system has a positive impact on the environment by lowering the carbon footprint of the industries within the IS but also gives economic benefits. The exchange of waste materials and by-products, companies can minimize their operational costs by sourcing raw materials from IS network, rather than purchasing them from outside. Industrial collaboration plays a vital role in encouragement for innovations and knowledge sharing. That results in development of novel solutions and processes which improve the overall efficiency and sustainability of industrial ecosystems.

The idea of IS can be extended to involve more than just the physical exchange of materials. In addition, it can include shared infrastructure, such as energy and water utilities, as well as collaborative efforts to implement environmentally friendly practices and technologies. Adopting this comprehensive approach strengthens the symbiotic relationships between companies but also establishes IS as a model for sustainable industrial development. This can attract investments and promote a positive reputation within the industry and local community (Chertow, 2007).

IS is a sustainable and efficient approach to resource utilization that involves the collaboration and exchange of materials, energy, and expertise between different industries to minimize waste generation and maximize economic and environmental benefits [4]. This concept is based on the idea of imitating natural ecosystems, in which organisms' waste becomes resource to another different organisms (Lehtoranta et al., 2011).

The implementation of IS allows businesses to develop a network of interconnection between industries that collaborate to optimize resource utilization and minimize environmental consequences. This can be accomplished by employing several mechanisms, including waste recycling, remanufacturing, and the transformation of industrial by-products or waste into valuable resources for other industries (Neves et al., 2019).

Proponents of IS acknowledge that the concept may not always lead to optimal utilization of resources and minimization of environmental impact. Critics cite factors such as the complex nature of logistics, disparate industry objectives, and constraints imposed by existing technologies for recycling and remanufacturing wastes. However, with meticulous planning, collective efforts, and supportive policies in place, these obstacles can be overcome, thereby realizing the advantages of IS. IS is a promising approach for fostering sustainable and mutually advantageous connections between industries (Lehtoranta et al., 2011).

The achievement of CAN be influenced by the application of effective or ineffective methodologies in the design process. The approach that will be employed hinges on the aspects of symbiosis that are of prime importance. The implementation of IS typically involves existing production processes and companies rather than the establishment of new IPs or the investments in new production systems near existing plants. Such changes are rarely made because of the significant investments cost. Therefore, they can be classified into two primary categories: retrofit design and new design. For the retrofit design, additional equipment is incorporated to improve the efficiency. Conversely, the new design entails the development of a completely novel system with all of its constituent parts. An IS employs a retrofit design as a key aspect. Another important factor to consider in the design of IS systems is the implementation of "total site" or "partial" improvements. In the case of total site integration, all relevant components, such as various systems and companies, are involved in IS creation and design. When discussing IS, it is important to understand that the process involves "total site integration," which refers to the complete integration of systems across all interested parties. If improvements are made only on one site or a few parts of the system within a single company, this is considered partial integration.

Pinch technology employs mass exchange and thermodynamic principles to enhance the mass and energy utilization in process plants. This method involves matching internal heat sources with suitable heat sinks to maximize energy recovery and minimize dependence on external resources (Linnhoff & Eastwood, 1997).

Pinch technology can play a significant role in the establishment of IS by allowing optimal utilization of resources and mitigating environmental consequences. Practically, there is a need for IS to foster sustainability and minimize waste (Lawal et al., 2021).

Several methodologies can be used in the design and optimization of ISs, such as *Material and Energy Flow Analysis* (Bao et al., 2010), *Resource Mapping and Matching* (Gu et al., 2013), *Industrial Ecology Tools* (Matilla, Pakarinen & Sokka, 2010), *Stakeholder Engagement and Collaboration tools* (Gondkar, Sreemagiri & Zondervan, 2012), *and Pinch Technology Integration* (Lawal et al., 2021). The implementation of Pinch technology for the design and partial or total optimization of IPs in an IS has not been widely adopted. Thus, the objective of this study is to identify the potential of Pinch technology in fostering IS within IPs while also examining the obstacles and prospects associated with its implementation.

IS also promotes the concept of "waste as a resource", encouraging companies to not view their waste streams as a burden, but as potential inputs for other industrial activities [13]. Pinch technology provides a systematic approach to identifying these opportunities by analysing the mass and energy flows within and between processes. Therefore, Pinch technology can be used in the integration of heat and mass between different production systems. By considering the principles of IS alongside the application of Pinch technology, companies can enhance their resource efficiency, foster collaboration, and constructive collaboration among industries, and contribute to sustainable development goals. This integration of Pinch technology and IS is a promising approach to address the challenges of resource scarcity, waste management, and environmental sustainability in industries.

The gap in using Pinch technology in the design of IS lies in the limited awareness and implementation of this approach in many industries. This review aims to show the status of Pinch technology implementation in the design of IS and to provide perceptions into the potential benefits and challenges associated with its adoption. Additionally, it aims to explore case studies and real-life examples where the integration of Pinch technology has successfully contributed to the development of IS, as well as to identify areas for further research and improvement in this field.

In the following sections, possibilities will be explored where the integration of Pinch technology has successfully contributed to the development and optimization of IS initiatives, highlighting the tangible benefits and results achieved through this approach.

INDUSTRIAL PARKS

IPs are designated areas set aside for industrial activities, typically located outside of urban areas to minimize environmental and social impact. These parks can be categorized based on the types of industries they host, such as manufacturing, processing, or research and development. The organization type of IPs can vary, ranging from privately owned and operated to government-managed facilities. Sustainability is a key consideration for IPs, as they strive to minimize their ecological footprint and promote environmentally friendly practices. This includes initiatives to reduce energy consumption, manage waste effectively, and minimize emissions. IPs often incorporate green infrastructure and sustainable design principles to achieve these goals.

IPs come in various forms, such as:

1) Technological parks, which are dedicated to research and development in specific fields such as biotechnology or information technology (Fan et al, 2017). The primary objective of technological parks is to foster a well-connected environment that facilitates the exchange of ideas, resources, equipment, and individuals. These connections occur between companies and major research institutions, such as universities. Technological parks collaborate with universities, governments, local authorities, and the business community to support the growth of small businesses. They provide consulting, educational, and administrative assistance, along with infrastructure. In addition, they connect diverse knowledge and external and internal experts in science and business, thereby fostering an environment conducive to the development of entrepreneurial ideas. Furthermore, the credibility of these parks ensures access to reliable resources and establishes connections with domestic and international business networks (Therin, 2009).

2) Eco-industrial parks (EIPs) and Positive Energy Industrial Parks (PEIPs), which aim to create a closed-loop system by integrating multiple industries and utilizing each other's waste byproducts as raw materials (Wang, Zhang & Lu, 2010). An EIP is a group of manufacturing and service businesses that share a common property and work together to improve their environmental, economic, and social performances. The collaboration in the management of environmental and resource issues, the business community have intentions to achieve a collective advantage that is greater than the available individual parts. This approach involves several components, such as green design for park infrastructure and plants (both new and retrofitted), cleaner production and pollution prevention, energy efficiency, and cooperation between companies. EIP strives to achieve positive impacts for neighbouring communities in addition to its own development (Lowe, N/A). The development of EIPs through the implementation of IS in IPs has increasingly become a standard practice (Ji, Shao & Wang, 2024). According to Lowe (N/A), EIPs must have a multitude of exchanges of by-products or networks of exchanges; numerous recycling business clusters; a collection of environmental technology companies; a collection of companies manufacturing environmentally friendly products; an IP designed around a specific environmental theme, such as solar energy; a park that features environmentally friendly infrastructure or construction; or a mixed-use development that incorporates industrial, commercial and residential components.

Undertaking the development of an EIP is a complex process that requires seamless integration across numerous fields of design and decision-making. The achievement of success leads on a new level of collaboration between various stakeholders, including public agencies, design professionals, project contractors, and companies located within the park. The potential inability to defeat traditional fragmentation within and between these groups poses a significant risk for fail. EIPs may have a higher development cost than traditional parks, depending on the design choices made in a project (Lowe, N/A). Several factors, such as design process, site preparation, infrastructure features, construction methods, and building design elements, may result in additional expenses. Whether these extra costs are offset by the savings generated from operating the park as an EIP depends on the acceptable payback period for the developer. Public development authorities might be better equipped to handle the potential increase in development costs than private developers, or the public sector may fund some aspects of the development with strong public benefits. Companies that use each other's residual products as inputs run the risk of losing a critical supply or market if a plant closes. However, this risk can be managed by keeping alternatives in mind and writing contracts that ensure supply reliability. The exchange of by-products could lead to continued reliance on toxic materials, so cleaner production solutions such as material substitution or process redesign should be prioritized over toxics trading within an EIP site. Some companies are not used to work "in community" and may fear on what the interdependence creates (Lowe, N/A).

Collaboration may pose challenges when an EIP comprises companies from diverse countries and cultures. On the contrary, numerous large and small corporations recognize interdependence as a significant competitive edge.

Natural systems - An IP can achieve compatibility with its surrounding natural environment by adopting strategies that minimize the potential for adverse ecological consequences while concurrently reducing operational expenses. That can be done using energy and material flows. Improving energy efficiency is a critical strategy for reducing costs and minimizing environmental impact. EIPs focus on optimizing building, lighting, and equipment design to achieve greater efficiency. In an eco-park, businesses typically view waste as materials that have not yet been repurposed internally or sold to external customers. By working individually and collectively, they strive to maximize the use of all resources and minimize the use of hazardous substances. The park may feature infrastructure for transporting by-products between plants, storing by-products for shipment to external customers, and providing common facilities for processing toxic waste. Additionally, companies within the EIP may participate in regional exchanges.

Several basic strategies are fundamental to developing an EIP. Individually, each adds value; together they form a whole greater than the sum of its parts.

Integration into Natural Systems assumes the site selection by evaluating the ecological carrying capacity and establishing design parameters within existing limitations. The aim is to mitigate local environmental consequences by integrating the EIP into the surrounding landscape, the hydrological system, and the ecosystem. Simultaneously, strive to minimize global environmental implications, particularly greenhouse gas emissions. It enhances energy efficiency by implementing facility design or renovation, cogeneration, energy cascading, and various other strategies. Moreover, improve efficiency through energy transfers between plants. That extensively utilizes renewable resources. Integration highlights the importance of clean production and pollution prevention, particularly regarding hazardous substances. Also, it ensures maximum reuse and recycling of materials among EIP businesses. Thus, it minimizes risks associated with toxic substances by implementing materials substitutions and site-level waste treatments. The integration in EIP can develop water management strategies that effectively conserve resources and minimize pollution by incorporating principles like those employed in the realms of energy and materials, such as implementing hierarchical uses at various quality levels.

EIP requires a more advanced management and support system than in a conventional IP. This system should be managed by either the companies themselves or a third party, and it should facilitate the exchange of by-products among these companies. Additionally, it should help these companies adapt to changes, such as when a supplier or customer moves out, through its enrolment responsibilities. Management could have connections to regional by-product exchanges and a site-wide telecommunications system. The park may provide shared support services, such as training centres, cafeterias, purchasing offices for common supplies, transportation logistics offices, and more. By sharing these costs, companies can save money and increase their savings.

EIP planners create structures and infrastructure to optimize the utilization of resources and minimize pollution generation for sustainable construction. They aim to minimize ecological impacts by conducting detailed site preparation and employing environmentally responsible construction techniques. The entire park needs to be designed for durability, maintainability, and adaptability to change. Towards the end of its lifespan, materials and systems can be easily recycled or reused.

The positive relationships between the developers of EIP and nearby communities should be reciprocated with numerous advantages from government services, educational systems, housing, etc. This integration with the host community can be achieved through various institutions, such as a business incubator that supports new or existing businesses in the area. Some may become tenants, while others may provide essential services or supplies to these tenants. Training programs will also contribute to a more skilled workforce and a stronger local economy that extends beyond the park's needs. Furthermore, a collaborative approach can potentially result in the formation of a public-private partnership to finance some aspects of an EIP's design. The primary directions in design of EIP are related to EIP Management, Construction / Rehabilitation, and Integration into the host community. IP management goes beyond offering standard services like recruitment and maintenance by fostering relationships between companies that utilize each other's waste. This approach helps enhance environmental performance for individual companies and the entire park. To achieve this, park management uses a site-wide information system that facilitates communication between companies and shares data on local environmental conditions and EIP performance. When constructing or renovating buildings, park management prioritizes the use of eco-friendly materials and technologies, such as recycling and reusing materials, and considers the environmental impact of materials and technologies throughout their life cycle. The aim is to support the local economy and social systems by providing training and education programs, promoting community business development, constructing employee housing, and engaging in collaborative urban planning.

The emerging sustainable economy presents several clusters focusing on significant environmental and energy industries. These clusters include Agro-EIPs, Resource Recovery Parks, Renewable Energy EIPs, EIPs that power plant anchors, and Green Petrochemical Parks. **3) Special economic zones (UNIDO, 2021)** are areas that have been designated to have specific economic regulations to attract foreign investment and stimulate trade. These zones often require a significant investment from the government. In some cases, the government may choose to manage an EIP model in which the operation of the park may be subcontracted to one or more private operators. This is known as the EIP private management model.

4) Free-trade zones which are areas where goods can be imported, stored**,** manufactured, and exported without being subject to customs duties or taxes [20]. IS, on the other hand, refers to the collaboration and exchange of resources, materials, and by-products among industries within an IP or geographical area. Positive Energy Industrial Parks are a specific type of IP that focuses on promoting clean and renewable energy technologies, reducing carbon emissions, and achieving sustainability goals.

TOTAL SITE INTEGRATION AS METHODOLOGY FOR THE DESIGN OF INDUSTRIAL SYMBIOSIS

As it was discussed earlier, the integration with Pinch technology can play a vital role in the design of IS by identifying opportunities for heat exchange and energy optimization between different processes and industries. Pinch technology provides a systematic approach to analyse energy flows and identify potential areas for heat recovery and optimization (Lawal et al., 2021).

Continuous processes are defined as those that operate continuously without interruption, such as chemical plants, refineries, and power plants. Pinch analysis is particularly well-suited for continuous processes due to their steady-state nature. The advantages of using Pinch analysis for continuous processes include the ability to identify optimal heat integration possibilities, minimize energy consumption, and reduce operating costs. Additionally, Pinch analysis allows for identification of minimal hot and cold utility requirements, as well as the determination of optimal process heat exchange targets.

With the use of Pinch analysis in continuous processes, engineers can effectively optimize energy usage, minimize waste, and improve overall process efficiency. This method is easier to apply to continuous processes because of their consistent and predictable operation, which allows for more accurate and reliable analysis. The first step in Process Integration is data collection. In this step are collected values of temperatures, flows, and other parameters of interest for possible heat exchange between streams. This can gather detailed information about process streams, temperatures, and heat transfer requirements. Based on collected data, in the next step are designed composite curves. Plot is created with composite curves of hot (HCC) and cold (CCC) streams to identify the Pinch temperature and the heat recovery potential. After that, Grand Composite Curve (GCC) is determined. Construction of GCC has a purpose to analyse the overall energy integration opportunities within the process. The solution of heat integration with Pinch technology is the design of Heat Exchanger Network (HEN). Mathematical optimization techniques or graphical methods are used to design HEN that maximizes heat recovery and minimizes utility consumption.

Batch processes, on the other hand, are characterised by discrete, non-continuous operations where production occurs in batches or cycles. These processes present unique challenges when it comes to applying Pinch analysis due to their transient and variable nature.

The Process Integration (PI) of batch processes is related to the changeable nature of processes, Time-depending streams, and specific time of heat recovery as key issues different from cases for PI of continuous processes. Batch processes exhibit varying operating conditions, making it difficult to apply the steady-state assumptions that underpin traditional Pinch analysis. The time-dependent nature of batch processes requires a dynamic approach to heat integration, as the heat transfer requirements and temperature profiles evolve throughout the batch cycle. The optimal timing for heat recovery within batch processes is crucial, as it impacts the effectiveness of energy optimization and heat exchange. Particularly important characteristics of batch processes are repeatability or non-repeatability of streams / processes and forming of specific time slices (process sequences). Designing HEN for batch processes requires a dynamic approach to account for the transient and time-dependent nature of these operations. One important aspect to consider in batch processes is the concept of repeatable and non-repeatable time slices. The repeatable time slices refer to process steps that occur identically in each batch cycle, allowing for consistent heat integration opportunities. Conversely, the non-repeatable time slices correspond to specific process steps that occur intermittently or with variations between batch cycles, posing challenges for heat recovery and integration.

Incorporating these time slices into the HEN design for batch processes involves a careful analysis of the process dynamics and the identification of opportunities to capture and utilize heat across repeatable and non-repeatable time slices. This dynamic approach to heat integration in batch processes requires the use of specialized techniques and modelling tools to optimize energy usage and minimize waste under varying operating conditions and batch cycles.

Furthermore, addressing the complexities of heat recovery timing within batch processes is essential to achieve effective energy optimization. Considering the evolving temperature profiles and heat transfer requirements throughout the batch cycle, engineers can strategically plan and implement heat recovery strategies to maximize the overall energy efficiency of the batch process.

The design of HEN for batch processes requires a tailored approach that accounts for the transient nature of operations, the distinction between repeatable and non-repeatable time slices, and the dynamic considerations of heat recovery timing. This approach aims to optimize energy usage and enhance process efficiency within the unique characteristics of batch processes.

Despite these challenges, advancements in dynamic Pinch analysis techniques and specialized software have allowed for the application of Pinch technology to batch processes. These approaches involve considering time-dependent constraints and using flexible heat integration strategies to address the unique characteristics of batch operations. The solution explores strategies for energy storage, intermediate heat exchange, and flexible utility use to optimize energy utilization during batch operations. The application of Pinch analysis techniques is to identify the minimum energy requirements for each batch and optimize energy usage in multiple production cycles.

When employing these methods in the design of IS, companies and IPs can effectively identify and leverage opportunities for resource exchange, waste reduction, and overall sustainability improvements. The strategic implementation of these methods can contribute to the development of closed-loop systems and the promotion of sustainable industrial practices.

BASIC PRINCIPLES OF TOTAL SITE INTEGRATION (GENERALIZED PINCH TECHNOLOGY)

Pinch technology is invented primarily to optimize production processes to minimize the use of energy. Later, it is extended to the minimization of raw materials and specific valuable components, as well as to the minimizing of wastewater, hydrogen production, footprint limitations, etc. Today, the methodology for PI can be generalized. The generalized principles of Pinch technology are given in the following text.

Heat Integration

Analysed processes (not only industrial) must have movement of materials, energy, items, inventory, or any other measurable flows. Those flows are streams that need to be integrated. Each stream must be characterised by quality and quantity parameters. In case of heat integration, the quality of the stream is the supply temperature of the stream (that can be detected in the process) and the target temperature (temperature that needs to be gotten through the process, heating, or cooling). The quantity of streams is the intensity of flow. In case of heat, that is, heat flow, or heat load. Thermodynamics defines the possible heat transfer due to the existence of driving force. That driving force in the case of heat integration is differences between temperatures. As the difference is higher, the driving force is bigger, and the heat transfer process is faster. Based on thermodynamics, heat can only be transferred from places with higher temperatures to places with lower temperatures. Not in the opposite direction. So, primarily quality, quantity, and driving forces must be determined for PI depending on the nature of process streams. After that, every stream must be characterised according to the quality values (Table 1). The quality values can declare streams as rich or poor according to the quality they contain. In case of heat integration, streams can be divided into hot streams (rich streams that have higher temperature than the target temperature and need to be cooled) and cold streams (poor streams with lower supply temperatures than targeting temperatures and have a need to be heated, to receive heat). According to the Problem Table Algorithm (Table 2), quality parameters are ordered by their values and create intervals as sequences in which are involved all streams that have quality values between determined intervals. Every interval contains certain segments of streams or the whole streams. All intervals are plotted together with quantities of each interval separately for reach and poor streams. These values create reach (RCC) and poor composite curves (PCC) (Fig. 1). If these composite curves are shifted equally to each other with the aim of making an intersection point, the intersection point is the Pinch point. The meaning of Pinch point is determining the non-flowing area. Simplified, that means that heat energy cannot be exchanged in Pinch point. If that is done, the solution is not optimal and increases the cost of the solution. The difference in qualities between RCC and PCC, for the cumulative value of interval loads, creates the GCC. The Pinch point in the GCC is determined with value zero. Another important piece of information can be calculated from the chart of RCC and PCC. The difference between RCC and PCC on the top right side determines the optimal amount of utility that must be provided as reach quality (heat from steam, hot water, etc.). The differences between RCC and PCC on the bottom left side determine the optimal amount of utility that must be brought as supplier for inadequate quality (cooling with cold water, ice, etc.).

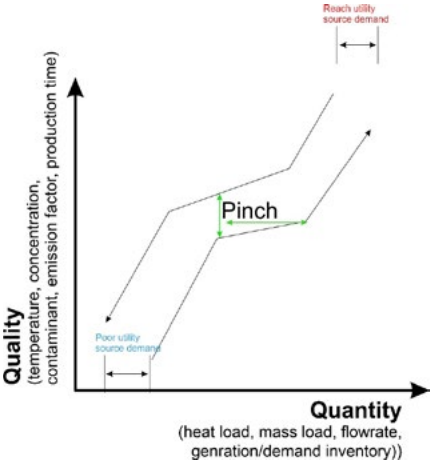
Table 1. Data extraction

Stream	Supply quality	Target quality	Driving force (DF)	Value of driving force (examples)	Quantity	Stream classification
S_1	SQ_1	TQ_1	$TQ_1 \square SQ_1$	Positive	Flow F_1	Rich
S_2	SQ_2	TQ_2	$TQ_2 \square SQ_2$	Negative	Flow F_2	Poor
S_i	SQ_i	TQ_i	$TQ_i \square SQ_i$	Negative	Flow F_i	Poor
S_{i+1}	SQ_{i+1}	TQ_{i+1}	$TQ_{i+1} \square SQ_{i+1}$	Positive	Flow F_{i+1}	Rich
S_n	SQ_n	TQ_n	$TQ_n \square SQ_n$	Positive	Flow F_n	Rich

<Table 2. Problem Table Algorithm

Intervals (arithmetic order of values)	**Segments of streams**	**Sum of quantities of rich and poor streams` segments in each interval**	**Interval load**	**Cumulative load**
SQ_2	S_2	$\sum_{i=1}^{n} F_{i_{RICH}} - \sum_{i=1}^{n} F_{i_{POOR}} \Rightarrow S_2$	IL1	IL1
SQ_1	S_2, S_1	$\sum_{i=1}^{n} F_{i_{RICH}} - \sum_{i=1}^{n} F_{i_{POOR}} \Rightarrow S_1 - S_2$	IL2	IL1+IL2
TQ_2	S_1	$\sum_{i=1}^{n} F_{i_{RICH}} - \sum_{i=1}^{n} F_{i_{POOR}} \Rightarrow S_1$	IL3	IL1+IL2+IL3
SQ_i	S_1, S_i	$\sum_{i=1}^{n} F_{i_{RICH}} - \sum_{i=1}^{n} F_{i_{POOR}} \Rightarrow S_1 - S_i$	IL4	IL1+IL2+IL3+IL4
TQ_{i+1}	S_1, S_i, S_{i+1}	$\sum_{i=1}^{n} F_{i_{RICH}} - \sum_{i=1}^{n} F_{i_{POOR}} \Rightarrow S_1 + S_{i+1} - S_i$	IL5	IL1+IL2+IL3+IL4+ IL5
SQ_{i+1}	S_1, S_i	$\sum_{i=1}^{n} F_{i_{RICH}} - \sum_{i=1}^{n} F_{i_{POOR}} \Rightarrow S_1 - S_i$	IL6	IL1+IL2+IL3+IL4+ IL5+IL6
TQ_1	S_i	$\sum_{i=1}^{n} F_{i_{RICH}} - \sum_{i=1}^{n} F_{i_{POOR}} \Rightarrow S_i$	IL7	IL1+IL2+IL3+IL4+ IL5+IL6+IL7
SQ_n	S_i, S_n	$\sum_{i=1}^{n} F_{i_{RICH}} - \sum_{i=1}^{n} F_{i_{POOR}} \Rightarrow S_n - S_i$	IL8	IL1+IL2+IL3+IL4+ IL5+IL6+IL7+IL8
TQ_i	S_n	$\sum_{i=1}^{n} F_{i_{RICH}} - \sum_{i=1}^{n} F_{i_{POOR}} \Rightarrow S_n$	IL9	IL1+IL2+IL3+IL4+ IL5+IL6+IL7+IL8+IL9
TQ_n				

Figure 1. Composite curves determination as relation between quality (quality intervals) and quantity (Cumulative Interval Load). The upper composite curve presents reach streams (RCC) and the lower is presenting poor streams (PCC).



*The upper composite curve presents reach streams (RCC), and the lower presents poor streams (PCC).

All these values are used for economic analysis. The economic analysis calculates the optimal cost for equipment (optimal number of items with specific characteristics) in which needs to be invested to realize the solution. Additionally, in economic analysis, the operation cost, capital cost, utility cost, and if there are other types of cost related to the equipment and realization of solution are also taken into consideration. The solution for each PI is a network of equipment for realization of that integration. In case of heat integration, the solution is HEN, a system of heat exchangers with certain performances such as heat exchange area and number of exchangers with maximal allowed heat exchange area. All costs are calculated for several values of minimal driving force differences. The minimal cost determines optimal difference of driving force. That optimal difference of driving force is the minimal temperature difference allowed to be used in all processes of heat transfer for all selected streams in all heat exchangers of the analysed case study. This step is called super-targeting. Super-targeting determines the optimal solution based on the type of heat exchangers and the cost (Fig. 2). The capital cost is based on the total heat transfer area (Equation 1) and the number of heat exchange units. The heat transfer area depends on the temperature differences between hot and cold streams in the heat exchanger temperature profile (Fig. 2). As the temperature difference is smaller, the heat transfer area is larger (Equation 1). Therefore, the cost of heat exchangers depends on temperature differences and heat transfer area. The total cost (Equation 4) is determined as the sum of capital costs (Equation 2), and operating costs (Equation 5).

$$A = \frac{Q}{K \cdot LMTD}$$

where

$$LMTD = \frac{\Delta_1 - \Delta_2}{\ln \frac{\Delta_1}{\Delta_2}}$$

$$CC = C_{equipment} + C_{instalation} + C_{instrumentation} \qquad (2)$$

$$C_{equipment} = C_{HE} = N_{shell}\left(a + b \cdot \left[\frac{A}{N_{shell}}\right]^{c}\right) \qquad (3)(1)$$

The relation between the capital cost of heat exchangers and heat transfer area is given with Equation 3. Coefficients a, b, and c are empirical values depending on the type of heat exchanger. The capital cost as well as the total cost depends on the heat transfer area (the highest cost) based on the driving force. The optimal value of temperature difference in all heat exchangers is determined as value of DTmin at which the total costs have minimal value (Fig. 2). The step after super-targeting is the design of the heat exchangers network as a solution for the heat integration problem.

$$TC = OC + CC \qquad (4)$$

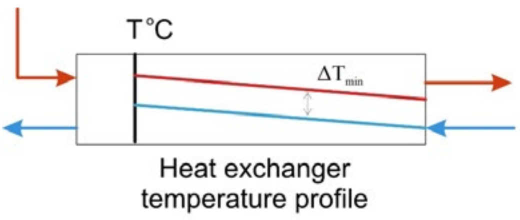
$$OC = m_{reach} \cdot C_{reach} + m_{poor} \cdot C_{poor} \qquad (5)$$

where

m - amount of utility

C - price of utility

Figure 2. Super-targeting, optimal solution and HEN design



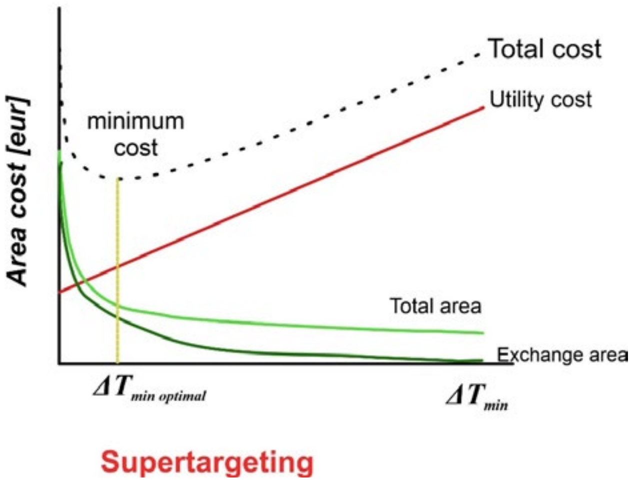


Figure 4. Integration of two companies through the storage systems (indirect connection)

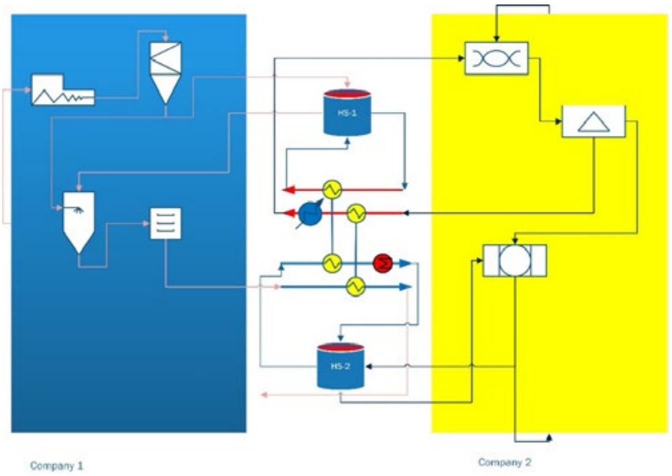
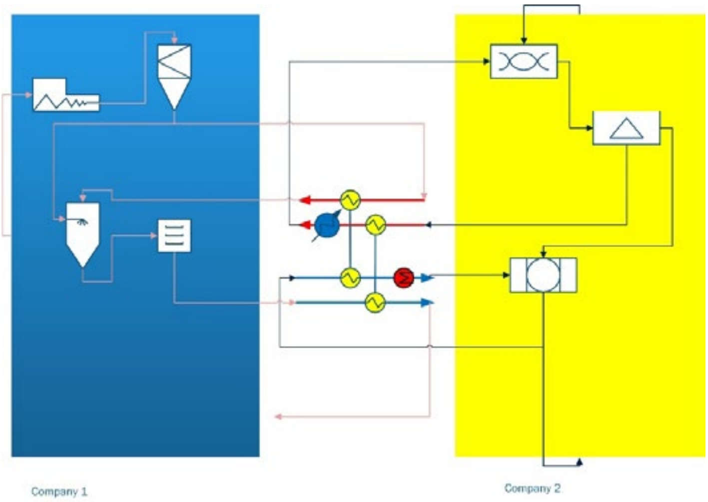


Figure 3. Integration of two companies through the continuous processes (direct connection)



In Fig. 3, can be seen the HEN designed for heat exchange between two companies. That is the main connecting point for heat transfer. These HEN systems can be partially belonging to each company or can be part of only one of them. In the case of continuous streams integration, the solution is given in Fig. 3. That solution has low flexibility. Therefore, it can be transformed into a more flexible solution by incorporating heat storage systems (Fig. 4). In the case of more flexible solutions, integration can be done either between continuous or batch processing streams.

This is a brief explanation of generalized Pinch analysis based on an example for heat exchange. Furthermore, this can be used for integration between external objects or inside objects (internal processes) for diverse types of qualities. In the following text will be explained possibilities in use of Pinch technology for various other purposes.

Mass Integration

Every production process uses some specific components as sources or reactants to produce the final product. The quality of raw material is the concentration of the components in selected streams. Higher concentration of component means higher quality and stream reach with that component. The driving force for mass processes is the difference in concentration of specific components. The quantity of streams is the mass flow of stream (total or component mass flow). Based on the generalized PTA, RCC and PCC as well as GCC can be designed. In case of mass integration RCC and PCC are shifting horizontally to find intersection point – Pinch point. The difference between composite curves below and above the Pinch have meaning of the minimum fresh resource requirement and minimum waste discharge, consecuently. The solution for mass integration is a network of several types of mass exchangers that makes extraction, separation, distillation, absorption, or adsorption of specific components of interest for the optimized process. The economic analysis is based on the operating cost, the investment cost, and the total cost for different values of differences for the driving forces. This analysis calculates the minimal allowed concentration that can be used for specific equipment. Equipment used for mass integration are various mass exchangers.

A mass exchanger is a type of direct-contact unit that employs a mass separating agent (MSA), to selectively remove components from a rich phase. The MSA should be partially or completely immiscible in the rich phase to facilitate the redistribution of solutes and the depletion of the rich phase. The operations that can be carried out using a mass exchanger include distillation, absorption, adsorption, extraction, ion exchange, leaching, and striping, among others. The main meaning of these operations is given in the following text.

The process of absorption uses a liquid solvent for selectively dissolve specific compounds due to their solubility preferences. It is an important mechanism in various industrial applications, such as the removal of sulphur compounds from flue gases with alkaline solutions or ethanol amines. Adsorption refers to the process in which a solid adsorbent exhibits the ability to adsorb specific components from a gaseous or liquid solution onto its surface. Extraction entails utilizing a liquid solvent to extract specific compounds from one liquid by leveraging their preferential solubility in MSA. Ion exchange is a technique that employs cations and/or anions to replace undesired anionic species in liquid solutions. The process of selectively separating certain components of a solid mixture by exposing it to a liquid solvent is known as leaching. Moreover, the process of removing volatile compounds from liquid or solid materials using a gaseous solvent is known as stripping. Therefore, mass exchangers can be vastly different for solving problems in mass integration. There is a variety of design and purposes of mass exchangers.

The design of solution for mass integration is like the heat Pinch integration. After data analysis and selection of streams, super-targeting is next step. The super-targeting in mass integration is more difficult than the one for heat integration. The complexity of the solution is depending on the type of equipment that should be used in the solution. Therefore, the equipment type must be defined. Capital cost of equipment can be estimated based on empirical equations specially developed for certain type of equipment with specific parameters. Equation 6 is empirical formula for capital cost estimation of stripper column based on the diameter and high of the column. The optimization of Mass Exchanger Network (MEN) can be done with calculation of annualized costs (fixed, operating, and total cost) for minimum allowed composition differences in concentration (ΔCmin) as driving force in mass operations (Fig. 5). That is analogue to ΔTmin for heat Pinch.

$$C_{\text{stripper column}} = 1800 \times H^{0.85} \times D^{0.95}$$

Selection of optimal solution is selecting the ΔCmin for minimal total annualized cost (Fig. 5). MEN can be designed based on the selected optimal driving force. Example of MEN is shown on Fig.6.

Figure 5. Optimal solution for mass exchange and MEN design

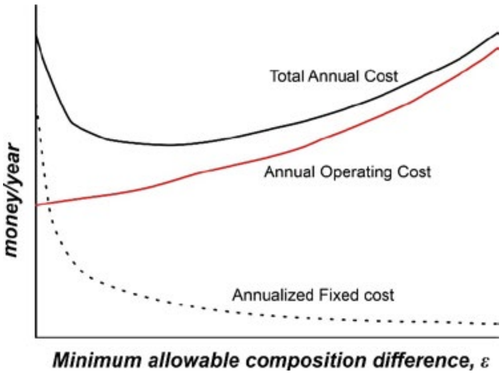
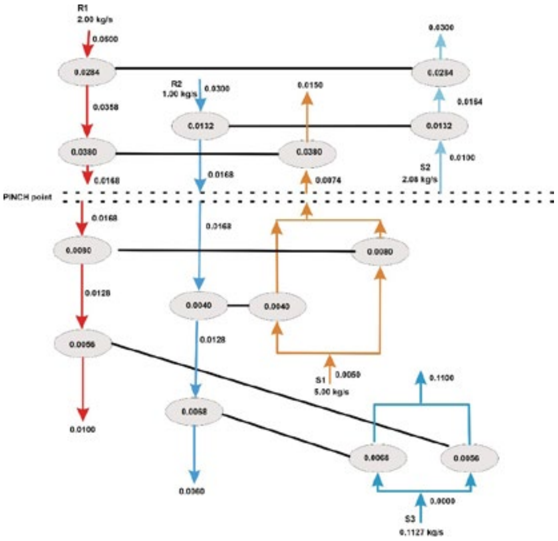


Figure 6. Mass Exchange Network (MEN) as a solution in mass integration



The connection between companies that have integrated parts of their systems can be rigid or flexible. The flexibility of connection can be increased with mass storage systems with avoiding direct dependency of both production systems.

As subareas of mass integration are developed so called "Water Pinch" and "Hydrogen Pinch". Water Pinch minimizes wastewater, and Hydrogen Pinch optimizes the production of hydrogen as an energy source (fuel).

The Pinch analysis goes further in some scientific areas where driving forces can be determined but the implementation of Pinch technology needs some revisions for its purpose. Thus, there are developed Pinch methodologies based on footprint to minimize the emission of pollution, and even involvement of Supply Chain management.

When an analysis should be performed on processes that make a footprint on the environment, parameters should be defined. The quality in the environmental impact is the emission of pollution in the environment. Quantity can be measured as produced units (items), energy needed for producing of one unit of product, as well as mass flow or molar flow of polluting components. When the carbon footprint is measured, the amount of CO2 is the quality of the streams. The target values are limitations that are given for such kind of emissions depending on the region where those emissions are emitted. Every analyzed region can have different standards for it, or it can be the same for all regions where the emission is done. The measures of quality include the carbon footprint, agricultural-land footprint, water footprint, and emergy, among others. Practically, the quality parameter is the footprint or emission factor per used energy for certain production. The quality parameter for receivers is the emission allowed (emission kg/J used energy) by the regulations in use for that area or region (Raymond & Dominic, 2013).

Carbon Footprint is defined as CO2 emissions intensity per unit of energy. Addressing climate change mitigation requires allocating energy effectively (De Benedetto & Klemeš, 2013). The carbon footprint can summarise the values of different resources expressed as carbon dioxide equivalents. This means that the carbon footprint can be used to calculate the carbon emission reduction potential of symbiotic integration). The carbon footprint can summarise the values of different resources expressed as carbon dioxide equivalents. This means the carbon footprint can be used to calculate symbiotic integration's carbon emission reduction potential (Dong et al., 2014).

The significance of the *Agricultural-Land Footprint* in relation to the intensity of land use for agricultural purposes is crucial for planning large-scale bioenergy production, with the aim of reducing potential conflicts with other traditional land uses, such as food production (Čuček, Klemeš & Kravanja, 2012).

The concept of *Water Footprint* pertains to the degree of reliance on local water resources that are necessary to produce biofuels. This reliance may have the potential to divert resources from other crucial uses. Moreover, climate change could lead to water stress or local water scarcity in specific regions (Allan, 1998).

Emergy transformation in the context of the Pinch analysis offers a quantitative measure of the efficiency with which solar energy is converted into various forms of downstream energy. In other words, the emergy content of any natural resource serves as an index of its scarcity or value by quantifying the cumulative amount of solar power required to form the resource. This provides a valuable tool for assessing energy conversion efficiency and the relative value of different resources (Howard, 1995). Emergy can be taken as the quality of streams.

Inoperability serves as a quantitative measure of the reduction in physical output caused by natural disasters, including droughts, earthquakes, and storms (Haimes & Yiang, 2001).

Cases with footprint Pinch have a solution in choosing the better source with a smaller environmental impact, or the effect will be on the range limited by regulations/laws.

Supply Chain integration

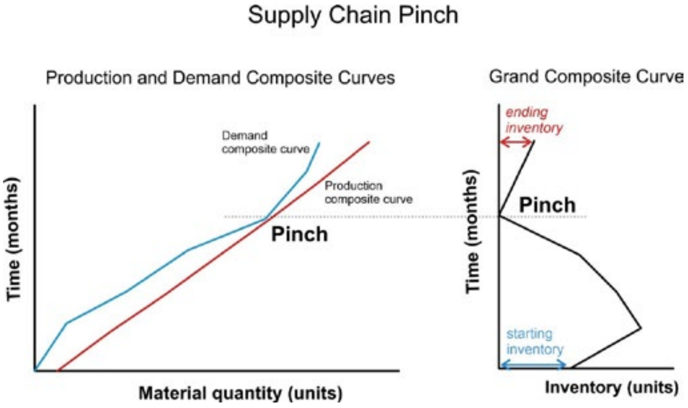
Another use of Pinch technology is determination of material allocation from active sources together with possible external sources and the sinks where they are needed. In practice, this is related to Supply Chain (SC). SC management can play a crucial role in organizations, as it enables them to optimize profitability through the efficient management of production, capacity, subcontracting, inventory, and stock levels. However, conventional SC management is challenging due to the excessive costs associated with documentation, which often results in inaccurate and useless data (Sharpe & Agarwal, 2014). In addition, traditional SC management lacks adaptability. Large enterprises struggle to accurately configure custom key requirements, which often leads to challenging workarounds or solutions. Furthermore, advanced analytics pose a significant problem, as noted by Chopra and Mendl (2016).

Conventional SC management is overly complex and requires highly specialized data analysts. Unfortunately, good data scientists are short on supply and in high demand, and the tools they use are not designed for widespread access and deployment to business users throughout the company (Bao et al., 2010). These issues result in low efficiency in SC management, which, in turn, impacts decision-making and strategy planning. To address this, renewable energy research has focused on making production economically practical. Pinch analysis is a valuable tool that employs less complicated mathematics than other optimization tools (Gu et al., 2013). Therefore, incorporating Pinch analysis into the SC of renewable energy enables more efficient SC management.

SC Pinch analysis is a methodology grounded in the principles of PI and was initially developed for thermal heat recovery in energy conservation (Kumana, 2002). Since then, it has been adapted to optimize SCs by identifying the most efficient utilization of resources and minimizing waste. Pinch analysis in SCs involves determining the points at which supply, and demand intersect at their lowest levels, optimizing production rates and resource allocation (Know et al., 2020). Remarkably, while Pinch analysis has its foundation in energy conservation, its application in SCs extends to various sectors, including biogas production, knowledge management, and the optimization of online shopping services (Zhang, 2009; Heckmann & Nickel, 2017). SC Pinch analysis provides a structured approach to managing intricate SC processes. It has been integrated with other methodologies, such as Monte Carlo Simulation, for improved forecasting and planning as superposition (Know et al., 2020). As a versatile tool, SC Pinch analysis has evolved from optimizing energy systems to a broader application in SC management. It facilitates efficient SC design and resource optimization and achieves competitive advantages by addressing modern supply chains' complexities and dynamic nature (Crandal, Crandal & Chen, 2009). The Pinch analysis uses aggregate planning that enables managers to determine the most advantageous production and inventory levels, considering the fundamental trade-offs before the current SC design. The objective of aggregate planning within a SC is to meet demand in a way that optimizes profit and minimizes the overall annual cost. A few parameters are considered essential for SC optimization with Pinch analysis. Production rate shows the number of units produced in-house during a specific period.

Additionally, the amount of overtime work and the number of units subcontracted during the same period are also considered. The workforce and the number of machines needed for production are also considered simultaneously. Furthermore, the inventory and the number of units stocked out at the end of the concerned time are also included in the calculations.

Figure 7. Example of Supply Chain composite curves (horizontally shifted) to meet the intersection point (Pinch point) between demand and production composite curve. The difference between both composite curves for the quantity of units gave the GCC for the SC.

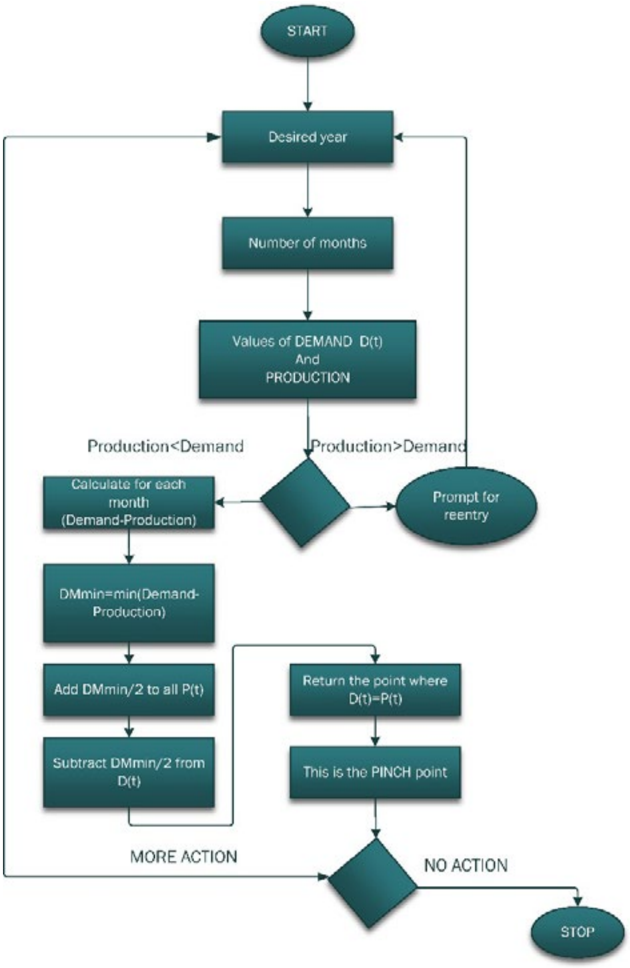


*The difference between both composite curves for the number of units gave the GCC for the SC.

The quality parameter in SC is time. Time gives a speed of transportation, production, or supply of items (units) to the receivers of them. The quantity is determined by the items flow (units per time). Two different cases can be recognized as Pinch analysis with and without storage systems (stockout). Based on these data, RCC and PCC can be constructed (Fig. 2). Reach streams are demands for supply, and poor streams are producers and/or stored items. The fresh sources are amounts of starting and ending inventory. Variables used for the Pinch concept in SC, includes demand like hot stream, and production as cold stream. The ΔTmin is represented as ΔMmin, which means how closely the demand and production composite curves can be pinched (or optimized). At the Pinch point, the material flow in a SC is balanced, enabling problem decomposition. The demand composite curve is a plot of cumulative demand as a function of time, and it must be matched by a production composite curve. The three critical indicators of a SC - material flows, material hold-up, and time - can be effectively managed by plotting demand and production composites on a graph of time versus material quantity (Singhvi & Shenoy, 2002).

Folorunso et al. (2010) gave instructions in SC Pinch analysis. First, there needs to be added the numbers of months (years). After that, material values for production and demand should be entered, respectively, monthly (e.g., January, February, etc.). Ensure that the production value does not exceed the corresponding demand value. If this is not the case, an exception should be thrown: "excess supply". The next step is the calculation of the ΔMmin for each pair of production and demand values by finding the minimum of (demand-production). The optimization is the following step. Values should be optimized by adding half of ΔMmin to all production values and subtracting it from all demand values. The Pinch point is the point at which production equals demand (difference in amount that needs to be supplied, and the quantity produced is zero). This algorithm is shown on Fig. 8.

Figure 8. Algorithm for optimizing Supply Chain with Pinch technology



Source: Folorunso et al, 2010.

TOTAL SITE INTEGRATION FOR INTERESTED SIDES FOR INDUSTRIAL SYMBIOSIS

Total site integration (TSI) is implemented in cases where integration between various production processes and/or companies is necessary to minimize expenses by reusing waste flows. The methodology entails conducting a Pinch analysis separately for each site as part of the standard procedure. By determining the composite curves and the values for ΔT_{min}, which may differ for all the involved processes (sites) and Pinch Temperatures calculated with ΔT_{min}, the TSI methodology aims to optimize the overall performance of the integrated system. The so-called "pockets" in GCC can facilitate additional heat recovery, allowing for the redistribution of heat at higher temperatures to lower temperature streams. Based on the data obtained from the PTA, a combined composite curve has been developed for all energy sources involved in the process, with their respective determined ΔT_{min} values. This curve utilizes stream segments from the double-shifted supply and target temperatures for heat integration. Creating a Combined Heat Source (CHS) curve for the TSI of selected processes via Pinch technology necessitates a holistic perspective that unifies individual process data across the site. This process typically involves constructing a Total Site Profile (TSP) and employing Site Composite Curves (SCC) or a Site Grand Composite Curve (SGCC) to identify opportunities for heat recovery and utility savings (Desai & Bandyopadhyay, 2009; Chew et al., 2013; Chew et al., 2014). Indeed, Pinch analysis has traditionally been applied to individual processes for quite some time, but its extension to TSI presents unique challenges and opportunities.

A prime example of this is the plus-minus principle adapted for TSI, which facilitates the identification of process modifications that can lead to significant energy savings (Chew et al., 2014). Incorporating different ΔT_{min} for each process can result in more practical heat recovery objectives than single uniform ΔT_{min} (Varbanov, Fodor & Klemeš, 2012). The formulation of a CHS curve for TSI through the application of Pinch technology is a complex, multistep procedure that necessitates an extensive examination of heat recovery prospects across the entire facility. This entails constructing a TSP and deploying SCC or SGCC to identify potential process adjustments that can optimize energy efficiency and result in significant cost savings. Implementing these principles in the context of TSI can result in considerable enhancements in heat recovery and reduction of utility costs, contributing to the overall efficiency and sustainability of industrial operations (Varbanov, Fodor & Klemeš, 2012). The utilities available at their respective source temperatures can determine the total site profiles. This indicates that each utility provides a portion of the required heat or cold. It is essential that the ΔT_{min} parameter is satisfied at each site.

Consequently, if there is an available utility with a higher temperature than the calculated ΔT_{min} for that site, the current ΔT_{min} in the construction of the heat exchange system will be higher than the optimal value. Furthermore, the utility profile (curves) will be in the form of stairs, where each step represents the temperature of the utility supply. To reduce utility usage, the overlap between sources and sinks is replaced with a utility that has a higher temperature (hot utility). The Site Utility Grand Composite Curve (SUGCC) is constructed based on this concept. The SUGCC is a graphical tool utilized in process engineering to depict the heat demand and supply within a site's utility system. It is a composite curve that integrates the heat from all utility streams at various temperature levels within a processing site (Perry, 2013). The SUGCC is an effective tool for detecting opportunities for heat integration and cogeneration, which can result in increased energy efficiency and decreased fuel consumption. Numerous studies have also made modifications and extensions to the SUGCC to expand its applicability. A revised SUGCC diagram has been proposed to include the production of shaft work and to offer a more precise estimate of the potential for cogeneration (Khoshgoftar Manesh et al., 2012; Sorin & Hammache, 2012). The Extended SUGCC encompasses sensible and latent steam heat, facilitating superior thermal matching between processes (Khoshgoftar Manesh et al., 2013). In summary, the GCC of the Site Utility is a fundamental concept in process engineering that optimizes the design and operation of site utility systems. It is a cornerstone for various methodologies to improve energy efficiency and cogeneration, as demonstrated by its adaptations and extensions in the literature cogeneration (Khoshgoftar Manesh et al., 2012; Sorin & Hammache, 2012; Khoshgoftar Manesh et al., 2013).

STORAGE IS A CRUCIAL PART OF THE NETWORK FOR SUCCESSFUL INTEGRATION FOR INDUSTRIAL SYMBIOSIS

the alignment of supply and demand can sometimes occur at different periods, which presents a challenge in synchronizing multiple processes, even within the same company. An efficient solution is required to address this issue. One such solution is using storage systems as part of the interconnection network. These systems can store materials, energy, or other items for a certain period until they are transferred to their intended destination. Furthermore, several types of Pinch technology applications use different storage technologies. For instance, heat energy can be stored in heat storage systems that have a heat exchange area and a filling material used for heat storage in the form of latent or sensible energy. Electricity can also be stored in storage facilities, such as batteries, designed using many different technologies.

Additionally, energy can be converted and stored through chemical reactions (chemical storage) or other forms in which it is restored. Similarly, materials can be stored in specialized tanks depending on their characteristics (solid or fluid storage). SC can store products/items in warehouses as part of the transportation system. In general, storage systems can be created based on the needs of the system developed for IS. Finding any report for IS that uses energy storage is complex. That is a little bit out of focus in IS.

THE SUCCESSFULNESS IN THE USE OF PINCH TECHNOLOGY IN THE REALIZATION OF PROJECTS FOR IS

Practical realization of projects for IS using Pinch technology has been demonstrated in various industries. Pinch technology can be applied inside the production process, between different production processes (in the same factory), between different factories (companies), inside the IP, and even at the regional level. Moreover, IS is divided into distinct levels of application. IS can be applied between companies inside the same IP, where the waste and byproducts of one company are utilized as inputs by another company, leading to resource efficiency and reduced environmental impact. The higher level of IS is the integration of multiple IPs or even entire regions, where the byproducts and waste streams of one industry are utilized as inputs by another sector, creating a closed-loop resource exchange and minimizing waste generation. Finally, IS can be applied nationally or globally, where countries or regions collaborate to optimize resource utilization and waste management on a larger scale. So, the integration made by Pinch technology can be done on the same levels of integration that have IS. The use of Pinch technology in IS design presents challenges and opportunities. Implementing Pinch technology requires a deep understanding of the processes and systems involved and accurate data on heat and mass flows. On the other hand, Pinch technology also provides a systematic and holistic approach to analyzing and optimizing resource utilization, energy efficiency, and waste minimization (Ebrahim & Kawari, 2000).

The integration does not need to be done on newly built or designed production or organizational systems. It can also be used for retrofitting design. The retrofit design approach using Pinch technology for IS involves identifying opportunities within existing processes and systems to improve resource efficiency and promote symbiotic relationships between industries. Companies can uncover potential areas for heat recovery, energy optimization, and waste stream exchange by conducting thorough energy audits and heat integration studies. This retrofit approach allows companies to enhance their existing operations and infrastructure, making them more sustainable and resource-efficient without needing significant capital investments.

Moreover, applying Pinch technology in IS can also lead to the development of innovative collaborations and partnerships between companies. By understanding the heat and mass flows between different processes, companies can identify opportunities for joint projects and resource sharing, leading to mutual benefits and improved overall efficiency. This collaborative approach enhances the economic and environmental performance of individual companies and fosters a sense of collective responsibility toward sustainable development and resource conservation. While this collaborative approach can bring numerous benefits, some critics argue that it can also limit individual companies' autonomy and decision-making power, potentially hindering innovation and progress. Positive and negative experiences can have the way of integration that has been done between companies. As previously seen, creating integrated parts of different processes is accessible for continuous processes. This integration can work perfectly and synchronize.

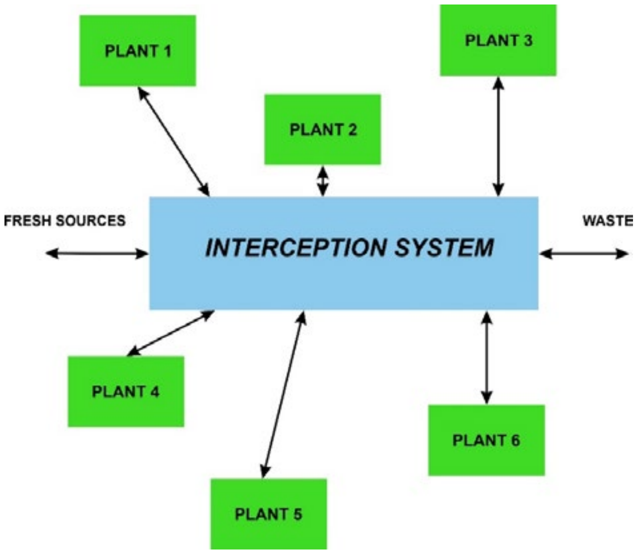
- Another question is: what if a malfunction happened in one of the integrated parts? That will stop the first process and automatically must be stopped the other integrated part. Therefore, the reserve plan must exist. The other integrated continuous process in heat exchange must have active connections with hot or cold utilities. In the moment of malfunction, the production cost will be increased. The integration of two continuous processes is robust and has no realization flexibility. What should be done for better flexibility? Flexibility makes all companies more independent in which parts are integrated. Therefore, flexibility can be higher if the system of integration, the system of symbiosis between companies, is based on batch processes or if there is some storage system between connected parts. Batch processes are time-dependent processes. So, they are active for a certain period. The source delivery from other companies does not need to be used when bringing it to the system. That means the source (heat, fuel, raw materials, water, etc.) can be delivered to storage, and the second or third system can take it without interruptions. In this case, the optimal costs can be achieved with good storage system design (the size, materials, connections, etc).

Storage systems make excellent flexibility between integrated systems. IS between companies is also questionable when companies have different rates of development. When one of the companies wants to increase its production size, it might need to deliver more sources from other companies' symbiosis. That means the companies must increase productivity or order the same resource outside the IS. From this point of view, integration and IS interrupt or stop the independency of other companies to increase the production capacity. This can lead to the destruction of IS, breaking or annulment of already signed contracts and agreements between companies.

El-Halwagi (2017) introduced a mass-integration model for the EIP problem that enables the exchange of wastes, byproducts, and fresh resources among multiple plants through a centralized facility, which facilitates the mixing of diverse streams and interception via separation and treatment units (as depicted in Figure 9). Lovelady and El-Halwagi (2009) proposed a procedure for designing EIP using mass integration, shown in Figure 10. They established the following steps: Extract process data set, set of sinks for each process (with mass flow F_{sink}, and component concentration $C_{c,sink}$), set of sources (wastewater, or similar, with mass flow F_{source}, and component concentration $C_{c,source}$), interceptors design, solving interceptors problem. Sets of processes and streams as sinks and sources should be extracted from the process flowsheet of all involved companies. All these selected streams are connected to the interceptor. An interceptor system should be designed based on the requirements of the processes involved and mass exchange or treatment systems. The design and alternatives of interceptors are generated on a few questions. El-Halwagi, Gabriel and Harell (2003) suggested the following questions as necessary for the design of interceptors: 1. Which streams should be recycled within the same process, and which streams should be sent to the EIP? What changes will they undergo in the EIP (e.g., mixing, separation, extent of separation)? 2. What interception technologies should be used? What are their tasks? Which streams should be assigned to these interception units? How much fresh should be used? Where? 3. How much waste should be discharged? Where?

Several graphical and algorithmic process integration techniques are developed for synthesizing cost-effective EIPs based on the answers to given questions. El-Halwagi (2017) suggested a graphical solution based on the material- recycle pinch diagram developed by Spriggs et al. Algorithmic and mathematical optimization approaches synthesize several types of EIP-design problems.

Figure 9. EIP mass integration suggested by Springgs



Source: adapted from El-Halwagi, 2017

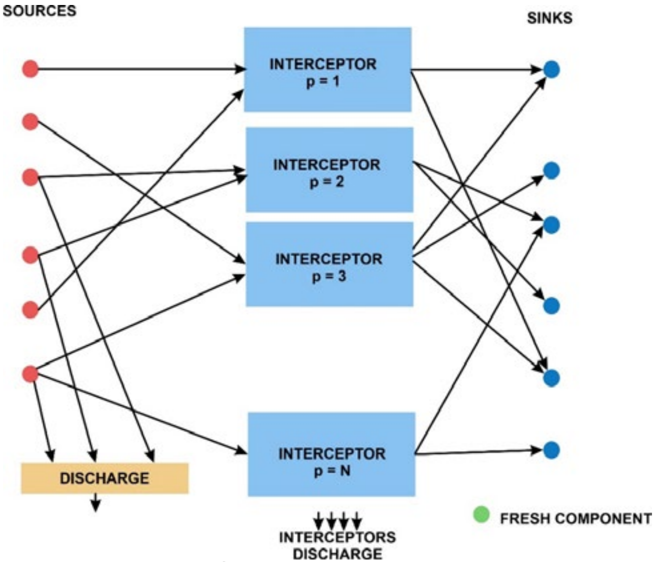
Optimization of costs for the interception system is based on Equation 7. Total Annualized Costs (TAC) depend on several interception units ($N_{interception}$), the amount of used fresh water (sink) streams and the amount of generated waste.

$$TAC_{\min} = \sum_{p=1}^{N_{interception}} Interception_{cost_p} + \mathrm{Price}_{fresh} \sum_{k=1}^{N_{sinks}} Fresh_k + \mathrm{Price}_{waste} \cdot F_{waste} \quad (7)$$

The analysis and design model developed by El-Halwagi is given in Figure 10. Furthermore, an additional method that employs chemical species as the foundation for integration involves the concept of carbon-hydrogen-oxygen symbiosis networks (CHOSYN), which was introduced by El-Halwagi (2017).

Moreover, the other standard organizational segments can be more easily managed than connected production processes. That is familiar transportation, transportation based on renewables, logistics, standard SC management, and even having a typical building for offices of administration and management with all other facilities needed.

Figure 10. Interaction system between sinks, sources and interceptors for creating an EIP



Source: adapted from Lovelady and El-Halwagi, 2009

CONCLUSIONS

Pinch technology analyses material and energy flows within industrial processes to optimize material, water, and energy streams, leading to cost savings and resource conservation. The principles of Pinch technology can be applied in various areas, such as waste management, energy recovery, and SC optimization. The review compares the Pinch technology steps for all its currently applied usage and connects it to IS in practice. IS involves companies within an IP collaborating and sharing resources to maximize the utilization of available resources before seeking external resources. The implementation of Pinch technology in the design of IS can be faced with many different problems. That is the reason for being careful with the approach used in design. Integrating systems gives many benefits, such as cost reduction, increased energy efficiency, and minimizing waste (waste heat, waste materials, wastewater). The interconnection of systems must be flexible for better work independence in symbiotic companies. That required additional equipment such as storage systems for heat storage, electricity storage (batteries), and material storage (reservoirs, tank storage, warehouses, etc.). Interconnection flexibility is better in discontinuous relations between companies or when emergency systems are activated in case of problems with the export/import of heat, materials, byproducts, etc.

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