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How Digital Technologies enable Industrial Symbiosis: findings from Italian and European practices.

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Abstract

This thesis investigates the synergies between digital technologies and industrial symbiosis, exploring the potential of various technologies in fostering sustainable industrial practices. The assessment begins with an investigation into the role of policymakers, elucidating incentives through legislation and policies from both European and Italian perspectives, with a focus on initiatives fostering symbiosis and promoting the integration of digital technologies. Subsequently, an initial literature review is performed to meticulously explore both the foundational concepts of industrial symbiosis and the varied landscape of digital technologies. A detailed examination of how literature has assessed the primary research question of this study so far: How do digital technologies enable industrial symbiosis? is then developed, leading to an in-depth discussion of the findings exhibited in Table 3a and 3b.

This final review highlights several notable gaps in the existing works, the main one being the lack of real cases evaluated for the assessment of the previously stated research query. Aiming to contribute to this evolving field, the evaluation shifts focus to the Italian context, presenting an analysis of active industrial symbiosis practices and the role played by the digital technologies that have been effectively adopted within this context. The primary discovery from this analysis is that Italian companies have a limited level of digitalization, with Digital Platforms, traditional and enhanced with Blockchain or AI, emerging as the most widely adopted technology within the real business landscape of Italy, right after cloud technologies, finding that classifies as an initial contribution of this research to literature.

To gain a better understanding of how these technologies practically enable industrial symbiosis, 6 real case studies of companies operating within the Italian and European context are evaluated with interviews being conducted as a primary method of data collection. To conclude, a theorical and practical comparison is presented, evaluating the alignment between the barriers, advantages, and drivers to digital technologies identified in literature and those experienced by companies in real life, which categorizes as the secondary contribution of this research to the existing body of literature. Additionally, relevant insights obtained directly "from the field" are provided along with the conclusions of the research, encapsulating the main outcomes derived from the study and considerations for further explorations in the field.

Keywords: Industrial Symbiosis, Circular Economy, Digital Technologies, Digital Platforms, Real Life Practices.

Abstract in italiano

Questa tesi investiga le sinergie tra le tecnologie digitali e la simbiosi industriale, esplorando il potenziale di varie tecnologie nel promuovere pratiche industriali sostenibili. La valutazione inizia con un'indagine sul ruolo dei responsabili politici, chiarificando gli incentivi attraverso legislazioni e politiche sia dal punto di vista europeo che italiano, con un'attenzione alle iniziative che promuovono la simbiosi e favoriscono l'integrazione delle tecnologie digitali. Successivamente, viene condotta una revisione iniziale della letteratura per esplorare attentamente sia i concetti fondamentali della simbiosi industriale che il variegato panorama delle tecnologie digitali. Viene quindi sviluppato un esame dettagliato su come la letteratura ha valutato la domanda di ricerca principale di questo studio fino a questo punto: come le tecnologie digitali abilitano la simbiosi industriale? portando a una discussione approfondita dei risultati presentati nella Tabella 3a e 3b.

Questa revisione finale evidenzia diverse lacune nelle opere esistenti, la principale delle quali è la mancanza di casi reali valutati per la risposta alla domanda di ricerca precedentemente enunciata. Per contribuire a questo campo in evoluzione, la valutazione si sposta sul contesto italiano, presentando un'analisi delle pratiche attive di simbiosi industriale e il ruolo svolto dalle tecnologie digitali che sono state adottate in questo contesto. La scoperta principale da questa analisi è che le aziende italiane hanno un livello limitato di digitalizzazione, con le Piattaforme Digitali, tradizionali e potenziate con Blockchain o IA, che emergono come la tecnologia più ampiamente adottata nel panorama aziendale italiano, subito dopo le tecnologie cloud, scoperta che classifica come un contributo iniziale di questa ricerca alla letteratura.

Per comprendere meglio come queste tecnologie abilitino concretamente la simbiosi industriale, vengono valutati 6 casi reali di aziende operanti nel contesto italiano ed europeo, con interviste come metodo principale di raccolta dati. Per concludere, viene presentata una comparazione teorica e pratica, valutando l'allineamento tra le barriere, i vantaggi e i driver delle tecnologie digitali identificati nella letteratura e quelli sperimentati dalle aziende nella vita reale, classificandosi come contributo secondario di questa ricerca alla letteratura esistente. Inoltre, vengono forniti approfondimenti rilevanti ottenuti direttamente "dal campo", insieme alle conclusioni della ricerca, che racchiudono i principali risultati derivati dallo studio e le considerazioni per ulteriori esplorazioni nel campo.

Parole chiave: Simbiosi Industriale, Economia Circolare, Tecnologie Digitali, Piattaforme Digitali, Pratiche Reali.

Contents

1 Introduction

A symbiosis is defined as a biological phenomenon denoting the "association of individuals of different species in a relationship where there is mutual benefit." This concept has transcended the confines of nature to shape a paradigm shift in the industrial landscape—Industrial Symbiosis (IS) [1]. Rooted in the principles of mutual benefit, IS involves a collective approach among traditionally separate industrial entities, fostering the exchange of materials, energy, water, and by-products to achieve a competitive advantage [2]. This concept, identified almost a decade ago as both a business opportunity and a catalyst for eco-innovation, seeks not only to optimize production efficiency but also to instigate mutual benefits across economic, environmental, and social dimensions [3]. The depletion of natural resources looms as a significant global environmental challenge, impacting the well-being of an expanding population and intensifying global inequalities. The environmental repercussions of existing consumption and production patterns, exacerbated by the globalization of production chains and trade, necessitate the implementation of sustainable consumption and production policies [4]. Industrial Ecology (IE), advocating for the reduction of virgin material and energy inputs through the utilization of waste, by-products, and waste energy, emerges as a viable solution [5]. Within the realm of IE, IS and eco-industrial parks (EIPs) assume pivotal roles, fostering the localized exchange of resources among entities and embodying the principles of a sustainable industrial ecosystem. Industrial symbiosis, as a concept, presents three primary opportunities for resource exchange: by-product reuse, utility/infrastructure sharing, and joint provision of services [6]. This application of the concept not only promotes the more sustainable use of materials but also actively contributes to the establishment of a circular economy.

This thesis embarks on a comprehensive exploration of the practical applications of digital technologies for IS. This includes presenting interviews conducted in Italian and European industrial scenarios, accompanied by an in-depth analysis of their impacts and barriers. Key drivers encompass resource efficiency, geographical proximity, legislation, and policies, all propelled by the common motivation to curtail raw material and waste-disposal costs while unlocking avenues for potential revenue generation [7]. Conversely, barriers to IS include environmental, economic, technical, regulatory/legal, social, and cultural dimensions.

The paper is organized into specific chapters to delve into this intersection of symbiosis and digital technologies. Chapter 2 explores the role of policymakers in incentivizing symbiosis through legislation and policies, offering both European and Italian perspectives. Chapter 3 presents a comprehensive literature review on how digital technologies enable industrial symbiosis, setting the stage for a detailed exploration in the subsequent sections. Chapters 4 and 5 focus on the evaluation of digital technologies enabling industrial symbiosis in the Italian context and the findings of real case studies implementing these technologies within both the Italian and European frameworks. Chapter 6 further examines how digital technologies enable industrial symbiosis, providing theoretical insights and comparisons derived from real-world experiences. Finally, Chapter 7 offers concluding remarks, synthesizing the insights gained from the exploration of industrial symbiosis, digital technologies, their interplay, and suggestions for future research.

2 Role of policy makers: Incentives through legislation and policies

In this chapter the role of policymakers is assessed, elucidating incentives through legislation and policies from both European and Italian perspectives, with a focus on initiatives fostering symbiosis and promoting the integration of digital technologies.

2.1. Industrial Symbiosis implementation incentives

2.1.1. Europe

Within the European Union (EU), industrial symbiosis developments have been highly recognized as a tool to achieve a more Circular Economy (CE) [8]. In this sense, the aim is to disseminate new business models and bolster the market for recycling by-products. This endeavour is intended to promote the adoption of more sustainable methods of manufacturing across European businesses at large [9]. The EU is steadfast in its long-term commitment to not only reduce waste production but also to repurpose waste as a valuable resource. The main goal is to transform Europe into a "recycling society," characterized by a dual approach: minimizing waste production and harnessing generated waste as a resource. Various directives, communications, and funded programs from the European Commission specifically focus on industrial symbiosis [10]. The communication titled "Roadmap to a Resource Efficient Europe" serves as a strategic guide to ensure the sustainable management of resources while fostering economic growth [11]. Likewise, the document "Closing the Loop—An EU Action Plan for the Circular Economy" underscores the significance of industrial symbiosis through collaborative efforts with EU member states to promote it [12]. Directive 2018/851 on waste is geared towards enhancing the efficiency of waste management, actively encouraging EU member states to adopt and implement industrial symbiosis practices [13]. In addition, the importance of IS is underlined by the “Circular Economy Action Plan” [14], which is one of the main building blocks of the European Green Deal, the new agenda of Europe for sustainable growth. The Circular Economy Action Plan of 2015, implemented by the EU, outlined 54 activities and four legislative proposals to shift from a linear to a circular economic model. It established targets for landfill, reuse, and recycling by 2030 and 2035, incorporating obligations for the separate collection of textiles and biowaste. Encompassing diverse policy areas, material flows, and sectors, the plan aimed for systemic change through innovation and investments, including a dedicated strategy for plastics. By 2019, all 54 actions were successfully implemented, solidifying the EU's leadership in circular economy policymaking. Moreover, the action plan inspired 14 Member States, eight regions, and 11 cities to adopt their own circular economy strategies [15]. The Green Deal strategy and the concept of CE concern more sustainable management of materials and resources, as well as more rational practices in waste management and recycling [16].

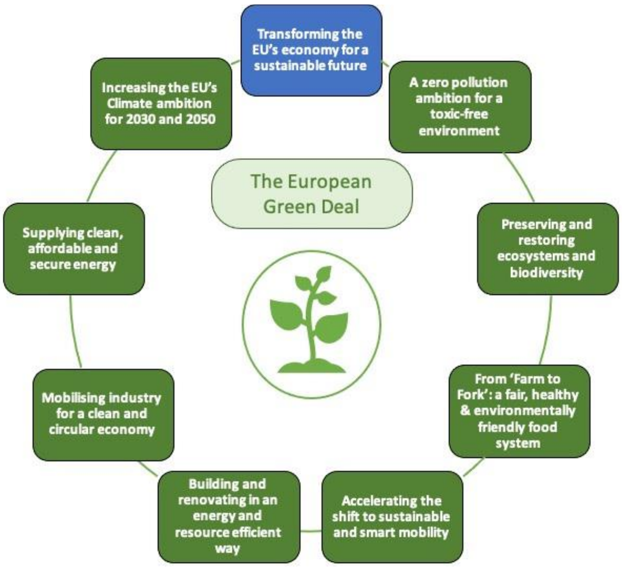

Figure 1. Elements of the European Green Deal [10]

The EU faces the challenge of effectively implementing CE and the Green Deal strategy, with a primary emphasis on achieving elevated levels of recycling for critical raw materials. This initiative envisions the implementation of a new legally binding climate law with the ambitious goal of achieving a complete reduction in net emissions of greenhouse gases by the year 2050 [17]. Additional focal points include fostering deeper stakeholder involvement and cultivating greater ecological awareness among enterprises operating in the raw-materials sector. In alignment with these objectives, the preceding European strategy, "Europe 2020," also underscored the importance of rational resource management. This strategy was organized around three core priorities: (1) smart growth, rooted in knowledge and innovation; (2) sustainable growth, centered on advancements in resource efficiency and the cultivation of a more environmentally friendly and competitive economy; and (3) inclusive growth, directed towards fostering a high-employment economy with social and territorial cohesion [18]. The Green Deal strategy and Circular Economy model share the common goal of conserving resources within the economy as product life cycles conclude. This objective is achieved by facilitating sustainable reuse and generating additional value from these resources. Effecting this transition necessitates transformative shifts in the entire value chain, spanning from product design to the development of innovative business and market models [19]. The European industrial strategy aims to enhance resilience and promote Europe's competitiveness, enabling the European industry to lead the green and digital transformation and become a global driving force in the transition to climate neutrality and digitalization. Decoupling economic growth from resource use and transitioning to circular systems of production and consumption are fundamental for achieving the EU's climate neutrality by 2050. In March 2020, the Commission introduced a new Circular Economy Action Plan, which the Council adopted conclusions on in December 2020. These conclusions underscore the role of the circular economy in ensuring a green recovery from COVID-19. Achieving climate neutrality by 2050 will pose different challenges for some Member States and regions than for others. For instance, some are more reliant on fossil fuels or have high-carbon-intensive industries employing a significant number of people. Therefore, the EU has introduced a Just Transition Mechanism to provide financial support and technical assistance to regions most affected by the transition to a low-carbon economy. The mechanism aims to mobilize at least EUR 65-75 billion in the period 2021-2027 for individuals, communities, businesses, Member States, or regions. With a total allocation of EUR 17.5 billion, the Just Transition Fund is the primary component of the mechanism, offering tailored support to mitigate the socioeconomic costs of the green transition for regions dependent on fossil fuels and high-emission industries. Notably, the European Circular Economy Stakeholder Platform, established in 2017 following recommendations from the European Economic and Social Committee, plays a crucial role. It is a collaborative effort between the European Economic and Social Committee and the European Commission, with a key success factor being the partnership between institutions, ensuring the active involvement of civil society actors in the transition process. Additionally, the Strategic Research and Innovation Agenda, launched in 2015, addresses the urgent need for comprehensive and interdisciplinary research to support European cities in maximizing sustainability, resilience, and livability amidst global competition. This agenda focuses on guiding urban innovation and technologies.

The European Union as a supra-national institution wields influence over policies in most of its member countries. In the realm of waste management, the Thematic Strategy on the Prevention and Recycling of Waste serves as a comprehensive framework encompassing key policies, overarching objectives, and guiding action principles. These principles entail, firstly, the imperative to manage waste in a manner that avoids detrimental effects on the environment or human health. Secondly, the strategy emphasizes the hierarchy of selecting the most environmentally sound options in waste management, ranging from prevention to disposal [20]. Europe has additionally established European support networks for industrial symbiosis and fostered European innovation partnerships. These initiatives include international programs like FISSAC, national programs such as NISP in the United Kingdom, regional programs exemplified by Cleantech Östergötland in Sweden, and local programs like the one in Dunkerque, France. The overarching challenge is evident: the European economy necessitates a profound transformation within a generation. This transformation spans various sectors, including energy, industry, agriculture, fisheries, and transportation systems, and requires significant shifts in both producer and consumer behavior [21].

2.1.2. Italy

Italian legislative efforts have aimed to cultivate a synergistic relationship among industries, emphasizing resource efficiency and waste reduction. This legislative review explores the key frameworks and policies driving the adoption of industrial symbiosis in Italy.

Italy has implemented a range of policy measures to embrace CE within the nation, exemplified by the enactment of Law 221 on December 28, 2015, alongside other legislative decrees [10]. These decrees provide definitive guidelines and criteria, addressing aspects such as the computation of differentiated collection rates for municipal solid waste and the criteria governing the eco-design of Waste Electrical and Electronic Equipment. Additionally, a recent document titled "Towards a model of Circular Economy for Italy," jointly authored by the Ministry of Environment and the Ministry of Economic Development, elucidates Italy's strategic stance on CE.

A by-product refers to a secondary or incidental product that is generated during the production or processing of a primary product. By-products often have value or utility and can be used, sold, or recycled. In the context of waste management and environmental sustainability, the distinction between by-products and waste is often defined by specific criteria and regulations.

Legislation pertaining to by-products in Italy is delineated in articles 183 and 184-bis of Legislative Decree n. 152/2006 [22]. In 2016, the Ministry of the Environment issued Decree n.264 on October 13, 2016, titled "Regulation containing indicative criteria to facilitate the demonstration of the existence of the requirements for the qualification of production residues as by-products and not as waste" [23]. Moreover, Ministerial Decree n.264/16, aimed at facilitating the transfer and sale of by-products, mandates the establishment of a public list of by-products at the Chambers of Commerce. Producers and users have the option to register on this list, although registration is not a prerequisite for authorization. Instead, it serves a merely informative function, enhancing the ease of exchanges. Given that the regulations concerning by-products are exceptional and deviate from conventional waste rules, the burden of proof pertaining to the conditions rests with those producing the residue and managing it as a by-product [24].

In response to an unprecedented crisis triggered by the pandemic, Italy's Recovery and Resilience plan aims to propel a robust recovery and equip the country for the future.

With a focus on sustainability and resilience, the program allocates 2.1 billion towards Circular Economy initiatives. These strategic reforms and investments are instrumental in steering Italy towards a more sustainable and resilient future, effectively positioning it to navigate the challenges and opportunities presented by the green and digital transitions. The outlined reforms specifically target impediments to enduring and sustainable growth, while investments are strategically directed to facilitate the digital and green transitions, as well as address social and territorial disparities. All proposed reforms and initiatives are subject to a stringent timeframe, requiring implementation by August 2026, as mandated by the Regulation on the Recovery and Resilience Facility. In the subject of climate and environmental policies, Italy's endeavors include advancements in waste management, optimization of water resources and the enhancement of energy efficiency in buildings [25].

The National Strategy for the Circular Economy

During the G7 Environment Presidency in Bologna in June 2017, Italy advocated for a collaborative plan to address resource efficiency and the circular economy. The G7 Environment Ministers, recognizing the significance of resource efficiency in sustainable development goals, committed to sharing metrics, identifying measurement gaps, and developing new indicators. They also pledged to share information on sustainable materials management globally, collaborate on a comprehensive analysis of the macroeconomic impacts of resource efficiency, and involve citizens, particularly the youth, in transitioning toward a more circular and resource-efficient economy.

The National Strategy for the Circular Economy seeks to enhance the competitiveness of secondary raw materials by introducing administrative and fiscal tools, making them comparable to virgin raw materials in terms of availability, performance, and costs [26]. The strategy influences various aspects, including green purchases in the Public Administration, criteria for defining the end of waste, extended producer responsibility, consumer roles, and the promotion of sharing practices and the "product as a service" model. It serves as a crucial tool for achieving climate neutrality objectives and outlines a roadmap with measurable targets until 2035. The Ministry for the Ecological Transition conducted a public consultation on the strategy's programmatic guidelines, structured into five sections, gathering over 100 contributions by the deadline of November 30, 2021. Italian circular economy projects in the National Recovery and Resilience Plan aim to address structural gaps hindering development. Challenges include shortcomings in waste treatment facilities, regional disparities, the need for modernization, inadequate collection systems, and the importance of preventing illegal waste disposal. The projects aim to extend beyond 2026, with ambitious goals for reducing plastic waste and microplastics by 2030 and mid-century. The success of these measures depends on technologically advanced solutions and centralized governance to strengthen local policies in implementing circular infrastructure.

Mission 1 focuses on digitalization, innovation, competitiveness, culture, and tourism. Under Tourism and Culture (M1C1), there is a reform initiative to adopt minimum environmental criteria for cultural events. Mission 2, centered around the Green Revolution and Ecological Transition, includes efforts for sustainable agriculture and the circular economy (M2C1). This involves reforms in the national strategy for the circular economy, waste management, and technical support to local authorities. Additionally, there are investment initiatives for establishing new waste management facilities, modernizing existing ones, and implementing "flagship" circular economy projects. In the domain of Energy Efficiency and Building Redevelopment (M2C3), there is a reform initiative related to the management of construction waste according to circular economy principles [26].

The European Commission has identified issues in waste management across several Italian regions, emphasizing the absence of an integrated waste collection and treatment network due to insufficient planning and weak governance. Legislative changes introduced a new national-level planning tool, Article 198-bis of Legislative Decree no. 152/2006, to address these shortcomings. The National Waste Management Program aims to contribute to resource sustainability, reduce environmental impacts, address socio-economic disparities, promote awareness, and support waste management contributing to climate neutrality. This program prioritizes overcoming the regional gap in waste management infrastructure, ensuring nationwide integrated waste management in line with European goals. Macro-objectives include reducing planning disparities, achieving socio-economic balance, optimizing the infrastructure system sustainably, meeting waste management goals, ensuring high-quality plant provision, promoting climate-neutral waste management, and defining priority actions for environmental communication and awareness in waste and circular economy matters. Prevention, which is positioned at the top of the hierarchy defined in Article 179 of Legislative Decree 152/2006, involves the adoption of anticipatory measures aimed at reducing waste production. This includes measures such as the reuse of products or extending their lifecycle, as well as addressing the negative impacts they may have on the environment and human health.

In 2020, the Italian Circular Economy Stakeholder Platform (ICESP) identified the establishment of a National Program for businesses as a priority in its document "ICESP Priorities for a Post-COVID-19 Recovery." The aim was to support the creation of industrial symbiosis processes and the eco-industrial conversion of production areas in the country, integrated with a series of fiscal incentives (and disincentives) to promote these pathways. The envisioned National Industrial Symbiosis Program, with territorial articulations, is to be based on a common language and tools to maximize resource and knowledge sharing opportunities. Expanding the existing by-products platform to include secondary raw materials could assist symbiosis processes. In line with this perspective, the National Recovery and Resilience Plan proposes reforming the existing circular economy strategy, introducing concrete measures to support industrial symbiosis projects through specific regulatory and financial instruments [26]. The goal is to enhance the use of recycled or secondary raw materials in the industrial process through industrial symbiosis practices. This orientation calls for a systemic approach where all stakeholders must create partnerships along the value chain. Stable cross-sector contacts and relationships between business associations, consortia, management entities, control bodies, and research institutions need to be incentivized through financial and legislative instruments. In the Italian context, some key players facilitating the diffusion of industrial symbiosis include ENEA (the National Agency for New Technologies, Energy, and Sustainable Economic Development), which focuses on research, technological innovation and sustainable economic development and SUN (Symbiosis User Network) that actively promotes circular economy models through industrial symbiosis, addressing legislative, standard, market, and best practice issues [26].

These initiatives should encourage synergies and interactions among various involved entities to maximize the impact of adopted measures. Such efforts should be promoted both at a general level and within different industrial sectors and production chains, fostering the exchange of information and ideas and integrating various specific actions and projects into a common and global logic.

2.2. Digital technologies implementation incentives

2.2.1. Europe

In the ever-evolving landscape of technological advancements, understanding the policy frameworks that govern digital technologies becomes paramount for a comprehensive evaluation of their impact. This section delves into an overview of the digital policies established in Europe, providing a contextual foundation for the subsequent assessment of digital technologies. Europe, as a prominent player in the global technological arena, has laid down a multifaceted framework that not only navigates the complexities of innovation but also endeavors to balance technological growth with ethical considerations, privacy concerns, and societal well-being. An exploration of these policies is instrumental in understanding the legislative context against which digital technologies operate, offering crucial insights that shape the discourse on their efficacy, ethical implications, and potential societal ramifications.

EU Digital Strategy

In an era where the internet and digital technologies are reshaping the global landscape, establishing a Europe suited for the digital era stands as one of the

European Commission's six primary political objectives. Indeed, in March 2021, the Commission put forth a strategy for the Digital Decade, driven by the 2030 Digital Compass, an initiative that outlines a comprehensive plan to realize the digital transformation of the European Union's economy and society [27].

The Digital Compass seeks to establish a secure and human-centered digital environment, empowering citizens and fostering the prosperity of businesses through digital capabilities. The Compass outlines four key directions for this journey: digital skills, secure and performant digital infrastructure, digital transformation of businesses and the digitalization of public services (Figure 2). This political agenda is in harmony with EU norms and standards, aimed at reinforcing the digital sovereignty of the EU. Various budgetary instruments will provide the necessary financial support to lay robust foundations for Europe's Digital Decade. The agenda advocates for an increased focus on efforts initiated in the preceding decade to expedite the digital transformation of Europe, leveraging advancements made toward the establishment of a fully operational Digital Single Market [27].

The Digital Single Market Strategy of the European Union laid the groundwork for enhanced digital harmonization among EU Member States. Introduced in 2015, its objective was to foster economic growth by promoting jobs, competition, investment, and innovation within the EU. This strategy was built upon three fundamental pillars:

“-Access: better access for consumers and businesses to digital goods and services across Europe.

-Environment: creating the right conditions and a level playing field for digital networks and innovative services to flourish.

-Economy & Society: maximizing the growth potential of the digital economy” [27].

Given the EU's emphasis on digital matters, fostering a more unified digital landscape is also a focal point for countries that are strategic partners of the EU. The objectives of the Eastern Partnership policy beyond 2020 incorporate specific actions aimed at advancing the Digital Single Market. These actions encompass investments in competitive and innovative economies, the development of knowledge societies, strengthening security and cyber resilience, and promoting digital transformation [27].

Europe’s Digital Decade: Digital Targets for 2023

Europe aspires to enhance the capabilities of businesses and individuals, fostering a digital future that is centered around humanity, sustainability, and increased prosperity. In this sense, the policy program of the Digital Decade, outlining specific targets and objectives for 2030, directs the digital transformation of Europe through the previously mentioned Digital Compass, which is presented below.

Figure 2. The Digital Compass [28].

The 2030 Digital Decade policy program establishes a yearly collaborative cycle to accomplish shared objectives and targets, implementing a governance structure built on an annual cooperation mechanism that engages both the Commission and Member States. The cooperation mechanism consists of:

-A systematic, transparent, and collaborative monitoring system, utilizing the Digital Economy and Society Index, employed to assess advancements toward each of the 2030 objectives.

-A yearly report issued by the Commission through which progress is assessed and recommendations for actions are offered. The initial 'Report on the state of the Digital Decade' was released in September 2023.

-Every two years, revised strategic roadmaps for the Digital Decade, where Member States delineate actions either adopted or planned to achieve the 2030 targets.

-A mechanism designed to aid the execution of multi-country projects, known as the European Digital Infrastructure Consortium [28].

The Commission has formulated trajectories at the EU level. Baseline trajectories depict the anticipated progress of the EU in line with existing trends, while projected trajectories delineate the yearly progression required to meet the 2030 targets. Monitoring the variance between estimated trends and the ideal path will enable the Commission to assess the gap in the required effort. A review of the targets is slated by 2026, considering technological, economic, and societal developments [28].

In this context, the building blocks of the Digital Compass and the goals intended to be achieved in each of them are displayed through Figure 3 below.

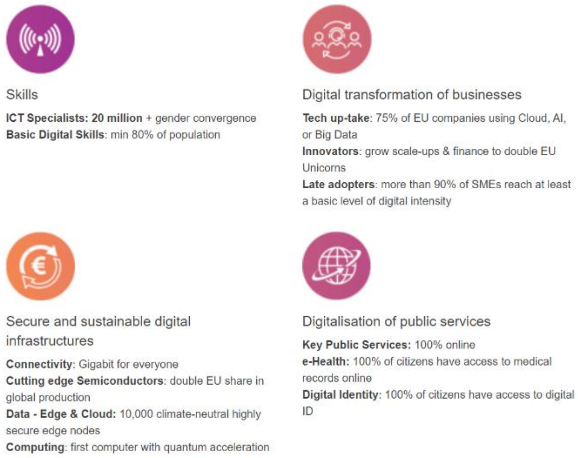

Figure 3. Components of the Digital Compass [28].

Digital Rights and Principles

On December 15, 2022, Ursula von der Leyen, the President of the European Commission, signed the European Declaration on Digital Rights and Principles. This endorsement was a collaborative effort, involving the President of the European Parliament, Roberta Metsola, and Czech Prime Minister Petr Fiala, who held the rotating Council presidency at the time.

Introduced by the Commission in January 2022, the Declaration underscores the EU's dedication to a secure, safe, and sustainable digital transformation, prioritizing people and aligning with fundamental EU values and rights [28]. These digital rights are constituted by:

-People at the center: Digital technologies ought to safeguard individuals' rights, uphold democratic principles, and guarantee responsible and secure conduct by all digital entities. The European Union advocates for these values globally.

-Freedom of choice: Individuals deserve to experience fairness in the online space, remain protected from illicit and harmful content, and feel empowered in their interactions with emerging technologies such as artificial intelligence.

-Safety and security: The online space must ensure safety and security, empowering and safeguarding users of all ages, from childhood to old age.

-Solidarity and inclusion: Technology ought to bring people together instead of creating divisions. Universal access to the internet, digital skills, digital public services, and equitable working conditions should be available to all.

-Participation: Citizens should have the ability to participate in the democratic process at various levels and exercise control over their personal data.

-Sustainability: Digital devices ought to contribute to sustainability and the shift towards environmentally friendly practices. Users should be informed about the ecological footprint and energy usage of their devices.

The initial evaluation of the application of digital principles is outlined in the 2023 Digital Decade Report. Additionally, the Commission is overseeing an annual Eurobarometer survey to track the progress of the measures taken by Member States. The inaugural Eurobarometer survey of this kind was released in June 2023 [28].

2.2.2. Italy

Exploring the digital landscape in Italy requires the understanding of the rules that guide technology use in the country. Italy, with its rich culture and growing tech scene, has specific regulations to manage the challenges and benefits of the digital age. This section introduces an overview of these policies, setting the stage for a closer look at how digital technologies operate in Italy. As the country aims for innovation while considering ethics and societal well-being, understanding these policies becomes crucial. In this sense, exploring the regulatory framework provides insights into how Italy manages digital technologies, laying the foundation for a detailed evaluation of their impact and relevance in the Italian context.

As a starting point, according to Eurostat, merely 42% of Italians aged between 16 and 74 possess fundamental digital skills, lagging behind the EU average of 58%, which significantly impacts the utilization of digital services. In the European context, Italy ranks lowest in terms of internet usage, with 17% of individuals aged 16 to 74 having never accessed the internet, nearly double the EU average of 9% based on Eurostat's 2019 data. Moreover, the statistics reveal that only 1% of Italian graduates hold an Information and Communications Technologies (ICT) qualification, placing Italy at the bottom in the EU. Although the percentage of ICT specialists in Italy has increased over time, reaching 3.6% of total employment, it still falls below the EU average of 4.2% [29].

The absence of digital skills stands as a primary barrier to the nation's progress. Addressing this limitation should be a top priority because:

-It adversely affects the delivery of digital services by both the public and private sectors, as well as citizens' access and utilization.

-It places a considerable portion of the population at risk of social and labor market exclusion.

-It impedes access to public participation and consultation.

-It elevates the likelihood of citizens being exposed to widespread misinformation [29].

Digital Italy 2025

Recognizing the significant impact of the deficiency in digital skills, the development of a comprehensive strategy to address and mitigate these challenges becomes imperative for fostering inclusivity and enhancing societal resilience. In this context, the strategy Digital Italy 2025 has been drafted, which outlines a distinct trajectory for "inclusive and sustainable development," charting a path that addresses the imperative of ethical, inclusive, transparent, and sustainable innovation for societal well-being. This vision involves: endeavors to enhance the digital skills of the population, a commitment to ethical, responsible, and non-discriminatory technological advancements ensured by the state and providing citizens with opportunities for lifelong learning to access future job opportunities [29].

Within this framework, the basic principles of the Digital Italy 2025 strategy are:

-Digital Education: Proficiency in computer culture and digital skills stands as a fundamental prerequisite for comprehensive citizenship. Both public and private sectors should allocate investments toward skill development, recognizing their pivotal role in driving growth, enhancing competitiveness, generating public value, and fostering the overall well-being of the nation. Moreover, educational institutions such as schools and universities, along with media outlets, should actively contribute to combatting various forms of digital illiteracy.

-Digital Citizenship: The integration of digital technology has the potential to cultivate a new paradigm of citizenship characterized by access to quality information, active participation in deliberative processes, civic engagement, and a more efficient relationship between citizens and public administration. By prioritizing citizens' rights, digital technology can serve as a common language in the interaction among citizens, public administrations, and businesses, thereby contributing to the reduction of societal inequalities.

-Ethical, Human, and Non-discriminatory Digital: The digital realm presents an opportunity for fostering equality and community and individual growth. Both public and private entities should actively contribute to dismantling various barriers—be they social, economic, geographical, technological, or cultural—that perpetuate inequality among citizens. This effort should extend beyond the utilization of digital services to encompass equal access to the opportunities presented by the digital era [29].

Italy’s Industria 4.0 Plan

In the rapidly evolving landscape of manufacturing, Italy’s Industria 4.0 Plan emerges as a pivotal initiative. Addressing the imperatives of the fourth industrial revolution, this plan strategically advocates for the integration of cutting-edge manufacturing technologies such as the Internet of Things (IoT), big data, and Artificial Intelligence

(AI). It is particularly relevant in enhancing the competitiveness of Italian industries, fostering innovation, and propelling them into a technologically advanced and interconnected future [30].

Due to Industria 4.0, Italy boasts one of the world's most appealing fiscal frameworks for innovative companies. The tax incentives are crafted to be effortlessly accessible to all types of companies, minimizing ambiguity and bureaucratic procedures. Complementing this, various other industrial policy measures are in place to assist a broad spectrum of companies, spanning from emerging startups to well-established multinational corporations.

The fundamental elements of the Industria 4.0 plan are encapsulated in the five fiscal measures outlined below:

1) Tax incentives for investments in innovative startups and Small and Medium Enterprises (SMEs): Both individuals and legal entities making investments in innovative startups and SMEs in Italy enjoy a significant reduction in Italian income tax, with individuals benefiting from an IRPEF allowance and corporations from an IRES deduction. This advantage equals 30% of the invested amount for both categories, capped at €1 million annually for individuals and €1.8 million for companies. The incentive extends to investments in Italian venture capital funds, and other entities primarily involved in investing in innovative startups and SMEs [30].

2) Super-depreciation: Involves a 40% increase in the standard depreciation deduction for investments in new industrial machinery, resulting in a proportional increase in acquisition costs for accounting purposes. As assets undergo fiscal depreciation over time, this results in a significant and enduring decrease in taxable income, consequently lowering the effective tax rate [30].

3) Hyper-depreciation: Much like the previous case, hyper-depreciation entails a significant 150% increase in the regular depreciation deduction. This substantial elevation in the acquisition cost, computed for accounting purposes, leads to a considerable decrease in the tax liability over an extended period. This incentive is targeted at specific industrial equipment characterized by an "Industry 4.0" nature (e.g., machinery capable of exchanging information with other systems through the Internet of Things). The objective is to incentivize companies to invest in the digital transformation of their production processes and supply chains [30].

4) Tax credit for Research and Development (R&D): Firms augmenting their R&D spending between 2017 and 2020 enjoy a 50% tax credit on the additional expenses incurred during this period, known as the incremental credit, with an

annual limit of €20 million. This incentive covers basic research, industrial research, and experimental development, encompassing personnel expenses, research agreements with other entities, and intellectual property costs [30].

5) Patent Box: This special fiscal arrangement involves a 50% reduction in corporate tax on income generated from the direct and indirect utilization of intangible assets, such as industrial patent rights, industrial design and models, know-how, and copyrighted software. To qualify for this benefit, there must be a direct connection established between R&D activities, qualified intellectual property, and the income generated, following the "nexus approach"[30].

3 Literature Review

3.1. Methodology for Literature Review

Before delving into the analysis of how digital technologies enable industrial symbiosis, it's fundamental to firstly state that this study employs the Systematic Literature Review (SLR) approach to perform a review that is both reproducible and transparent [31], [32]. The structured methodology illustrated in Figure 4 was followed to find and choose the appropriate studies.

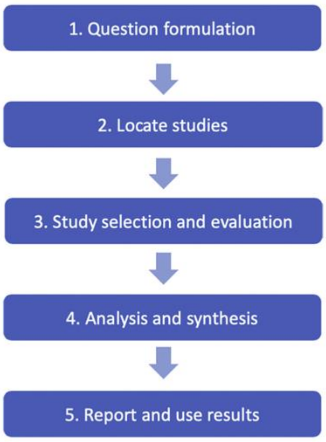

Figure 4. SLR methodology [32].

In addition to academic research, non-traditional sources of information, known as grey literature, were incorporated in this study. This was mainly done since grey literature often contains the most recent information, offering updates that might not yet be formally published in academic journals or books. Furthermore, it can also provide a more comprehensive understanding of practical applications, policies, and real-world data of industrial symbiosis, digital technologies and how the latter could facilitate the former.

Question Formulation

The core review question formulated was: How do Digital Technologies enable Industrial Symbiosis?

In this context, secondary questions were developed whose purpose was to provide a comprehensive understanding of the two main elements composing the primary query. These additional interrogations are:

1) What is Industrial Symbiosis? Which are the key concepts encompassed by this topic? Which are the barriers to its implementation?
2) What is a Digital Technology? Which are the most relevant digital technologies nowadays? Which are the advantages and disadvantages of the most relevant digital technologies?

Location of Studies

This subsection aims to present the search engines and search strings employed for the collection of relevant information required to answer the questions previously formulated.

ScienceDirect, Scopus and Google Scholar were used to identify scientific papers related to industrial symbiosis, digital technologies and how the latter could facilitate the former. ScienceDirect was chosen because it provides access to a vast collection of high-quality scientific articles, journals, and books covering research related with the themes being explored in this review. In accordance with this, Scopus was selected mainly since it is the largest citation and abstract database of scientific and academic content [32]. Finally, Google Scholar was employed not only because it provides a significant collection of research articles but also because of its reach: it includes research that has been published through diverse scientific journals, and thus, an even deeper understanding of how literature has approached the topics under review could be obtained.

The standard Google search engine was additionally employed to find grey literature sources like consulting reports and company information that helped obtain an up-to-date perspective on the reviewed topics.

The search strings applied to locate the relevant studies in the previously stated search engines are presented in Table 1 below. It's important to note how, in the case of the secondary questions, some outputs of the first part of the overall question served as inputs for the subsequent interrogations. For example, the first secondary questions states: "What is Industrial Symbiosis? Which are the key concepts encompassed by this topic? Which are the barriers to its implementation?"

Once the first part of this question was answered, "What is Industrial Symbiosis?", some of the research studies used to assess this query also provided insights and information useful to address the following part of the question, "Which are the key concepts encompassed by this topic?" Therefore, the search strings employed for this interrogation were obtained by analyzing the most repeated concepts present in the research papers evaluated to assess the first part of the query.

The same logic was applied to the second secondary question. In fact, in order to answer, “Which are the advantages and disadvantages of the most relevant digital technologies?”, the digital technologies that were taken into consideration for the review were the ones obtained by answering “Which are the most relevant digital technologies nowadays?”

Table 1. Search strings employed for location of research paper.

	Review question	Search strings
1	What is Industrial Symbiosis?	"Industrial symbiosis" OR "circular economy" OR "industrial symbiosis definition" OR "industrial symbiosis concept"
1	Which are the key concepts encompassed by IS?	"Industrial symbiosis key concepts" OR "industrial symbiosis evolution" OR "industrial districts" OR "industrial ecology" OR "eco-industrial park" OR "sustainable development" OR "transition to sustainability" OR "resource exchange"
1	Which are the barriers to the implementation of IS?	"Industrial symbiosis barriers" OR "industrial symbiosis implementation barriers" OR "industrial symbiosis challenges" OR "industrial symbiosis implementation challenges"
2	What is a Digital Technology?	"Digital technology" OR "digital technologies" OR "digital technology definition" OR "digital technology concept" OR "digitalization" OR "digital transformation"
2	Which are the most relevant digital technologies nowadays?	"Key digital technologies" OR "most important digital technologies" OR "most important digital technologies in manufacturing" OR "relevant digital technologies" OR "adoption of digital technologies"
2	Which are the advantages and disadvantages of the most relevant digital technologies?	"Blockchain" OR "blockchain technology" OR "blockchain advantages" OR "blockchain disadvantages" OR "artificial intelligence" OR "artificial intelligence advantages" OR "artificial intelligence disadvantages" OR "big data analytics" OR "big data and advanced analytics" OR "big data analytics advantages" OR "big data analytics disadvantages" OR "digital platforms" OR "digital platforms advantages" OR "digital platforms disadvantages" OR "Industry 4.0" OR "Industry 4.0 technologies" OR "fourth industrial revolution" OR "Industry 4.0 advantages" OR "Industry 4.0 disadvantages"
3	How do Digital Technologies enable Industrial Symbiosis?	"Digital technologies enable industrial symbiosis" OR "digital technologies facilitate industrial symbiosis" OR "digital technologies AND industrial symbiosis" OR "digitalization AND industrial symbiosis" OR "digital transformation AND industrial symbiosis" OR "Industry 4.0 AND industrial symbiosis" OR "digital technologies enable circular economy" OR "digital technologies facilitate circular economy" OR "digital technologies AND circular economy" OR "digitalization AND circular economy" OR "digital transformation AND circular economy" OR "Industry 4.0 AND circular economy" OR "blockchain AND industrial symbiosis" OR "artificial intelligence AND industrial symbiosis" OR "Big data analytics AND industrial symbiosis" OR "digital platforms AND industrial symbiosis" OR "blockchain AND circular economy" OR "artificial intelligence AND circular economy" OR "Big data analytics AND circular economy" OR "digital platforms AND circular economy"

Study Selection and Evaluation

To select the scientific articles that would be employed as a basis for the literature review, the following considerations were considered: Only studies and other information published in 2007 and onwards were included to obtain contemporary research and state-of-the-art digital technologies applied in practice. For scientific research, it was aimed to select the most cited papers when the search results were large. On the contrary, when the results were scarce, it primarily served as an indication of the lack of academic research in a specific domain and thus, the selection process was simplified. It's relevant to mention that to address the second secondary question, results were additionally filtered since digital technologies are being currently evaluated from numerous fields of research. In this sense, scientific papers evaluating digital technologies from a humanistic perspective were not considered (e.g., effect of digital technologies on human behavior, possible implications of digital technologies on society, digital technologies, and education, etc.)

Each type of information source was screened to filter out false positive results from the automated search engines as follows:

1) Scientific studies: the title and the abstract were examined.
2) Consulting reports: the executive summaries and introductions were examined.
3) Company websites: homepages were examined, and further information was obtained of the companies through the world wide web to ensure its market relevance on the topic.

Since the core focus of this research regards the primary question: "How do Digital Technologies enable Industrial Symbiosis? A more in detail assessment of the literature findings and study selection is presented in subchapter 3.4, where Table 2 and Table 3 provide a comprehensive overview of the scientific research evaluating this topic. In this context, although it was defined that the analysis would focus on contributions released after 2007, when assessing the primary question all the studies are dated from 2015 onwards, which confirms the novelty of the research.

Analysis and Synthesis & Report Results

The subsequent sections of research will describe the findings of the literature review. Through these sections the results obtained will be assessed and synthesized. It's therefore essential to keep in mind the main objective of the review: understanding how digital technologies enable industrial symbiosis. This will be carried out by firstly evaluating industrial symbiosis, its key concepts, and barriers to adoption. Subsequently, the analysis will switch towards digital technologies, the most relevant ones nowadays and their related advantages/disadvantages. Finally, an assessment of the scientific contributions that have appraised how industrial symbiosis is enabled through digital technologies will be presented.

3.2. Understanding Industrial Symbiosis

Industrial Symbiosis represents a holistic strategy that assembles a diverse range of operations within a network to stimulate eco-innovation in the organizational culture. It harnesses latent resources, encompassing materials, energy, capacity, and assets, while also fostering the exchange of knowledge and expertise throughout the system. Furthermore, IS leads to innovative approaches for sourcing essential inputs and the continuous enhancement of technical processes. This collaborative framework not only optimizes resource utilization but also cultivates sustainable practices and resilient ecosystems within industries.

In the following section, the paper will delve into a technical exploration of fundamental concepts within the topic of industrial symbiosis with the main purpose of providing a precise understanding of these foundational ideas, emphasizing on their theoretical basis.

Concept Evolution

The concept of industrial symbiosis has undergone a significant evolution over time, reflecting changing perspectives on industry's relationship with the environment and society. This journey begins with the traditional view of industrial systems as separate from the natural world and progresses towards the contemporary understanding of industrial symbiosis as a crucial component of sustainable development. Industrial symbiosis is a subfield of Industrial Ecology, which has evolved over time to address the challenge of making sustainable development operational and economically feasible. This evolution can be traced back to the early 1920s and has gradually gained prominence. According to Chang Yu [33] It could be described as follows:

-Early 1920s: The industrial system was traditionally seen as separate from the natural environment. Factories and cities were considered distinct from nature, and little attention was paid to the environmental impact of industrial activities.

-Mid-20th Century: With the growth of industrialization and urbanization, concerns about environmental degradation began to emerge. Environmental movements and legislation started to address pollution and resource depletion.

-1970s: The 1970s marked a significant turning point with the advent of the environmental movement and increased awareness of ecological issues. This led to the birth of the field of Industrial Ecology, which aimed to study and improve the environmental performance of industrial systems.

-Emergence of Industrial Symbiosis: Industrial symbiosis, as a concept, emerged as a response to this challenge. It represents a shift in thinking, emphasizing the interconnectedness of industrial systems and the biosphere. Industrial symbiosis seeks to create mutually beneficial relationships among industries, where waste and byproducts from one industry become valuable inputs for another, thereby reducing waste, conserving resources, and minimizing environmental impact.

-Ongoing Development: Since its inception, the concept of industrial symbiosis has continued to evolve and gain recognition in the fields of sustainability, environmental management, and industrial design. It has been applied in various contexts to promote sustainability and resource efficiency.

Early Notions of Industrial Symbiosis

3.2.1. Industrial District

The foundation of the Industrial Symbiosis concept was laid in the early 1900s with the introduction of the Industrial District concept. Industrial districts refer to areas where a cluster of closely related or interconnected firms and industries are located in proximity to one another [34]. Economists such as Alfred Marshall started to delve into the advantages of the geographical concentration of interconnected industries. These districts are characterized by a high level of specialization, knowledge sharing, and collaboration among firms within the same area. They are also thought to stimulate innovation, support business adaptability, and facilitate endogenous regional development in an increasingly global marketplace [35]. Examples of well-known industrial districts include the textile, ceramic tile, and machine tools networks in Northern and Central Italy [36].

3.2.2. Industrial Ecology

The concept of industrial ecology emerged later, in the late 20th century, as a response to growing concerns about environmental sustainability and resource management. Historically, environmental concerns focused on minimizing the industrial system's impact on its surroundings. However, industrial ecology suggests that the industrial system can be viewed as an ecosystem in its own right, characterized by the distribution of materials, energy and information flows [37]. This system heavily relies on resources and services from the biosphere, making it inseparable from nature. It draws from principles of ecology and systems thinking to optimize resource use, reduce waste, and minimize environmental impact within industrial processes and systems. Industrial ecology mainly aims to mimic natural ecosystems by incorporating innovation into industrial production processes. It specifically focuses on the development of eco-industrial parks as a sustainable industrial development approach.

While the idea of industrial ecology has been present for decades, it gained significant traction in the 1990s, particularly in the United States and Japan. In recent years, it has gained renewed attention in academic and business circles. To clarify its meaning, it's essential to distinguish between "industrial metabolism" and "industrial ecology." Industrial metabolism encompasses all the materials and energy flows within the industrial system. It involves analytical and descriptive approaches to understand how materials and energy move through human activities, from extraction to eventual reintegration into natural cycles. Industrial ecology goes beyond this by aiming to understand the workings of the industrial system, its regulation, and its interaction with the biosphere. It then seeks to restructure the industrial system based on insights from natural ecosystems. While there isn't a standardized definition for industrial ecology, S. Erkman [37] proposes that it emphasizes three key elements:

-A systemic and integrated view of the industrial economy and its relationship with the biosphere.

-A focus on the physical flows of materials within and outside the industrial system, rather than abstract monetary units or energy flows.

-Consideration of technological dynamics, particularly the long-term evolution of key technologies, as a crucial element for transitioning from an unsustainable industrial system to a sustainable industrial ecosystem.

3.2.3. Eco-industrial Parks

Expanding on the principles of industrial ecology, the concept of eco-industrial parks naturally evolved as a complementary concept. An industrial park represents a sizable parcel of land that is subdivided and developed to accommodate multiple firms concurrently. It is characterized by its infrastructure, which is shared among the various firms and the proximity of these firms to one another [38]. Industrial parks come in various forms and are known by different names, including industrial clusters, business parks, science and research parks, bio-technology parks, and more recently, eco-industrial parks.

An Eco-Industrial Park is a strategically planned community of businesses that engage in cooperative efforts with one another and the local community to optimize the efficient sharing of a wide range of resources. These resources include information, materials, water, energy, infrastructure, and natural habitats. The overarching objective is to attain economic advantages, elevate environmental quality, and promote the equitable development of human resources, benefiting both the participating businesses and the local community.

Cote and Hall [38] proposed that an eco-industrial park is an industrial system designed to: conserve natural and economic resources. Reduce production, energy, treatment costs and liabilities. Improve operating efficiency, product quality, worker health and public image, and provide opportunities for income generation through the use and sale of waste materials.

On the other hand, Lowe et al. [39] defined an eco-industrial park as a community of manufacturing and service businesses that seek enhanced environmental and economic performance through collaboration in managing environmental and resource issues. They aim to achieve a collective benefit greater than the sum of individual benefits that each company would realize by optimizing its individual interests.

These definitions collectively emphasize several key attributes of eco-industrial parks, including resource sharing, sustainability, enhanced economic performance and cooperation within a community. Additionally, the evolving concept of eco-industrial parks acknowledges that they can vary in complexity, ranging from simple material symbioses between two or more firms to more intricate models, such as international eco-industrial parks, regional industrial networks, or virtual eco-industrial parks that transcend traditional geographic boundaries [40]. In essence, eco-industrial parks represent a dynamic approach to sustainable industrial development, guided by principles of community, cooperation, resource efficiency, and systemic thinking. Their effectiveness, especially in comparison to traditional industrial parks, remains a subject of ongoing evaluation within the field of industrial ecology.

3.2.4. Sustainable Development

To provide a more comprehensive perspective on this evolutionary progression, it is essential to introduce and elaborate on two additional fundamental concepts. Sustainable development is a concept that remains a dynamic and ever-evolving construct, often likened to a multifaceted puzzle. Sir Jonathon Porritt's once said, "Sustainable development is one of those ideas that everybody supports but nobody knows what it means" [41]. This enigma is perpetuated by the lack of a singular, universally accepted definition, despite numerous attempts by scholars and policymakers to articulate one [42]. However, amidst this complexity, there is a shared understanding that sustainable development comprises three crucial dimensions: economic, social, and environmental [43].

At the heart of sustainable development lies the definition articulated by the Brundtland Commission, defining it as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [44]. This foundational definition encapsulates two pivotal concepts: the notion of "needs," with a particular emphasis on fulfilling the essential needs of the world's impoverished populations, and the recognition of limitations imposed by the state of technology and social organization on the environment's capacity to fulfill present and future needs. Moreover, a diverse array of stakeholders, including governments, businesses, and civil society organizations, are actively engaging with the "sustainability challenge," infusing their distinctive interpretations of sustainable development into their operational frameworks. This dynamism underscores that sustainable development is not a fixed formula but a fluid concept, subject to interpretation and adaptation [45].

In summary, sustainable development is a dynamic and multifaceted concept that encompasses economic, social and environmental dimensions, where human involvement should be constrained to within the natural systems' carrying capacity, all the while safeguarding their vitality and ability to recover.

3.2.5. Circular Economy

In the evolutionary timeline of sustainable industrial practices, the concept of the circular economy is one of the most recent ones to be introduced. Circular economy gained prominence in the 21st century and it takes the core of industrial ecology and pushes it further by focusing on closing the resource loop, promoting recycling, and designing products and systems with an emphasis on longevity and reusability. This progression reflects an evolving awareness of the need to move from linear, resource-depleting models, as exemplified by traditional industrial practices, to circular, regenerative frameworks. Commonly agreed definitions of the CE are those proposed by the Ellen MacArthur Foundation. First, the CE is defined as a global economic model to minimize the consumption of finite resources, by focusing on intelligent design of materials, products, and systems. The CE aims at overcoming the dominant linear (e.g. take, make and dispose) economy model. Progressively in this way, closed-loop patterns, completely focused on balancing economic, environmental, and societal impacts, have substituted old industrial practices [46]. As Geissdoerfer et al. [47] discuss, the emergence of circular business models can be seen as a response to these pressing environmental challenges. Over time, there has been a transformation in how businesses perceive their role in society, moving from a purely profit-driven approach to one that incorporates ecological and social considerations. Circular business models prioritize resource efficiency and the reduction of waste, thereby mitigating environmental impacts. These strategies are designed to prolong the lifecycle of products, reduce material and energy consumption and minimize waste.

The core principles of a circular economy can be defined as follows: First, it advocates the elimination of waste and pollution by thoughtful product design, ensuring that waste ceases to exist when a product's biological and technical components, seamlessly integrate into either biological or technical materials cycles. This shift emphasizes moving from pollution control to pollution prevention through intentional design. Second, it promotes the prolonged use of products and materials through practices such as reuse, repair, remanufacturing, and recycling. Additionally, it emphasizes the regeneration of natural systems by avoiding non-renewable resource use and the preservation or enhancement of renewable resources. A systemic perspective is encouraged, highlighting the importance of understanding how interconnected parts influence one another [48]. Lastly, the circular economy concept stands by the idea that waste should be considered a form of nourishment with the purpose of reintroducing products and materials into the biosphere through non-toxic, revitalizing cycles, and technically, through quality improvements, often referred to as "upcycling."

The concepts presented thus far serve as a crucial building block in comprehending the evolution and origins of industrial symbiosis. This historical context contributes to a comprehensive and holistic understanding of the development of this sustainable industrial practice. Building upon this foundational knowledge, the focus finally shifts to the concept of industrial symbiosis.

3.2.6. Industrial Symbiosis

Industrial Symbiosis represents a natural progression in this evolutionary journey, embodying the practical application of these principles. Industrial symbiosis is a central concept in the field of industrial ecology, defined as a collaborative approach where traditionally separate industries work together to gain a competitive edge by sharing materials, energy, water, and byproducts [49]. Industrial symbiosis is considered one of the evolutionary paths towards higher diversity and complexity of regional strategies, emphasizing the importance of collaboration and synergy between businesses. Importantly, IS activities are not constrained by geographical proximity and seek to promote innovation and long-term cultural change by involving diverse organizations in a network. This network facilitates the sharing of knowledge, leading to mutually beneficial transactions in sourcing inputs, handling non-product outputs, and enhancing business processes. The origins of IS can be traced back to the 1990s when it was inspired by eco-industrial park projects, with EIPs being described as communities of businesses cooperating to efficiently share resources for economic, environmental, and societal benefits [50]. The collaboration in industrial symbiosis can lead to environmental and economic benefits that surpass what individual organizations could achieve independently.

Historically, industrial systems were often viewed as distinct entities, disconnected from the biosphere. Factories and cities were considered separate from nature, and little attention was paid to the environmental impacts of industrial processes. A crucial moment in the evolution of industrial symbiosis occurred at the United Nations conference during the Rio Summit in June 1992. This conference raised the critical question: "How can sustainable development be made operational and economically feasible?" It marked the beginning of a shift towards more sustainable industrial practices [51]. In summary, the concept evolution of industrial symbiosis reflects a transition from viewing industrial systems as separate from the environment to recognizing the potential for industries to collaborate, share resources and create mutually beneficial relationships with the natural world. This evolution underscores the importance of sustainability, resource efficiency, and interconnectivity in shaping the future of industrial practices.

Since 2007, there has been a notable surge in publications on industrial symbiosis, reflecting its growing importance. The concept's evolution is marked by a shift from isolated analyses towards a collective exploration of case studies, both implemented and potential, across various regions globally. While Europe and Asia, notably China, have witnessed a higher prevalence of industrial symbiosis due to supportive public policies, cases have also been identified in North America, Oceania, North Africa, and South America [7]. The key industrial sectors involved, including manufacturing, power plants, refineries, and waste management companies, underscore the increasing interest in integrating waste and by-products into production processes. Over the past two decades, IS has evolved from case-specific studies to a more theoretical, systematic, and diverse field. Researchers have focused on developing IS theories and assessing the suitability of IS concepts for practical application at both local and global levels. A special issue in the Journal of Industrial Ecology in 2012 provided a comprehensive overview of IS research. It redefined IS as a tool for promoting innovative green growth and presented a three-stage model of IS development. The special issue covered four key aspects: pushing the boundaries of IS, considering the role of information and social factors, designing IS networks, and implementing IS [3]. As the research community delves deeper into this field, there is a growing emphasis on quantifying environmental and economic impacts. Furthermore, the recent expansion into urban symbiosis underscores the concept's potential for reducing carbon emissions and waste sent to landfills and incinerators [7]. Over the years, the concept of industrial symbiosis has evolved, moving away from localized waste and by-product exchanges toward innovation, knowledge sharing and efficiency in material use.

3.2.7. Barriers to Industrial Symbiosis

While the advantages of industrial symbiosis are widely acknowledged, its widespread implementation is hindered by a great number of barriers. These barriers span various domains, from economic and technological to regulatory and social factors. In this section, a comprehensive analysis will expose the barriers that impede the realization of industrial symbiosis, in order to highlight the complexities faced by industries striving to embrace this sustainable approach.

Several research studies examining the potential for industrial symbiosis have highlighted the absence of suitable policies as a significant impediment to its adoption. Key barriers include low taxes on landfill disposal, the need for policies that incentivize and regulate industrial symbiosis, insufficient financial resources to promote this practice and deficient regulatory frameworks [52], [53].

Barriers to industrial symbiosis, as revealed in a study performed by Linda Kosmol [54], encompass a diverse range of challenges that hinder the successful implementation of this sustainable development concept. According to the study, these barriers could be classified into three main categories: hard factors, soft factors, and contextual factors. Hard factors, accounting for 32% of the identified barriers, encompass quantifiable challenges related to the economic, technological, and financial aspects of industrial symbiosis, such as follows:

-Economic Barriers: These challenges are primarily financial in nature and include issues such as investment, feasibility, benefit sharing, and costs. Investment barriers relate to different investment cycles and change costs, which can discourage participation. Feasibility barriers stem from conflicts between industrial symbiosis and financial gains. Benefit sharing issues arise from the difficulty of assigning value or identifying cost-benefits beforehand. Cost-related barriers involve expenses associated with promotion or transportation. Economic barriers also include factors like uncertainty, such as uncertain profits and margins, and risks that affect the financial viability of industrial symbiosis initiatives.

-Technology Barriers: These are challenges related to the technological aspects of industrial symbiosis. Stable demand issues arise from the lack of necessary quality, quantity, and continuity of material and energy flows. Feasibility barriers in technology are due to materials being unsuitable for reuse. Resource-related barriers stem from a lack of technical resources, including space or pretreatment technologies. Geographic distribution challenges result from the difficulties caused by physical distances between participating entities. Effort-related challenges refer to changes in flows, procedures, and processes that can hinder industrial symbiosis.

-Financial Barriers: Financial challenges include various cost-related issues, such as transaction costs and investment costs. Funding challenges arise from a lack of financial support or research funding, while resource-related barriers pertain to insufficient financial resources. Capital challenges may involve difficulties in acquiring internal or external capital to support industrial symbiosis initiatives.

Consequently, soft factors constitute 49% of the identified barriers in the study, presenting more complex, non-quantifiable challenges, such as:

-Cooperation Barriers: These challenges are related to inter-firm partnerships within industrial symbiosis. Cooperative issues arise due to differences in company strategies, including aversion, unwillingness, and discontinuity in collaboration. Conflicts of interest and objectives can hinder cooperation, along with the lack and difficulty of multi-actor decision-making. Organizational incompatibilities result from differences in company culture, power structures, and sizes, while trust-related issues can stem from competitive attitudes or social isolation. A lack of support tools, such as information systems for communication, coordination, and collaboration, can hinder cooperation. A lack of shared understanding, inconsistent terminology, or unfamiliarity with industrial symbiosis concepts can contribute to barriers in cooperation.

-Management Barriers: These challenges pertain to both a company's and an industrial park's management, as they play a key role in facilitating industrial symbiosis. Commitment-related challenges may include a lack of interest and engagement toward sustainable development or resistance to behavioral change. Resource-related barriers involve time constraints or a shortage of available and qualified personnel.

Strategy barriers may be due to misalignments with a company's policies or inappropriate hierarchical organizational structures. Resistance from organizations can stem from unwillingness to risk existing supply chains or aversion to changing procedures and processes.

-Knowledge Barriers: Knowledge-related challenges often involve a lack of knowledge to identify and implement industrial symbiosis opportunities. This can include technical, market, and environmental knowledge gaps, as well as a lack of expertise or experts. Awareness barriers can be caused by unfamiliarity with industrial symbiosis concepts, a failure to recognize waste as a potential input, or unknown benefits. Additionally, the difficulty and lack of knowledge sharing can hinder industrial symbiosis efforts.

-Information Barriers: These barriers are related to information availability and sharing. Challenges include a lack of information on resource quality and quantity, collaboration methods, or inefficient information flows. Barriers to information sharing encompass general limitations in sharing information and resistance or difficulty in doing so. Confidentiality issues may arise due to limited information disclosure or unnecessary confidentiality. Furthermore, information systems may be lacking or inadequately designed for sustainability or the management of information systems.

Lastly contextual factors contribute to 19% of the barriers. This category revolves around policy regulation and the public market environment. Some of these contextual challenges include the following:

-Policy/Regulation Barriers: These barriers are related to regulatory conditions. Lack of support is a major factor, including deficiencies in the regulatory framework or insufficient support from public institutions. Restrictions may involve outdated regulations that do not support innovation or bureaucratic issues. Uncertainty, particularly regarding legislation and regulation, is also a common barrier and misalignment can occur when cooperation between companies cannot be mandated by the government.

-Public/Market Barriers: Awareness challenges may include a lack of consumer interest in environmental issues or limited internal communication in municipalities. Public and community actors can also be barriers if they show resistance to industrial symbiosis efforts. Additionally, the lack of stakeholder involvement or missing market incentives to reuse waste can pose challenges for industrial symbiosis initiatives [54].

These findings demonstrate that inadequate government policies and regulations, such as low taxes on landfill disposal, insufficient funding, and inconsistent regulatory frameworks, can obstruct the progress of symbiotic relationships. Moreover, reluctance among companies to establish symbiotic ties arises from limited knowledge of the concept or in potential partners, coupled with issues related to trust, data sharing and profitability uncertainties. Additionally, the implementation of waste reduction measures by companies can inadvertently limit the availability of waste streams essential for the development of symbiosis [55].

Another study performed in the Gladstone region of Australia demonstrated that another of the primary barriers to IS, is the limitations faced by industrial managers. Most managers in the study lacked the necessary technical knowledge or were reluctant to adopt new technologies required for IS to thrive. To address this, there is a need for educational initiatives and programs to make managers aware of the benefits and feasibility of IS practices, enabling them to make informed decisions. There is also a high concern over reputation among the companies; as industries are protective of their image, any potential risk to the stability of existing operations or harm to their reputation can lead to reluctance to embrace IS. Economic factors also play an important role in this study. The establishment of fair pricing structures and incentives for waste product reuse is crucial for making IS economically viable. It is well known that some industries prioritize short-term economic outcomes over long-term environmental goals, so encouraging a longer-term perspective on economic returns, possibly through incentives or subsidies, is necessary. Furthermore, competition with raw material suppliers is an important factor that can deter industries from IS [56].

As it has been disclosed, achieving successful industrial symbiosis demands concerted efforts to address a complex set of barriers. These encompass technical, economic, regulatory, and community-related challenges, and overcoming them requires collaboration between industries, the government, and the local community to promote the benefits of IS and adapt regulations to create a favorable environment to implement this sustainable practice.

3.3. Understanding Digital Technologies

The present section aims to evaluate the most influential digital technologies of nowadays. This is done by presenting the main characteristics of each technology, with the purpose of providing an overview of the basic traits of each digital tool so that in the following sections, whenever these tools are discussed in regards industrial symbiosis, the reader has a clear concept as a reference.

As a starting point, it’s crucial to understand what the term “digital technology” indicates. In fact, the term "digital" originates from the Latin word "digitus," meaning finger, which historically referred to one of the earliest tools used for counting. When information is preserved, transferred, or sent in a digital form, it gets translated into numerical values, typically at the fundamental level of machines as "zeroes and ones." A digital technology therefore symbolizes a technology that operates through microprocessors, which includes computers and software reliant on computers like the Internet. It also encompasses other gadgets such as video cameras, mobile devices like phones, and personal digital assistants [57].

Digital technologies permeate and reconfigure all aspects of economic and social endeavors. Their implementation disrupts some existing activities, while in other instances, they yield a more gradual impact, augmenting and working in conjunction with established activities [58]. Digitalization holds significant power by not only enabling automation but also by monitoring and archiving information and data regarding tasks and activities. This process creates a record that can be examined, offering opportunities for enhancing processes and work organization [59] and predictions about future events [60].

Digital technologies find applications across various sectors, extending from agriculture and manufacturing to professional services, healthcare, and beyond [58]. In this context, many are the technologies that could classify as "digital". However, the present section will focus on the most evaluated digital technologies among literature, which encompass: Blockchain Technology, Artificial Intelligence - Machine Learning, Big Data Analytics, Digital Platforms, and Industry 4.0 enabling technologies [61], [62], [63].

3.3.1. Blockchain Technology

As a starting point, the discussion in the present section will be initiated by the examination of Blockchain, an innovative technology that has earned significant attention over the past few years by redefining the concepts of security and trust.

Blockchain can be defined as "a distributed data structure comprising a chain of blocks" [64]. Indeed, Blockchain serves as a decentralized database or a worldwide ledger responsible for recording all transactions that occur within a Blockchain network. These transactions are assigned timestamps and are grouped into blocks, each of which is distinguished by its unique cryptographic hash. These blocks are organized into a sequential chain, where each block references the hash of the preceding one, thus forming the renowned "Blockchain." A network of nodes collectively maintains and records the transactions within the Blockchain, ensuring uniformity. The Blockchain is replicated across all nodes within the network, allowing any node to access and review the transactions [64]. To provide further clarity, Figure 5 below provides a visual representation of the basic structure of a Blockchain.

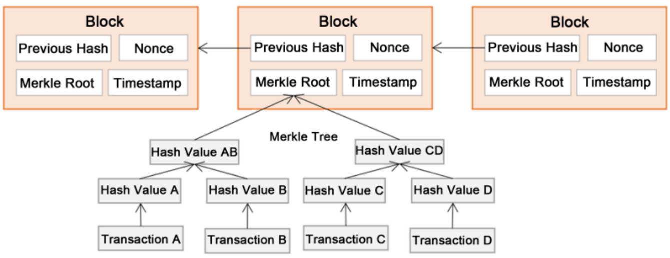

Figure 5. Blockchain structure [64].

As can be observed from Figure 5, every block includes the cryptographic hash of the preceding block. All hash information is automatically generated, ensuring that no data within the hash can be altered. Consequently, each subsequent block reinforces the verification of the preceding block, enhancing the overall security of the entire Blockchain [65]. Indeed, "the more blocks in the chain - the safer and more reliable the Blockchain" [66].

Blockchain technology encompasses four distinct types, categorized according to their level of access to Blockchain data [66]. Figure 6 illustrates this classification along with corresponding class definitions.

Name of the class	Definition
A public Blockchain	Does not have any restrictions on reading of the blocks and on submitting of the transactions for inclusion into the Blockchain
A private Blockchain	Has limited to a predefined list of users of the direct access to the blocks and submitting transactions
A permissionless Blockchain	Does not have any restrictions for the users which are eligible to create the blocks of transactions
A permissioned Blockchain	Has the list of the predefined users which are eligible to performed to process the transactions

Figure 6. First classification of Blockchain technology [67].

A further classification is based on transaction processing and data access. As detailed in Figure 7, Blockchain exhibits various access levels, each offering distinct opportunities [67], [68].

Access to the data	The processing of the transactions	
	Permissioned	Permissionless
Public	Proprietary colored coins protocols	Existing cryptocurrencies (Bitcoins)
Regulated	The direct access to the reading and creating of the transactions for clients and regulators (limited)	Colored coins protocols (Colored Coins Protocol) which can limit to creating of the transactions
Private	The direct access to the data of the Blockchain is limited and the advantages of the Blockchain are partially lost	It is not possible to apply

Figure 7. Second classification of Blockchain technology [67].

Overview on Smart Contracts

Now that the groundwork has been laid by defining essential Blockchain concepts, it is pertinent to introduce the notion of smart contracts. These digital contracts operate within a Blockchain network and have gained relevance nowadays due to their automation, transparency, security, efficiency and cost-reduction benefits [69].

In simple terms, smart contracts are essentially software programs hosted on a blockchain network that are executed once specific conditions are met. Their primary purpose is to automate the completion of agreements, guaranteeing immediate certainty for all parties involved, without requiring intermediaries or causing delays. Additionally, they can automate workflows by initiating the next step when conditions are satisfied [69].

On the other hand, a more technical definition focuses on how smart contracts are distinguished by a unique address and comprise a set of executable functions and state variables. These functions are activated when transactions are directed towards them, each transaction bearing required input parameters for the contract functions. Following function execution, the state variables within the contract undergo changes based on the logic embedded in the function [70].

These contracts can be scripted in various high-level languages such as Solidity or Python [71]. Language-specific compilers (e.g., Solidity or Serpent) are employed to compile these contracts into byte code. Once compiled, the contracts are deployed onto the Blockchain network, receiving unique addresses. Any participant on the Blockchain network can initiate the functions within the contract by transmitting transactions to it and lastly, the contract code is executed across all network nodes as part of the block verification process [70].

Through Figure 8 a visual representation of a smart contract's structure is presented.

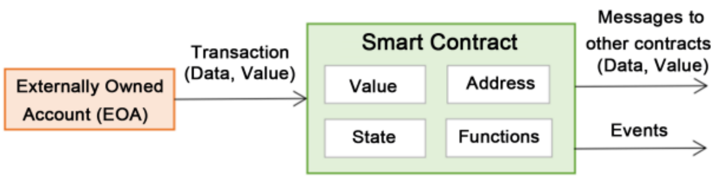

Figure 8. Smart contract Structure [70].

Advantages of Blockchain Technology

Having examined the essential concepts related to Blockchain technology, the main benefits presented by this technology are hereby assessed.

-Decentralization: A key advantage of Blockchain technology is that it's a decentralized system. Its significance lies in the elimination of third-party intermediaries or central administrators. This autonomous operation ensures that all participants in the Blockchain network collectively make decisions. Each system maintains its own database, and safeguarding this database is critical. When third-party organizations are involved, there's a heightened risk of data breaches and security concerns, demanding time and financial resources for protection. Blockchain offers a solution by embedding transactions with their proof of validity and authorization, enabling independent verification and processing, thus averting security risks and associated costs [65], [70].

-Inalterability: Every action is registered on the Blockchain, and the recorded data is accessible to all participants within the Blockchain, remaining unalterable and irremovable. This recording process ensures the transparency, immutability, and trustworthiness of Blockchain [70].

-Trustworthiness: The trustworthiness of the Blockchain relies on the confidence of multiple participants who are unfamiliar with each other. The fundamental concept is to ensure genuine and valuable transactions among these unfamiliar individuals. This trust can be reinforced through the incorporation of additional shared processes and records [65], [72].

-Transparency: The transparency of the Blockchain is a product of the transaction duplication process. Indeed, each transaction is duplicated on every computer within the Blockchain network. This duplication allows every participant to access and view all transactions, ensuring that every action is visible to all participants, leaving no room for covert activities [65], [72].

-Self-correction: The design of Blockchain allows it to detect and rectify any issues when needed, enhancing the traceability of Blockchain technology [73].

Disadvantages of Blockchain Technology

Moving forward, the main challenges that impede the smooth application of blockchain technology will be assessed henceforth.

-High energy consumption: The primary drawback of Blockchain technology is its high energy consumption. This power consumption is essential for maintaining a real-time ledger. Each time a new node is created, it engages in communication with other nodes, fostering transparency. Miners in the network continuously work to solve numerous solutions per second to validate transactions, demanding significant computational power. While this approach provides extreme fault tolerance, ensures uninterrupted operation, and guarantees the immutability and censorship resistance of data on the Blockchain, it comes at a cost of consuming both electricity and time [65], [74].

-Signature Verification: Signature verification poses a significant challenge in the context of Blockchain. This is because every transaction necessitates a cryptographic signature, demanding substantial computational power for the signing process [65]. This computational intensity is one of the factors contributing to the high energy consumption previously noted.

-Opportunity to split the chain: Another challenge associated with Blockchain is the potential for chain splits. Nodes running on older software may not recognize transactions in a new chain, even if it has the same historical data as the chain based on the older software. This occurrence is referred to as a 'fork,' which comes in two varieties: the 'soft fork' and the 'hard fork’ [65], [75].

-Costs: High expenses pose a significant drawback in the context of Blockchain technology. The average transaction cost typically ranges between 75 and 160 dollars, with a substantial portion allocated to energy consumption [73]. Another contributing factor to this situation is the elevated initial capital investment required for Blockchain [65].

3.3.2. Artificial Intelligence – Machine Learning

Artificial Intelligence classifies as one of the most relevant digital technologies of nowadays. Many definitions of this technology have been constructed since its conception, among which, it's possible to find the one offered by McCarthy J [76], which states that AI "is the science and engineering of making intelligent machines, especially intelligent computer programs. It is related to the similar task of using computers to understand human intelligence, but AI does not have to confine itself to methods that are biologically observable" [76].

With the aim of expanding the AI concept, it's relevant to cite Bhbosale V [77], which highlights how the two main objectives of AI can be classified in:

1) Creating Expert Systems: "The device or machine which exhibits intelligent behaviour, learns, thinks, demonstrates, explains, and gives suggestions to its users" [77].
2) Implementing Human Intelligence in a computer: "Creating systems that understand, think, learn, and behave like human beings" [77].

Taking these definitions into consideration, it is then possible to state that artificial intelligence, at its simplest form, is a discipline that merges computer science with extensive datasets to facilitate the resolution of problems [78].

To get a better understanding of this problem-resolution ability, some of the main applications of AI will now be discussed:

-Customer service: Online virtual agents take the place of human agents throughout the customer journey. They respond to common inquiries, such as those related to shipping, and offer tailored recommendations, promote additional products, or recommend sizes for users [78].

-Social media: Social media platforms such as Facebook, Twitter, and Snapchat host billions of user profiles that need to be efficiently stored and managed. AI has the capability to organize and handle vast amounts of information, enabling the analysis of extensive data to identify the latest trends, popular hashtags, and the diverse needs of users [77].

-Computer vision: This AI technology empowers computers and systems to extract valuable insights from digital images, videos, and other visual inputs and subsequently, initiate actions based on those results [78].

-Robotics: Traditionally, conventional robots are programmed to perform repetitive tasks. However, with the integration of AI, smart robots can be developed, capable of carrying out tasks based on their own experiences, without the need for pre-programming [78].

-Recommendation engines: AI algorithms can leverage historical customer' consumption data to identify patterns, which in turn can be utilized for the enhancement of more efficient cross-selling tactics. These insights are employed to provide pertinent additional product suggestions to customers as they proceed through the online retail checkout process [78].

To conclude the introductory concepts regarding AI, Figure 9 below presents an overview of the main areas of Artificial Intelligence, categorizing its applications into cognitive science, robotics, and natural interfaces.

Artificial Intelligence	Cognitive Science Applications	Expert Systems Learning Systems Fuzzy Logic Genetic Algorithms Neutral Networks Intelligent Agents
	Robotics Application	Visual Perceptions Tactility Dexterity Locomotion Navigation
	Natural Interface Applications	Natural Languages Speech Recognitions Multisensory Interfaces Virtual Reality

Figure 9. Areas of Artificial Intelligence [79].

Machine Learning: A sub-field of Artificial Intelligence

Artificial Intelligence also includes greatly acknowledged subdomains such as machine learning and deep learning. Within these domains, AI algorithms are employed to construct expert systems that generate predictions or classifications using input data [78].

More in detail, Machine Learning involves the study and application of mathematical algorithms capable of enhancing their performance autonomously, without requiring human intervention. These algorithms take historical data as input and generate new predictive values as output and have found application across numerous domains to solve a wide array of tasks. Nevertheless, the diverse nature of these tasks often requires the use of specific machine learning algorithms in order to achieve the highest possible accuracy in attaining the desired results [80].

Before evaluating the different types of algorithms, it's fundamental to understand that an algorithm can be defined as "a procedure used for solving a problem or performing a computation. Algorithms act as an exact list of instructions that conduct specified actions step by step in either hardware- or software-based routines" [81].

In this context, Machine learning algorithms (as illustrated in Figure 10) are categorized into various groups based on their intended objectives:

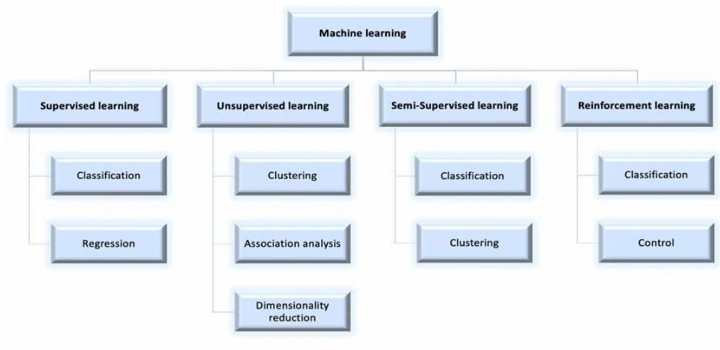

Figure 10. Types of Machine Learning Algorithms [80].

-Supervised Learning: "defined by its use of labelled datasets to train algorithms to classify data or predict outcomes accurately. As input data is fed into the model, it adjusts its weights until the model has been fitted appropriately, which occurs as part of the cross-validation process. Supervised learning helps organizations solve a variety of real-world problems at scale, such as classifying spam in a separate folder from the inbox." [82].

-Unsupervised Learning: "analyses and clusters unlabelled datasets. These algorithms discover hidden patterns or data groupings without the need for human intervention. Its ability to discover similarities and differences in information makes it the ideal solution for exploratory data analysis, cross-selling strategies, customer segmentation, and image recognition." [83].

-Semi-Supervised Learning: "an approach to machine learning that combines a small amount of labelled data with a large amount of unlabelled data during training. Semi supervised learning falls between unsupervised and supervised learning." [80].

-Reinforcement Learning: "addresses sequential decision-making problems that are typically under uncertainty. Examples of this include inventory management with multiple echelons and multiple suppliers with lead times under demand uncertainty; control problems like autonomous manufacturing operations or production plan control; and resource allocation problems in finance or operations" [84].

Considering the various choices available for machine learning algorithms, the selection of the most appropriate one depends on a thorough understanding of the data available and the final objective that is aimed to be reached.

The Increasing Influence of Generative Models

Generative AI, encompassing models like ChatGPT, has gained notorious importance in recent years. This type of AI constitutes a subset of deep-learning models (sub-field of machine learning referring to a neural network comprised of more than three layers), capable of ingesting extensive datasets, such as Wikipedia or the complete works of artists like Rembrandt, and "learning" to produce statistically plausible outputs upon request. These generative models function at a fundamental level by encoding a simplified representation of their training data and subsequently leveraging this knowledge to generate new content that retains a likeness to the original data while introducing distinct elements [78], [85].

Recent advances in the field of generative artificial intelligence have the potential to revolutionize content creation across various domains, including the generation of audio, code, images, text, simulations, and videos, heralding a paradigm shift in our approach to creative endeavours [85].

Up to this point, a range of crucial concepts that lay the foundation for the understanding of Artificial Intelligence have been evaluated. These key terms provide the necessary knowledge to analyse the advantages and disadvantages associated with this digital technology.

Advantages of Artificial Intelligence

Among the advantages of employing AI algorithms, the most relevant ones are described here below:

-Minimization of Human Errors: When programmed accurately, AI-enabled computers exhibit flawless performance. Furthermore, AI models rely on predictive analysis, eliminating the margin for error, which not only conserves time and resources but also ensures precise and efficient outcomes [77], [79], [86].

-Automation of Repetitive Tasks and Processes: AI facilitates the automation of repetitive, monotonous tasks across various domains, including data collection, data input, customer-centric operations, email replies, software testing, invoice creation, and more. This allows employees to allocate their time to tasks that demand human skills and expertise and thus, increase efficiency of the operations [77], [79], [86].

-Efficient Management of Large Data Sets: AI possesses the necessary capabilities and algorithms to swiftly analyse and draw insights from extensive data sets within minimal time. It can rapidly identify and extract the pertinent information essential for analysis, offering the capacity to further interpret and refine this data through processing and transformation [79], [86].

-Decision-Making Acceleration: AI speeds up the acquisition of trustworthy and valuable insights. Therefore, in conjunction with essential algorithms, AI empowers machines to consolidate data and make predictions efficiently, and since AI systems are consistently accessible, it’s possible to expedite prompt decision-making processes [86].

-Full time Availability: AI-driven systems offer round-the-clock availability, ensuring access whenever needed. In contrast to humans, AI-based systems can maintain productivity without time constraints, since they are designed to operate for extended hours and adeptly manage repetitive and unvarying tasks [77], [79], [86].

-Development of Dangerous and Risky Activities: AI applications find utility in tasks and environments dangerous to human workers. AI systems effectively reduce the risks associated with perilous assignments. For example, robots are capable of tackling hazardous activities like coal mining, deep-sea exploration, aiding in disaster relief efforts, and more [77], [86].

Disadvantages of Artificial Intelligence

Although many are the benefits that can be obtained from this digital technology, it's equally relevant to understand which are the obstacles that could prevent its seamless implementation. Consequently, the main AI disadvantages are listed below:

-Ethical Concerns: The release of ChatGPT in 2022 was a significant milestone in AI, showcasing its versatility in tasks like legal writing and code debugging. ChatGPT and similar tools rely on foundation models, large-scale generative models trained on unlabelled data. These models can adapt knowledge from one context to another, but they raise ethical concerns such as bias, false content generation, and lack of transparency [79], [87].

-Impact on Employment: The impact of AI on jobs is often seen as a concern. Like previous disruptive technologies, AI will shift the demand for specific job roles. Although managing AI systems and addressing complex problems will still require human resources, particularly in areas like customer service, the key challenge will be helping individuals transition to these evolving job markets. [77], [79], [87].

-Privacy: Privacy discussions have increased as the usage of AI tools becomes more widespread around the world. Those discussions often revolve around data privacy, data protection, and data security. Consequently, investments in security have become a top priority for businesses as they aim to eliminate vulnerabilities and safeguard against surveillance, hacking, and cyberattacks [87].

-Accountability: AI regulation varies by location, with ongoing efforts to establish local legislation. Although ethical frameworks have emerged to guide AI model development, they may not be sufficient to prevent harm due to distributed responsibility and limited foresight into consequences [87].

-Resources: The implementation of AI systems, especially those personalized to specific companies' needs, require a lot of economical and temporal resources. Additionally, the transition process of an organization towards more digital environments also represents a challenge for firms that should be tackled without overlooking the current organizational culture [77], [79].

3.3.3. Big Data Analytics

The analysis switches now towards another major influential digital technology in recent years: Big Data Analytics. In simple terms, big data analytics is "where advanced analytic techniques operate on big data sets" [88].

Over the years, the pace of digitalization has risen, leading to a continuously more digital world where the volume of data created and stored has grown significantly within a short period of time [89]. In this context, big data is becoming more relevant across numerous research domains, including social networks, the semantic web, data mining, information fusion, computational intelligence, and machine learning [90].

Before digging more in detail into the advanced analytic techniques employed to evaluate large data sets, it's crucial to first understand why these two scopes (Big Data and Analytics) have been put together.

In fact, Russom P [88] presents an interesting overview on this subject, stating how big data offers enormous statistical samples that enhance the outcomes of analytical tools. Most tools designed for data mining or statistical analysis are typically tailored for large datasets. As a general guideline, the greater the dataset's size, the more precise the statistical results and other analytical outcomes become. Moreover, recent advances in analytic tools and databases have greatly enhanced the capabilities for processing big data, enabling efficient handling of complex queries and data tables. This improved performance is now economically feasible due to reduced data storage and processing costs, making big data analytics accessible to businesses of all sizes. Additionally, modern analytics tools are adaptable to messy data, accommodating non-standard, transactional, and low-quality information. In this sense, the focus should be on leveraging big data for valuable insights rather than the technology itself. This approach allows businesses to adapt to the ever-changing economic landscape, where recognizing and exploring change has become crucial [88].

Big Data Attributes

Focusing on Big Data, it's possible to identify five fundamental attributes: variety, velocity, volume, veracity, and value. Figure 11 here below presents an overview of the aforementioned.

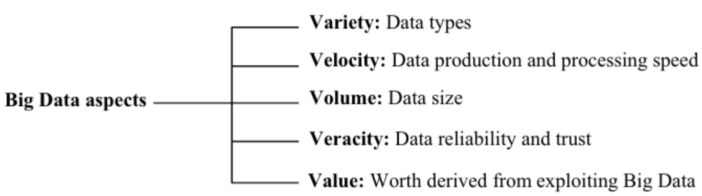

Figure 11. Big Data attributes [90].

These characteristics are crucial to comprehend Big Data Analytics; therefore, a more detailed definition of each aspect will be now presented.

-Variety: Variety refers to how highly diverse Big Data is in terms of data types and sources. Among these, Web sources are the most cited, including logs, clickstreams, and social media, from which textual information on ongoing events, traffic datasets pertaining to vehicular traffic on roads, and scheduled events such as music concerts and sporting events can be obtained [88], [90].

-Velocity: Velocity measures the pace at which data is transmitted and received, encompassing the dynamic nature of data, the rate at which data is generated, and the pace at which real-time results are obtained [88], [90].

-Volume: Volume regards the magnitude of the data set, extending from megabytes and gigabytes to terabytes or even petabytes. However, big data can also be quantified by measuring the number of records, transactions, tables, or files. In some cases, organizations find it more practical to quantify big data based on time. For instance, because of the seven-year statute of limitations in the U.S., many companies opt to retain seven years of data for risk assessment, compliance, and legal analysis purposes [88], [90].

-Veracity: Veracity concerns the level of trustworthiness of data based on the credibility of its source. For example, in cases where data is received from sensors, there is a possibility that certain devices could be compromised [90].

-Value: Value pertains to the potential insights that an organization can extract through the analysis of big data, encompassing both the significant potential value and the remarkably low value density [90], [91].

Big Data Formats

Big Data can be found in the following different formats:

-Structured data: Structured data is characterized by having a well-defined format and a relational structure, making it manageable through standard SQL-type languages commonly found in relational database management systems. Strings, numerals, and dates are types of structured data [88], [90].

-Unstructured data: Unstructured data lacks a specific format and can take various forms, including videos, text, time-related information, and geographic location data. The rapid growth and handling of this type of data presents significant challenges for current computational capabilities [88], [90].

-Semi-structured data: The rise in this data type is attributed to the growing utilization of industry standards like SWIFT, ACORD, HL7, and the widespread use of XML for business-to-business data exchange, often structured hierarchically. Traditional database management systems techniques are inadequate for managing semi-structured data; thus, it requires the use of comprehensive and intelligent rules [88], [90].

Big Data Sources

An exponential increase in data originates from a wide range of sources, including the internet, social media networks, sensors, and cultural content descriptions [90]. More in detail, the following can be described as the main Big Data Sources of nowadays:

-Internet: The internet serves as a vast source of data generation, connected devices like GPS units, smartphones, and window sensors provide various services that result in the generation of substantial amounts of raw, predominantly unstructured data [89], [90].

-Social media/ multimedia: A vast quantity of data is created through user comments and personal views expressed on social platforms like Twitter, Facebook, LinkedIn, and blogs. Additionally, images, text, videos, and audio content are sourced from both open networks such as YouTube, Picasa, and Flickr, as well as private collections [89], [90].

-Sensors: Sensor networks generate vast volumes of data and are deployed across various applications, including cultural environments and meteorological research and prediction systems [89], [90].

-Web services: Data gathered via web services or digital repositories, including descriptions of cultural items retrieved from open web resources like Wikipedia [90].

-Other devices: There are other types of data that may not be as prominent as social media data, but their presence should not be underestimated. Examples include data from power meters [90].

Big Data Analytics Techniques

In response to the surge in data volumes, scientists have developed a comprehensive suite of big data methodologies designed to efficiently analyze and extract insights from vast datasets within strict time constraints. These techniques have proven to be useful not only in the investigation and examination of large-scale data but also in discovering valuable patterns and rules. Their main role regards data management, analysis, visualization, and their most relevant contribution is related to enhancing informed decision-making processes [90].

The methods employed in big data analytics that will be next discussed have been broadly categorized into the following six classes: machine learning - data mining, cloud computing, semantic network analysis - web mining, visualization techniques, optimization techniques and social network analysis.

1) Machine learning – data mining techniques: Data mining and machine learning techniques form a vital component of big data analytics. They serve as powerful tools to extract valuable insights from large datasets. These methods, such as

cluster analysis, association rule learning, classification, and regression, are used to summarize data into meaningful information. However, as the data generation rate continues to surge, it is imperative to adapt and extend traditional data mining algorithms to effectively handle big data. Algorithms like hierarchical clustering, k-means, fuzzy c-means, clustering large applications, CLARANS, and balanced iterative reducing and clustering using hierarchies must be enhanced to ensure their applicability in the future. Additionally, the utilization of parallel programming models like Hadoop and Map/Reduce is crucial for scaling up data mining and machine learning techniques, enabling the analysis and parallel processing of vast datasets [89], [90].

2) Cloud computing: Cloud computing is emerging as a fundamental resource for efficient data processing, marking a significant shift in the contemporary era of computational information. This model provides service-oriented computing and abstracts the underlying software-equipped hardware infrastructure from users. Among the different Big Data applications, the primary objective of cloud computing is to navigate and analyze vast datasets to extract valuable insights for future decision-making. Cloud computing serves as a parallel distributed computing system that facilitates Big Data analytics, enabling seamless data sharing and informed decision-making without unnecessary redundancy [89], [90], [91].

3) Semantic network analysis – web mining: Semantic network analysis encompasses various domains, including web mining, Natural Language Processing (NLP), and text analytics. It serves as a technique for identifying patterns within extensive network repositories, unveiling hidden insights on websites for data analysis. NLP focuses on enabling computer programs to understand spoken human language, covering activities such as extracting relationships from documents, recognizing sentence boundaries, and searching for and retrieving documents. NLP plays a pivotal role in structuring unstructured text, facilitating text analytics, which involves extracting valuable information from textual sources. Indeed, text analytics encompasses a range of tasks, from annotating text with meta-information to text clustering, sentiment analysis, and categorization [90]. Switching the focus to web mining is a method used to uncover patterns within extensive web repositories [92]. Indeed, it uncovers previously undisclosed information about websites, enabling users to conduct data analysis and assess a website's effectiveness [89].

4) Visualization techniques: Visualization methods are employed to comprehend and interpret data by generating tables, images, and diagrams. When dealing with Big Data, visualization becomes more challenging due to data complexity.

To address this, an extension of conventional visualization techniques is adapted to suit large-scale data, involving feature extraction and geometric modeling to condense data sizes before visual representation. To achieve a detailed and intuitive data interpretation, many researchers implement batch-model software rendering in parallel, aiming to attain the finest data resolution [89], [90].

5) Optimization techniques: Optimization techniques are described as effective quantitative problem-solving approaches across various multidisciplinary domains, including biology, physics, economics, and engineering. Various computational strategies like particle swarm optimization, genetic algorithms, scheduling algorithms, quantum annealing, etc. show promise in tackling global optimization challenges due to their inherent quantitative nature and parallel processing capabilities. Nevertheless, they are resource-intensive in terms of memory and time consumption, making it necessary to enhance their scalability in real-time settings [89], [90].

6) Social network analysis: The social network analysis method is used to examine social relationships within the social network theory. This method has become increasingly important in the context of social and cloud computing. It performs well when dealing with data of moderate size, but its performance degrades when confronted with high-dimensional data [89].

Advantages of Big Data Analytics

Highlighted here below are some of the most significant benefits of employing big data analytics:

-Enhancement of predictive analyses and pattern identification: Big data analytics offers numerous advantages across various sectors. It supports social media, private entities, and government agencies in uncovering hidden behavioral patterns, making it particularly valuable in healthcare where it can aid in predictive analysis [93].

-Value extraction: The internet has given rise to an abundance of content, encompassing vast quantities of text, audio, images, and videos. To streamline, categorize, and structure this immense content pool, various techniques and technologies designed for handling substantial data volumes can be employed. These processes enable individuals to access pertinent and contextually relevant information through a unified and efficient access system [89].

-Improved customer relations: Big data analytics offers the potential for an improved customer experience and enhanced customer relations in multiple ways. It enables comprehensive data analysis from various sources such as GPS devices, cell phones, computers, and medical devices in emerging economies, allowing for the optimization of services for the population. Moreover, it facilitates more precise social-influencer marketing, customer-base segmentation, and the identification of sales and market prospects. In the face of recent global economic shifts, big data analytics helps in understanding evolving consumer behaviors, defining churn patterns, and gaining deeper insights into consumer actions derived from clickstreams [88], [89].

-Business intelligence: Regarding business intelligence, the application of big data analytics can be advantageous. This may lead to the generation of a greater quantity of precise business insights, an enhanced understanding of alterations in business dynamics, improved capabilities for planning and forecasting, the identification of underlying factors contributing to costs and the increase in the efficiency of operations by gaining a better understanding of the processes [88], [89], [91].

-Specific analytic applications: Certain specialized analytic applications stand to gain substantial advantages from big data analytics. For instance, applications geared towards identifying fraudulent activities, assessing risk levels, or tracking market needs. On the cutting edge, the utilization of big data analytics could facilitate the automation of decisions within real-time business processes, such as instant loan approvals or prompt fraud detection [88], [89].

Disadvantages of Big Data Analytics

While the advantages of this digital technology are significant, it is also important to recognize the potential barriers to its implementation. Therefore, the primary drawbacks of Big Data Analytics are outlined here below:

-High performance computer systems: To achieve real-time data processing, there is a need to integrate robust high-performance computing infrastructure with exceptionally efficient systems capable of addressing scientific, engineering, and data analysis challenges, irrespective of the scale of data. However, a significant challenge in the development of high-performance technology lies in the complexity of computational science and engineering codes [88], [89].

-Big data indexing schemes: Retrieving specific information in a timely manner from distributed storage becomes increasingly challenging as data volumes grow. The solution lies in the development of new indexing algorithms and techniques designed to expedite the retrieval process. Further investigation is necessary to develop effective algorithms for retrieving data from extensive datasets [89], [90].

-Data quality: the reliability of data quality is essential for making informed decisions. Ensuring data quality poses a substantial challenge in various data analysis scenarios [92]. This challenge becomes particularly evident in data visualization, where maintaining accurate data is critical. To address data quality issues effectively, organizations must implement robust data governance practices that guarantee data integrity [89], [91].

-Big data security: Enterprises face a significant challenge in addressing big data issues while enhancing security measures. In situations where data is generated at a very fast pace, the prompt identification of malicious data becomes increasingly complex. Hence, traditional security measures must evolve to accommodate the unique features of big data, including data patterns and data variability, with the objective of providing real-time protection [89], [91].

-Inadequate personnel and skills: Many organizations are relatively new to big data analytics, which demands a different skill set compared to business intelligence and data warehousing, where most organizations have already cultivated their expertise. Challenges related to skills encompass the complexity of designing a big data analytics system and the issues associated with rendering big data accessible and practical for end users [88].

3.3.4. Digital Platforms

The discussion will now move towards another digital technology that has gained huge importance over the past few years: Digital platforms. Indeed, serving as technological frameworks, they exert an ongoing influence on entire industries through their ecosystems of social actors [94]. For instance, Airbnb offers more than 6 million accommodation options across 100.000 cities in 220 countries and regions [95]. Uber has a network of about 5,4 million drivers worldwide, more than doubling its driver base over the last four years [96], surpassing local taxi firms. Facebook coordinates around 2,9 billion monthly active users [97], exceeding newspaper subscriptions by a wide margin. All these digital platforms exploit the widespread presence of continuously advancing information technology, including cloud computing, in-memory databases, and big data analytics solutions [94].

Definition of Digital Platforms

Digital platforms exhibit three fundamental attributes: they are enabled by technology, facilitate interactions among various user groups, and empower these user groups to perform specified functions [98], [99]. This concept is supported by Constantinides P [100] who defines digital platforms as a collection of digital assets, either services or content, designed to enable engagement among its users. Nevertheless, the specific nature of the platform is determined by the specific objectives its participants aim to achieve [101].

It's relevant to mention that the interpretation of digital platforms' definitions varies to some extent based on the specific field of study [102]. For instance, in research that focuses on the technological aspects of digital platforms, the primary emphasis has been on their technological and digital attributes, including features like layered architecture and modularity [103]. If the focus is instead on information systems, there has been significant emphasis on the socio-technical aspects of digital platforms. This encompasses studying how these platforms impact organizational structures and international standards [99]. In economics, the conversation has developed concerning the demand and supply functions within these platforms and how they diverge from those in other market environments [104]. And as a final example, within an industrial context, digital platforms are described in relation to attributes like market value, ownership, sector or industry placement, governance structure, country of origin, geographic scope, and core purpose [105].

Since the options for a specific definition of digital platforms are broad, this research will focus on the one that best aligns with the principal thematic under analysis: How digital technologies enable industrial symbiosis. Under this scope, Bonina C [102] proposes that digital platforms represent a unique category of information technology (IT) artefact, possessing specific characteristics that offer unique development opportunities. Moreover, digital platforms constitute a socio-technical phenomenon that demands thorough examination of their operations within a social environment. When viewed collectively, this socio-technical approach to platforms has implications for the development results. Hence, digital platforms can be defined by evaluating their technical attributes, their interaction within a social framework, and the resulting implications for development opportunities [102].

Classification of Digital Platforms

Although the focus has been narrowed down, the technical attributes of platforms still vary based on their type and intended function. Therefore, it's fundamental to mention that this research will evaluate these technical attributes in accordance with the classification proposed by Cusumano M [98], through which digital platforms are categorized into two main groups based on their primary purpose: transaction platforms and innovation platforms.

A summary of the main characteristics of transaction and innovation platforms can be found in Figure 12 below. In this context, a further evaluation will be presented solely for transaction platforms. This is because the attributes of innovation platforms do not make them relevant within the scope of the present research.

Type of digital platform	Transaction	Innovation
Purpose	Matches users or user groups, the value for a user increases with the number of users in a user group	An extensible codebase as a core that enables the adding of third-party modules that complement the core
Key target groups	Participants to a transaction	Application developers
Key governance issues	Attracting users from the relevant groups (indirect/direct)	Relationship between developers and platform owners
Theories	Multi-sided markets, indirect and direct network effects	Boundary resources, platform openness, platform ecosystem
Developmental questions	Income/job opportunities, filling institutional voids, removal of market frictions	Creation of app economies, development of tools (apps) to solve local challenges
Examples	MPesa, Whatsapp, Skype. Airbnb, Mercado Libre, Uber	Apple iOS, Linux, Android, SAP

Figure 12. Key characteristics of transaction and innovation platforms [106].

Transaction Platforms

A large amount of research has focused on digital platforms categorized as transaction platforms, often denoted as multi-sided markets or exchange platforms. These platforms primarily aim to enable interactions between various entities, such as organizations and individuals. Among their functionalities, it's possible to find the linkage of buyers and sellers, connection of recruiters and job seekers, and facilitation of interactions between drivers and passengers [102].

The concept of digital platforms, particularly in terms of facilitating transactions, emerged during the turbulent period of the dot-com era around the turn of the millennium. During this time, the term 'platform' became closely linked with numerous innovative startup business models that leveraged internet-based applications to enable transactions among various participants in a market. These platforms thrived by harnessing network effects to their advantage [102].

In broad terms, transaction platforms exhibit three main characteristics:

1) Facilitation of interactions among two or more distinct participant groups, each considered a separate "side."
2) Minimization of transaction costs, such as search, contracting, and monitoring expenses, for participants on one side to connect with those on the other side.
3) Generation of same-side and cross-side network effects by linking various participants [107].

Value Creation and Value Capture

When all these diverse features of transaction platforms are considered collectively, the fundamental source of value creation can be concisely described as the facilitation of services and information exchange among various participants within a multisided market. This can be attributed to two specific aspects: The first aspect involves matchmaking, which entails the capability to assist individuals or entities in searching and discovering suitable counterparts for conducting transactions. In the other hand, the second aspect pertains to diminishing obstacles and difficulties within the subsequent interactions and transactions [98]. Social media platforms, as an example of transaction platforms, provide additional possibilities for collaborative value creation, as they empower users not only to exchange content but also to generate it [108].

Transaction platforms capture value through different methods, such as establishing fees for access to their services through membership subscriptions or pay-per-use models. They also generate revenues by taking a commission, typically a percentage of the value charged by the service-providing party [102]. Many transaction platforms, especially social media platforms, also generate income by commercializing user data obtained from user profiles and behaviors, analyzing it, and making it available for targeted advertising. However, this practice has drawn criticism due to concerns about the undisclosed and unethical utilization of such data [109].

Understanding Network Effects

The most significant economic and business influence of transaction platforms results from what are commonly referred to as "network effects." These effects, also known as demand-side economies of scale or network externalities, signify the extent to which the addition of each new participant to a network enhances its value for all existing participants [110].

Let's take Facebook as an example. In the absence of other users to connect with, Facebook held no value. However, its value increased as users could connect with more people: the addition of another user to Facebook significantly amplifies the number of other users they can engage with. Consequently, as more users are linked to Facebook, the potential value of the platform for every other user grows [107].

In this context, network effects can be categorized as:

1) Direct network effects: arise when the introduction of a new participant alters the value for all other participants on the same side, just like the Facebook case.
2) Indirect network effects: in this scenario, augmenting the number of participants on one side influences the value for all participants on the opposite side. To illustrate, let's consider the Facebook example again. The worth of Facebook to an advertiser rises substantially as the user base expands [107].

Overview of Core Concepts of Digital Platforms

As a closing remark before evaluating the advantages and disadvantages of transaction digital platforms, and to provide a more complete understanding and clear picture of digital platforms, Figure 13 is presented. It provides an overview of the definitions of core concepts that have been highly employed in different fields of scholarly research. Since the present analysis was mainly focused on transaction platforms, it is possible that some concepts were not evaluated. However, that is exactly the main purpose of Figure 13: providing the reader an overall idea of the main concepts encompassed within the term “digital platform”.

Concept	*Definition*
Multisided platform	Mediating different groups of users, such as buyers and sellers
Multisided markets	Bring together (or match) distinct groups, whereas the value for one group increases as the number of participants from the other group increases
Direct network externalities	The value of the platform depends on the number of users in the same user group
Indirect network externalities	The value the platform depends on the numbers of users in a different user group
Digital platform (technical view)	An extensible codebase to which complementary third-party modules can be added
Digital platform (sociotechnical view)	Technical elements (of software and hardware) and associated organisational processes and standards
Ecosystem (technical view)	A collection of complements (apps) to the core technical platform, mostly supplied by third-party
Ecosystem (organisational view)	Collection of firms interacting with a contribution to the complements.
Applications	Executable pieces of software that are offered as apps, services or systems to end-users
Boundary resources	Software tools and regulations facilitating the arms' length relationships between the involved parties
Platform openness	The extent to which platform boundary resources support complements

Figure 13. Core concepts of digital platforms [99].

Advantages of Digital Platforms

Here below some of the key benefits of employing Digital transaction Platforms have been outlined:

-Limitless processing of information: The decreasing costs and extensive memory and processing capabilities that drive the cloud-based infrastructure hosting transaction platforms make it possible to store and process information to an almost limitless extent [111].

-Safe user experience: The processing capabilities of the foundational infrastructure of digital platforms are so substantial that there is no competition in their utilization [111]. This means that numerous users can utilize transaction platform services simultaneously without experiencing any adverse impact. Moreover, this processing capacity allows for rapid and large-scale searching and sharing of information, significantly reducing the challenges and expenses associated with these activities if performed in a non-digital manner [102].

-Transaction cost reduction: Transaction platforms are particularly valuable in the sense that they facilitate cost reduction in transactions. They enable various agents to more conveniently discover one another, thus diminishing many of the obstacles within the transaction process [112].

-Multiple benefits: Social media transaction platforms like Facebook, Twitter and Instagram expand the availability of resources (such as time, expertise, and support), access to information (like job opportunities and benefits advice) and streamlining collective action and influence (enabling social campaigns or providing a voice in local matters) [102].

Disadvantages of Digital Platforms

Although the benefits of utilizing this digital technology are substantial, it's crucial to acknowledge the possible obstacles to its adoption. Hence, we will now highlight the main disadvantages of Digital transaction Platforms:

-Chicken-and-egg problem: A significant hurdle for newly emerging digital platforms is the "chicken-and-egg problem." This issue arises because the platform requires the presence of both sellers and consumers to offer a meaningful value proposition. However, neither side is willing to participate until the other side has a substantial presence [113].

-Data security: Despite the implementation of sophisticated firewalls and encryption measures, there is a persistent risk of malicious actors breaking through these defenses and obtaining access to confidential data. Furthermore, digital systems frequently depend on intricate software programs that have their own vulnerabilities. If any component fails or experiences issues, it could lead to the compromise of entire databases [114].

-Ethical concerns: Negative aspects associated with social media transaction platforms like Facebook, Twitter and Instagram include the spread of misinformation and disinformation, resulting in ideological polarization. Additionally, these platforms may lead to service discrimination based on users' preferences and contribute to issues such as addiction and behavioral changes. Another concern involves the surveillance of citizens [102].

-Impact on societal and global interest issues: A notable concern involves the potential for direct manipulation and societal control of digital platforms, which can significantly impact civil society. The paradox lies in the fact that with sufficient influence within the blogosphere, even a lone developer has the capability to compel a powerful entity like Apple to react. However, it's typically quite challenging to observe any promotion of transparency on the primary digital platforms. This gives rise to several crucial concerns related to power dynamics and the immediate effects of these digital advancements on daily existence, such as surveillance, labor market interactions, and the equitable distribution of wealth, rather than relying solely on a simplistic argument grounded in technical rationality [99], [109], [115].

3.3.5. Industry 4.0

The focus now switches towards the field of Industry 4.0. This industrial revolution marks a pivotal transformation, intertwining cutting-edge advancements in technology with traditional factory processes. Industry 4.0 encapsulates a paradigm shift that integrates cyber-physical systems, the Internet of Things (IoT), artificial intelligence, and data-driven decision-making to redefine and revolutionize the manufacturing landscape.

Concisely, Industry 4.0 primarily relies on combining information and communication technologies with industrial technologies. Its primary aim is to enhance the effectiveness of production and management systems to yield increased profitability [116]. Indeed, Industry 4.0 aims to establish a cyber-physical system that fosters the evolution of a digital and intelligent factory. This evolution leads to an exceptionally adaptable production model for tailored and digitalized products and services. It emphasizes ongoing interconnections among individuals, products, and devices throughout the production workflow [117]. Certainly, through digital transformation, intelligent factories will simplify tasks for their workforce, even amidst increasingly intricate operations. In brief, this transformation aims to make production appealing, sustainable within urban settings, and profitable simultaneously [117].

The Cloud: Enabler of Industry 4.0

Before evaluating the most relevant Industry 4.0 technologies, it is fundamental to introduce the concept of Cloud computing, a transformative force empowering smart manufacturing and industrial automation by facilitating seamless data sharing, enabling real-time processing, and fostering interconnected systems.

Cloud computing encompasses a service provided on a subscription basis that offers access to networked storage space and computing resources. It enables users to retrieve their data from any location and at any time. Unlike a conventional computer setup that demands physical proximity to the data storage hardware, the cloud eliminates this requirement, allowing users to access their information without being in the same physical location as the storage hardware [118].

Various cloud options are available for subscription based on individual requirements. For instance, for home users or small business proprietors, the probable choice is to utilize public cloud services. These cloud options are listed and briefly explained here below.

1) Public Cloud - Access to a public cloud is available for any subscriber equipped with internet connection and authorized admission to the cloud space [118], [119].
2) Private Cloud - A private cloud is created for a particular group or organization and restricts entry solely to that specific group [118], [119].
3) Community Cloud - A community cloud is utilized jointly by multiple organizations with similar cloud requirements [118], [120].
4) Hybrid Cloud - A hybrid cloud fundamentally combines a minimum of two cloud types, encompassing a mix of public, private, or community clouds [118], [120].

Businesses currently employ cloud-based software for enterprise and analytics purposes. However, with the advent of Industry 4.0, more manufacturing-related activities will necessitate enhanced data sharing across different sites and company borders. Simultaneously, the performance of cloud technologies is expected to advance, achieving incredibly quick reaction times of just a few milliseconds. Consequently, machine data and functions are likely to increasingly transition to cloud platforms, facilitating the expansion of data-driven services for production systems. Even the systems responsible for monitoring and regulating processes might shift to cloud-based operations. Some companies, particularly vendors of manufacturing-execution systems, have initiated the provision of cloud-based solutions [63].

Types of Industry 4.0 Technologies

The categorization of Industry 4.0 Technologies varies depending on the development and utilization of each specific technology [121]. Although the literature does not present a unanimous agreement on the appropriate method for categorizing these technologies [122], [123], [124], [125], the majority of studies revolve around the following nine clusters of Industry 4.0 Technologies: Additive Manufacturing, Artificial Intelligence, Artificial Vision, Big Data and Advanced Analytics, Cybersecurity, Internet of Things, Robotics, Virtual and Augmented Reality, and Simulation [61] , [62] , [63].

A concise evaluation of said technologies will be presented next. However, some of these digital tools such as Artificial Intelligence and Big Data and Advanced Analytics have already been evaluated by the present research and therefore the reader can find their respective analysis on previous pages.

1) Additive Manufacturing: It encompasses all manufacturing methods involving the addition of material to produce novel, complex, and long-lasting components. This computer-controlled industrial procedure incorporates 3D printing, through which three-dimensional objects are fabricated by depositing materials, typically layer by layer [126].

2) Artificial Vision: It involves capturing a digital image or video, typically using a camera, of industrial operations. The process entails gathering a sequence of data, analyzing this information, and subsequently making decisions based on the evaluation [127].

3) Cybersecurity: Within a highly interconnected setting, it's vital to establish dependable and secure communications among systems to safeguard against potential theft, manipulation, or destruction of data. This is crucial to prevent alterations in manufacturing processes, maintain product quality, and avert complete operational shutdowns resulting from cyber-attacks [128].

4) Internet of Things: IoT aims to address communication issues among every object and system within a factory [129]. Internet of Things integrates smart and independent machinery, sophisticated predictive analysis, and collaborative interactions between machines and humans to enhance productivity, efficiency, and dependability [130].

5) Robotics: As manufacturing processes increasingly require customization and greater adaptability, machines must perform diverse tasks collectively without

the need for reprogramming. Consequently, robots are evolving to be more self-sufficient, adaptable, and collaborative, enabling them to interact with each other and work safely alongside humans. In the near future, they will even have the capacity to learn from human interactions [131].

6) Virtual and Augmented Reality: enables the simulation of real-life scenarios for training employees, preventing hazardous situations, enhancing decision-making, and following procedures. Moreover, VAR facilitates the development of an improved version of reality, blending live direct or indirect views of actual physical environments with computer-generated overlay imagery [121].

7) Simulation: During the engineering phase, three-dimensional simulations of products, materials, and manufacturing procedures are currently employed. Along with this, simulations utilize real-time data to replicate the physical environment in a virtual model, encompassing machinery, products, and human interactions. This enables operators to test and refine machine settings for upcoming products virtually before implementing physical changes, thus reducing machine setup times, and enhancing quality [63].

Smart Factories

In order to provide a complete overview of Industry 4.0 technologies and their impact on manufacturing systems, a further analysis of the main attributes of smart factories will now be presented.

Manufacturing firms generate substantial volumes of big data through embedded sensors and interconnected machinery. Employing data analytics enables manufacturers to explore past trends, recognize patterns, and enhance their decision-making capabilities. Smart factories leverage data from various facets within the organization and their broader network of suppliers and distributors, fostering comprehensive insights. By integrating data from human resources, sales, or warehouse operations, manufacturers can base production decisions on sales margins and workforce needs. This process can establish a comprehensive digital replica of operations, known as a "digital twin." [132]. Furthermore, the network structure of smart factories relies on connectivity. Instant data gathered from sensors, devices, and machinery within the factory can be readily accessed and utilized by other factory assets. This data can also be shared across different elements within the enterprise software stack, encompassing enterprise resource planning (ERP) systems and various business management software [132].

The Four Stages of Smart Factories

The journey towards turning a manufacturing factory smart involves four distinct levels used to evaluate progress through the enhancement process:

Stage One: Basic Data Availability

At this stage, a factory or facility isn't truly 'smart.' Although data exists, it isn't easily accessible or analyzed. If analysis occurs, it's time-consuming and may introduce inefficiencies into the production process [133].

Stage Two: Proactive Data Analysis

At this stage, data can be accessed in a more organized and comprehensible manner. It is centrally available and structured, with visualizations and displays aiding in its interpretation. This facilitates proactive data analysis, although it still requires a certain level of effort [133].

Stage Three: Active Data

At this level, data analysis benefits from machine learning and artificial intelligence, allowing for insights to be derived with less human intervention. The system is more automated than at stage two and can predict potential issues or irregularities, proactively anticipating potential failures [133].

Stage Four: Action-Oriented Data

The fourth stage builds upon the dynamic nature of stage three to devise solutions for problems and, in certain cases, take action to address an issue or enhance a process without human intervention. At this level, data is gathered and scrutinized for problems before generating solutions and, where feasible, implementing actions with minimal human involvement [133].

Overview of Application on Different Industries

Different industries and nations will adopt Industry 4.0 at varying paces and through diverse approaches. Sectors characterized by a wide array of product variations, like the automotive and food-and-beverage industries, stand to gain significant flexibility, potentially leading to productivity increases. Conversely, industries that prioritize high-quality output, such as semiconductors and pharmaceuticals, will benefit from enhancements driven by data analytics, reducing error rates [63].

Nations possessing high-cost skilled labor will leverage increased automation alongside a growing demand for highly skilled workers. Meanwhile, numerous emerging markets, benefiting from a young and technology-proficient workforce, may seize the opportunity and potentially introduce entirely new manufacturing paradigms. To proactively influence this transformation, manufacturers and system suppliers must take deliberate steps to adopt the nine foundational elements of technological progress. Additionally, they must address the necessity to tailor infrastructure and education to suit these advancements [63].

Advantages of Industry 4.0

Below, some of the primary advantages of Industry 4.0 have been highlighted:

-Enhanced efficiency: The integration of digital technologies like IoT, AI, and data analytics leads to improved operational efficiency, reducing downtime and enhancing productivity [63], [134], [135].

-Customization and flexibility: Smart factories have the capability to efficiently manufacture tailor-made products that cater to the unique requirements of individual customers. Across various industry sectors, manufacturers aim to achieve a cost-effective method of producing small quantities, often referred to as a "lot size of one." Employing advanced simulation software tools and integrating novel materials and technologies like 3-D printing, manufacturers can readily craft limited runs of specialized items for specific clients. While the initial industrial revolution focused on mass production, Industry 4.0 emphasizes mass customization [63], [132], [134].

-Innovation and competitiveness: Adoption of advanced technology encourages innovation, increasing competitiveness by creating new products and services [63], [134], [136].

-Predictive maintenance: IoT sensors enable predictive maintenance, helping to identify potential machine failures and reduce equipment downtime [137].

-Data driven decision making: Access to real-time data and analytics allows for informed and timely decision-making, optimizing processes and resource allocation [63], [134], [136].

-Supply Chain Integration: An effective Industry 4.0 approach necessitates a transparent and efficient supply chain, intricately focused into production operations. This integration revolutionizes how manufacturers source their raw materials and distribute their final products. Manufacturers, by sharing specific production data with suppliers, can enhance the coordination of deliveries. For instance, if there's a disruption in the assembly line, adjustments can be made to deliveries, avoiding unnecessary delays or expenses. Moreover, leveraging insights from weather patterns, transportation partners, and retailer data enables companies to employ predictive shipping, ensuring that finished goods arrive precisely when consumer demand peaks [132].

Disadvantages of Industry 4.0

While the advantages of Industry 4.0 are significant, it's essential to recognize the potential barriers to its adoption. Therefore, the primary drawbacks of this industrial revolution will now be outlined:

-Initial High Costs: Implementation of Industry 4.0 technologies requires substantial investments in equipment, training, and infrastructure [136], [138], [139].

-Cybersecurity Risks: With increased connectivity, there are higher risks of cyber-attacks and data breaches, posing threats to sensitive information and operations [136], [138], [140].

-Workforce Adaptation: The rapid technological shifts may necessitate upskilling or reskilling the workforce to operate and manage the sophisticated systems, which could lead to workforce displacement or skill gap challenges [63], [136], [138].

-Interoperability and Standardization: The evolution of manufacturing systems substantially impacts the risk of vulnerability, introducing additional uncertainties within the ecosystem. The principal hindering factor was the necessity for technological integration. Achieving successful integration among components, tools, and methodologies necessitates the establishment of an adaptable interface. This is crucial as harmonizing various languages, technologies, and methodologies can present considerable challenges [132], [136].

-Cross coordination among organizational units: According to research conducted by McKinsey & Company [141] the extensive communication necessary for Industry 4.0 initiatives and the introduction of new technologies might be significantly impacted by challenges in coordinating across different organizational units. Additionally, a study by PwC [142] revealed that numerous companies have not yet formulated compelling business cases and feasibility studies that distinctly justify the necessity of investing in the data and systems architecture essential for implementing Industry 4.0 applications.

3.3.6. Digital Technologies and Drivers for their adoption among Manufacturing Firms

To close this section, the following and final discussion aims to provide a general view of the drivers for the implementation of Digital Technologies among manufacturing firms. Although the possibilities of industrial symbiosis synergies are not restricted to manufacturing activities, the scope of this discussion was narrowed to manufacturing firms since the primary economic engagements currently involved in the synergies are linked to the manufacturing industry [143].

In order to obtain a sustainable competitive advantage over time, firms must be able to adapt to a continuously changing environment, in which the achievement pace of unprecedented milestones escalates rapidly. The emerging digital technologies can be seen as a clear example of one of the most relevant advancements for humankind in the last decade, and thus, as it could have been expected, businesses have started to dedicate their efforts into exploiting these technologies by means of creating, delivering and capturing value.

Focusing on manufacturing firms, Yang, Fu and Zhang [144] state that the main incentives behind a company's initiatives on adopting digital technologies can be classified as internal or external.

Internal Drivers

Among the internal drivers, Yang, Fu and Zhang [144] highlight how the incorporation of digital technologies within manufacturing companies primarily stems from internal operational challenges or the desire to enhance operational efficiency [145], [146]. In fact, numerous manufacturing companies have been investigating the use of swifter and more precise digital management systems to supplant the conventional, ineffective management approach [147]; as well as understanding how to utilize the IoT and big data for streamlining and enhancing operations and supply chains. Typically, the operational issues and goals are well-defined. Hence, the adoption process typically follows a bottom-up, problem-solving approach, which generally encompasses problem recognition, objective setting, development of digital solutions, execution, feedback, and adjustments [144].

The second internal motivation underlined by Yang, Fu and Zhang [144] for which manufacturing organizations adopt digital technologies is related to the strategic objectives of the corporation. Indeed, many are of the opinion that embracing digital technologies holds the capacity to incite both incremental and disruptive innovation [148], [149], [150]. Additionally, some companies implement digital technologies in anticipation of a future product development [151] or as an element of their sustainability plan [152].

External Drivers

Switching the focus to external drivers, numerous articles suggest that the adoption of digital technologies by manufacturing companies is significantly influenced by customer requirements [153], [154], [155]. The rising market demand for digitalized products, processes, and services across various industries compels companies to embrace digital technologies to enhance their ability to meet customer needs and effectively manage client relationships [154]. Moreover, the adoption of these technologies can be also justified from a marketing perspective, as it cultivates a favorable impression of businesses as forward-thinking and technologically innovative [144].

A second external incentive presented by Yang, Fu and Zhang [144] regards the willingness of companies to stay on the cutting edge of technological advancements and maintain strong collaborations with supply chain partners. Certainly, when a core player chooses to implement a specific digital system, it often instigates other entities within the supply chain to adjust to that system [156]. This is due to the fact that the digitization of a supply chain is typically provoked by the leading company because of its greater negotiating power, through which it exerts its influence and provides practical examples to the remaining players of the chain [144].

The final external force evaluated is competition. As a matter of fact, Yang, Fu and Zhang [144] state how embracing digital technologies is seen as a strategy to improve the competitive edge of manufacturing companies, particularly when their rivals have started the journey of digital transformation.

3.4. How Digital Technologies Enable Industrial Symbiosis – A Comprehensive Literature Review

Having presented a review on the key concepts encompassed by Industrial Symbiosis and Digital Technologies, it is now the moment to thoroughly examine how these technologies enable symbiosis practices. Indeed, the implementation of digital technologies for the circular economy overall has gained significant attention in scholarly research in recent years. The methodology employed to obtain the relevant studies to assess this subject has already been explained in subchapter 3.1. The analysis led to the identification of 30 articles, dated from 2015 onwards, which corroborates the novelty of the research.

In this context, the following table (Table 2) aims to examine the synergies between these two key domains, with a focus on their integration within the context of industrial symbiosis. It presents a concise overview of the existing research categorized by the presence of relevant keywords, in order to provide a quick reference guide to the literature and enable to identify papers that are particularly relevant to the intersection of these two main topics. The selected keywords appear in a minimum of two papers among the chosen articles and were divided into two primary categories:

-Circular Economy Keywords: This category includes terms associated with the circular economy framework, emphasizing the principles of sustainable practices within industrial ecosystems. These key concepts are: Circular Economy (CE), Industrial Symbiosis (IS), Sustainable Development (SD), Circular Business Models (CBM), Industrial Ecology (IE) and Waste Management (WM).

-Digital Technologies Keywords: In this category are encompassed areas such as Digitalization* (DT), Blockchain Technology (BT), Artificial Intelligence (AI), Machine Learning (ML), Big Data Analytics (BDA), Digital Platforms (DP), Industry 4.0 (I4.0) and Internet of Things (IoT), which play a great role in enhancing resource efficiency and collaboration within industrial symbiosis networks.

*Digitalization encompasses digital technologies and digital transformation as well.

Table 2. Synergies between CE and Digital technologies. Studies are organized in increasing chronological order.

			Circular Economy Keywords						Digital Technologies Keywords							
Author(s)	**Reference**	**Year**	**CE**	**IS**	**SD**	**CBM**	**IE**	**WM**	**DT**	**BT**	**AI**	**ML**	**BDA**	**DP**	**I4.0**	**IoT**
Cutaia et al.	[157]	2015		X				X						X		
Ferrera et al.	[158]	2017		X	X										X	X
Tsenga et al.	[159]	2018	X	X									X		X	
Rajput and Singh	[160]	2019	X												X	
Kerdlap et al.	[161]	2019		X	X		X	X							X	
Garcia-Muiña et al.	[162]	2019	X	X	X	X									X	
Naderi et al.	[163]	2019		X	X						X				X	
Colla et al.	[164]	2020		X	X				X		X	X			X	
Kolmykova et al.	[165]	2020	X		X	X			X		X				X	
Lütje and Wohlgemuth	[166]	2020		X			X				X	X				
Bag et al.	[167]	2021	X		X										X	
Lütje et al.	[168]	2019	X	X			X				X	X				
Rosa et al.	[169]	2019	X												X	
Kröhling and Martínez	[170]	2020		X						X						
Cohen and Gil	[171]	2021	X					X							X	
Barile et al.	[172]	2021		X					X					X		
Kumar et al.	[173]	2021	X		X										X	
Ponis	[174]	2020		X		X	X			X					X	
Järvenpää et al.	[175]	2021	X	X											X	
Krom et al.	[176]	2022	X	X										X		
Prakash and Ambedkar	[177]	2022	X	X	X				X						X	
Termizi et al.	[178]	2022		X						X					X	
Akbari and Hopkins	[179]	2022	X		X						X		X		X	X
Godina et al.	[180]	2022		X						X						
Costa et al.	[181]	2022	X	X				X		X						
Minde and Bäcklund	[182]	2023	X	X		X					X					
Pathan et al.	[183]	2023	X						X		X					
Neri et al.	[184]	2023	X						X						X	
Bruel and Godina	[185]	2023	X	X			X			X						
Mallawaarachchi and Jayakodi	[186]	2023	X	X												X

Though there is a broad array of studies that consider circular economy and digital technologies collectively, only a limited few investigate the connection between industrial symbiosis and digital technologies [187].

Therefore, to get a clear understanding of the relation between IS and DT, Table 3 is presented.

Table 3 stands as a structured literature review of the research papers presented in Table 2 that focus on the dynamic interactions of digital technologies and industrial symbiosis, with the main purpose of facilitating the identification of trends, gaps and potential areas for further research. Each column in the table represents a critical facet, enabling a profound exploration of the main insights gleaned from these works. The selection spans diverse sectors, methodologies, and case studies, resulting in a compilation of the advantages and impediments that respectively foster and restrict the assimilation of digital technologies within an industrial symbiosis approach. Furthermore, this table encapsulates the associated driving forces incentivizing the industries and companies that aim to enhance the sustainability and efficiency of industrial processes through IS, to embrace digital technologies. The columns will be clearly defined, providing a structured presentation of the information analysed.

The "Year" column acts as a chronological marker, enabling the tracking of the evolving research within this specific topic.

The "Sector Evaluated" column plays an important role in identifying the particular industry or domain associated with each case study or paper, providing essential context for understanding the research focus. In cases where the paper does not explicitly mention the sector it belongs to, "Not Specified" is used.

Likewise, the "Country" field is instrumental in indicating the specific geographic location connected to each paper. This element enriches the analysis by offering insights into regional influences on the dynamics of industrial symbiosis. "Not Specified" is employed to acknowledge the absence of country information in the paper.

The "Research Approach" provides a reference point for understanding the strategies employed to investigate, analyse and contribute to the topic. This encompasses a variety of methodologies, such as "Literature Review", which involves a comprehensive review and synthesis of existing academic literature, establishing a foundational understanding of the research area. "Framework" refers to qualitative methodologies with fundamental structures that offer a systematic approach to conceptualize, design research instruments, and analyse data. "Procedures and Algorithms" represent quantitative methodologies that are characterized by a set of well-defined and finite instructions or steps for accomplishing specific outcomes.

Additionally, the "Application" column provides insights into the practical aspect of the study, categorizing it into "Illustrative Example," which is used when a research study offers tangible real-world demonstrations of a particular concept, "Industrial Case Study," which involves a detailed examination of real-life industrial situations, and "Interviews," which pertains to the collection and analysis of data obtained through interviews with experts for gaining insights, perspectives, and qualitative data. "Does not apply" is used when the paper does not explicitly mention any of the previous application methods.

Furthermore, "Digital Technology Evaluated" articulates the specific digital technologies leveraged in the paper's discourse.

"Advantages" and "Barriers" provide insights into the benefits and challenges arising from the integration of said digital technologies into IS processes. "Not Specified" is employed to acknowledge the absence of advantages information in the paper.

The "N companies" reveals the total number of industrial players actively participating in industrial symbiosis, illustrating the scale of collaborations. "Not Specified" is employed to acknowledge the absence of the specific number of companies in the paper.

Finally, "Drivers" elucidates the motivating factors that incentivize companies to strategically adopt digital technologies for optimizing IS.

Due to design considerations and with the aim of providing a clear comprehension of the information presented in Table 3, it has been divided into two complementary tables: Table 3a and Table 3b. In this sense, Table 3a ranges from the "Sector Evaluated" to the "Application" column, while Table 3b spans from the "Digital Technology Evaluated" to the "Drivers" field. The connection between these tables is given by a distinctive characteristic of each study analysed by indicating the respective authors, reference and year of publication.

Table 3a. Overview of scientific research focusing on IS and Digital Technologies. Studies are organized in increasing chronological order.

Author(s)	Reference	Year	Sector Evaluated	Country	Research Approach	Application
Cutaia et al.	[157]	2015	Agriculture, manufacturing, water supply and sewerage, waste management	Italy	Literature Review	Industrial Case Study
Ferrera et al.	[158]	2017	Not specified	European countries (not specified which)	Framework	Does not apply
Tsenga et al.	[159]	2018	Not specified	Not specified	Literature Review	Does not apply
Kerdlap et al.	[161]	2019	Not specified	Singapore	Literature Review & Framework	Industrial Case Study

Author(s)	Reference	Year	Sector Evaluated	Country	Research Approach	Application
Garcia-Muiña et al.	[162]	2019	Ceramic manufacturing	Italy	Procedures and Algorithms	Industrial Case Study
Naderi et al.	[163]	2019	Manufacturing	Portugal	Procedures and Algorithms	Industrial Case Study
Colla et al.	[164]	2020	Steel manufacturing	Not specified	Literature Review	Does not apply
Lütje and Wohlgemuth	[166]	2020	Industrial parks	Not specified	Framework	Illustrative example
Lütje et al.	[168]	2019	Not specified	Not specified	Literature Review & Framework	Does not apply
Kröhling and Martínez	[170]	2020	Peer-to-Peer Markets, Eco-Industrial Parks	Argentina	Procedures and Algorithms	Industrial Case Study
Barile et al.	[172]	2021	Eco-industrial parks	European countries (not specified which)	Literature Review	Industrial Case Study
Ponis	[174]	2020	Manufacturing	Greece	Literature Review & Framework	Illustrative example
Järvenpää et al.	[175]	2021	Waste management	Finland	Framework	Industrial Case Study
Krom et al.	[176]	2022	Industrial parks	Norway	Literature Review	Industrial Case Study
Prakash and Ambedkar	[177]	2022	Diverse manufacturing sectors: aerospace, automobile, electronics, textile, etc.	Not specified	Literature Review & Procedures and Algorithms	Interviews
Termizi et al.	[178]	2022	Eco-industrial park	Not specified	Literature Review	

Author(s)	Reference	Year	Sector Evaluated	Country	Research Approach	Application
						Illustrative example
Godina et al.	[180]	2022	Eco-industrial parks	Not specified	Framework	Does not apply
Costa et al.	[181]	2022	Construction	Brazil	Framework	Illustrative example
Minde and Bäcklund	[182]	2023	Steel manufacturing and energy utility	Sweden	Literature Review	Industrial Case Study
Bruel and Godina	[185]	2023	Not specified	Not specified	Literature Review & Framework	Does not apply
Mallawaarachchi and Jayakodi	[186]	2023	Construction	Not specified	Literature Review & Framework	Does not apply

Table 3b, complement of Table 3a, is therefore presented below.

Table 3b. Overview of scientific research focusing on IS and Digital Technologies. Studies are organized in increasing chronological order.

Author(s)	Reference	Year	Digital technology evaluated	Advantages	Barriers	N Companies	Drivers
Cutaia et al.	[157]	2015	Digital platform for SMEs at a regional level	1.Automated input/output matching 2. Simplified information requested to companies as an input. 3. Input/output taxonomy relying on official code systems (EU regulation) for diverse inventory types.	1. Quantitative and temporal variables of supply side must be in alignment with those of the demand side. 2. Lack of cooperation and trust between companies.	80 SMEs involved	Raw material acquisition cost reduction and/or new sources of revenues enabled.
Ferrera et al.	[158]	2017	IoT based platform	1. Simplification of the transfer of data from machinery, systems, and sensors to end-user software. 2 Interoperable linkage for appliances, devices, terminals, subsystems, and services 3. Cohesive integration of heterogeneous devices, systems, and subsystems	Applicable only for digitalized factories (I4.0 environment).	Not specified	The framework proposed by the study, based on an IoT platform, enables the evaluation of the utilization of resources and energy across all process's principal flows to support the efficiency appraisal and decision making procedure within an IS paradigm.

Author(s)	Reference	Year	Digital technology evaluated	Advantages	Barriers	N Companies	Drivers
Tsenga et al.	[159]	2018	Industry 4.0 technologies: Cyber-physical systems, the Internet of Things (IoT) and Cloud Computing	1. Increased profitability and reduced resource consumption and waste generation. 2. Mathematical and computational optimization models are essential tools for decision-makers seeking to enhance IS practices by offering decision support. 3. Employing data-driven analyses within operations to generate dependable information within supply chains and industrial networks. This is a crucial aspect of fostering IS within an eco-industrial park.	Not specified	Not specified	Gaining insights into the optimization of resource utilization and sharing operational data to create universally applicable metrics for IS, Leveraging big-data analysis to benchmark factors such as mutual trust, corporate cultur and sustainable consumption within inter-industry networks

Author(s)	Reference	Year	Digital technology evaluated	Advantages	Barriers	N Companies	Drivers
Kerdlap et al.	[161]	2019	Collaborative platforms for IS	1. Few technical barriers for the implementation: technology that relies primarily on digital systems and would require minimal to nearly no changes in physical infrastructure 2. Reduction in the amount of waste materials that get mixed in with waste sent to incinerators	Achieving a critical mass of users for the collaborative platform to successfully facilitate IS exchanges	Not specified	High reward compared to implementation effort.
Garcia-Muiña et al.	[162]	2019	a) Internet of Things (network of sensors in production plant) + b) Simulation Software	a) Acquisition of real time measures of production processes b) Experimentation without risk, optimization of design, detailed insights.	a) Application: Complete digitization of manufacturing process. b) Complex, limited scope.	Not specified	Assessment of sustainability performance of ceramic tile formulations with raw materials coming from IS collaborations through simulation software that employs real time data of manufacturing processes as an input.

Author(s)	Reference	Year	Digital technology evaluated	Advantages	Barriers	N Companies	Drivers
Naderi et al.	[163]	2019	a) Industrial Internet of Things b) Big Data c) Virtual Reality d) Artificial Intelligence	a) Used to analyze a large amount of production data, transforming it into statistical models and key performance indicators for increased productivity. b) Conversion of big data into smart data with meaningful insights for improved efficiency. c) Support in the analysis of operations in a faster way. d) Aid in decision-making by providing users with the right information to make informed decisions.	Not specified	Not specified	1. Optimization of manufacturing operations. 2. Improve efficiency and productivity within the production processes. 3. Promote the development of IS or networks within eco-friendly industries that offer opportunities to enhance environmental efficiency and generate a positive social impact within production systems.

Author(s)	Reference	Year	Digital technology evaluated	Advantages	Barriers	N Companies	Drivers
Colla et al.	[164]	2020	a) IoT b) Sensing and monitoring devices c) Machine Learning d) Virtual Reality and Augmented Reality e) Blockchain f) Digital platforms	a) Support the implementation of IS by making valorization of residues into resources. b) Collection of extremely detailed information on the by-products, water, off gas or energy streams c) Verification of integrity of information shared between parties that exchange streams. d) Report of information in a practical and understandable way e) Certification of secure transaction through digital platforms f) Acceleration of transactions due to velocity of internet, cost reduction and confidentiality due to the cloud.	1. Presence of outliers and noise in data can hamper its meaningfulness with respect to the problem being analyzed. 2. Cybersecurity, need of employees with sufficient skills and creation of a "culture of cybersecurity"	Not specified	High number of tools and techniques available to collect relevant information on the crucial streams, to clean it, understand it, visualize it, which facilitates the implementation of IS.

Author(s)	Reference	Year	Digital technology evaluated	Advantages	Barriers	N Companies	Drivers
Lütje and Wohlgemuth	[166]	2020	Holistic IT-supported IS tool (digital platform) with system dynamics and AI algorithms	1. The stage of IS identification can be significantly accelerated. 2 Additional modules added to a traditional digital platform: simulation and modelling with the help of AI 3. Expansion of the outlook of a IS digital platform to future scenarios and setting objectives for developing target-focused transformation pathways.	1. Resources (temporal and monetary) needed to train the underlying AI algorithm 2. Acquisition of relevant data bases of IS material exchanges, IS measures and structural IS formations for generating templates and actions which the AI algorithms can use for the learning process (training and testing)	Not specified	Added value to a traditional IS digital platform through modules that allow to simulate and model different IS transformation routes with two fixed points: from the current state to the envisioned future scenario, ('zero waste,' 'zero emissions,' or 'CO2-neutral' park) or when the Industrial Park aims to bring its business performance in line with science-based targets (SBT).

Author(s)	Reference	Year	Digital technology evaluated	Advantages	Barriers	N Companies	Drivers
Lütje et al.	[168]	2019	Machine Learning	1. Enable the simulation of scenarios where IS systems are optimally utilized. 2. Allow the examination of the impacts of specific IS activities and disruptive occurrences 3. Permit the simulation of the required adaptability range of flows (minimum-maximum flow) to ensure the IS.	1. Establishment of global infrastructure of information networks (IoT) so that pertinent data from the actual world can be automatically gathered, interconnected, and shared for subsequent processing through intelligent, adaptive analytical models and machine learning techniques.	Not specified	Machine learning is a robust decision support tool valuable to meet dynamics of IS systems like varying material and energy flows and evolving entity compositions.

Author(s)	Reference	Year	Digital technology evaluated	Advantages	Barriers	N Companies	Drivers
Kröhling and Martínez	[170]	2020	a) Internet-of-Things (IoT) b) Blockchain c) dApps	a) Providing real-time data on energy consumption, production, and storage for IS. These devices enable prosumers to actively manage their energy resources. In the negotiation process, agents representing companies use data from IoT devices to make informed decisions and adapt their strategies. b) Ensuring secure and transparent transactions in P2P markets. Blockchain technology is used for creating and executing smart contracts. c) Use of dApps to implement software agents that represent prosumer companies in P2P markets, facilitating the negotiation of smart contracts.	Not specified	Not specified	Need for efficiency, cost savings, and improved negotiation outcomes in P2P markets to foster IS.

Author(s)	Reference	Year	Digital technology evaluated	Advantages	Barriers	N Companies	Drivers
Barile et al.	[172]	2021	Online digital platforms, web platforms	1. Facilitation of knowledge sharing among companies about the available symbiotic opportunities 2. Reduction of information asymmetries 3. The simulation and evaluation tools within the platform foster the conditions of success and viability of the IS network.	1. Implementation efforts: economical, cultural orientation towards sustainability, analysis of energy and material flows. 2. Measurement of value created through the platform.	Not specified	The breadth and depth of real-time information accessible through web platforms help overcome the conventional barriers that limit the transparency of industrial systems concerning resource extraction and environmental emissions.

Author(s)	Reference	Year	Digital technology evaluated	Advantages	Barriers	N Companies	Drivers
Ponis	[174]	2020	Blockchain	Transparency and immutability of transaction records for IS, secure transactions, token-based reward system to incentivize participation, integration of various functional areas for seamless ecosystem operation in IS.	Lack of technical expertise by potential participants and uncertainty regarding legislation and regulations in support of ISN initiatives and blockchain adoption in specific regions. In terms of technical implementation, the technology is again limited by 'soft' issues that may arise during the initiation phase, such as the persisting lack of trust in the technology, which most of the times comes as a result of its inherent complexity leading decision makers to a deficient understanding of underlying.	Not specified	Help overcome the barriers mentioned earlier by introducing a creative circular business model for Industrial Symbiosis Networks (ISNs) in Greece, which is backed by open-source blockchain technology. This technology appears to be well-suited for addressing significant challenges in the development and functioning of ISNs, including issues related to trust, sharing information and compatibility.

Author(s)	Reference	Year	Digital technology evaluated	Advantages	Barriers	N Companies	Drivers
Järvenpää et al.	[175]	2021	a) Internet of Things b) Big data analytics c) Sensors	a) Enables real-time tracking of energy and material usage. For IS, this means the communication within the factory and across factories and actors in the co-operation network, that could enable efficient and timely operations. Information sharing is important for successful IS and data visualization communicates the information for stakeholders. b) Helps develop complex system models, characterize consumption, and optimize operations. c) Provide data on container fulfillment and material volume.	Not specified	The paper discusses multiple companies involved in the three cases, including waste producers, waste users, and waste collectors. The precise number of companies varies among the cases	Implementation of industry 4.0 to fix the gaps and discontinuities in the IS information flow. Supporting the optimization of operations that are dependent on waste or by-product flows and need for accurate and timely information on material availability, supply and transportation.

Author(s)	Reference	Year	Digital technology evaluated	Advantages	Barriers	N Companies	Drivers
Krom et al.	[176]	2022	Digital platforms (matchmaking)	1. Could help overcome the prevailing informational, cooperative and technical barriers to IS 2. Could help address data confidentiality issues through a structure that minimizes the necessity of sharing sensitive corporate information.	1. Achieving a critical mass of users on both ends of the platform (supply and demand) 2. Challenging to implement due to the low standardization of goods exchanged (by-products).	Not specified	Could help overcome some of the existing barriers to IS.
Prakash and Ambedkar	[177]	2022	Industry 4.0 technologies: a) ICT based knowledge networks b) Big data analytics c) IoT d) Cyber-physical systems e) ICT collaborative platforms	a) Assist in IS execution b) Allows the capture of wide waste generation sources to facilitate the formulation of strategies for effective IS waste reuse c) & e) Potential to enable the establishment of a zero-waste management ecosystem. d) Can facilitate coordination among material, energy, and product flows across various production systems to promote cross-organizational collaboration.	Transformation of a traditional manufacturing plant into a I4.0 manufacturing plant.	Not specified	Promotion of cross-organizational collaborations among companies to achieve a competitive advantage through the exchange of materials, energy, and other resources.

Author(s)	Reference	Year	Digital technology evaluated	Advantages	Barriers	N Companies	Drivers
Termizi et al.	[178]	2022	a) IoT + b) Blockchain based data manageme nt platform	a) Interchange of data between various workplaces seamlessly. Real-time monitoring systems and data transfer have the capability to enhance and maximize productivity. b) Secure communicatio n and transactions, facilitates the traceability of resource exchange transactions.	a) Technological challenges: security vulnerability, interoperabilit y,and information technology (IT) and operation technology (OT) convergence, IoT network implementatio n b) Identification of appropriate blockchain algorithms a) + b) High development efforts for successful execution: ensuring the synchronizatio n between the IoT platform and the blockchain architecture	Not specified	The platform allows all stakeholders, to provide data regarding material, energy, and waste flows. These data can be used for material targeting, pre-feasibility analysis, identifying receiving and supplying enterprises, and optimizing the IS network.

Author(s)	Reference	Year	Digital technology evaluated	Advantages	Barriers	N Companies	Drivers
Godina et al.	[180]	2022	Blockchain	1. Enables quick transactions and easy integration of new participants. Improvement of the transparency, communication, awareness and security within an urban IS network. 2. Transparency: Every transaction is recorded and thus auditing is simplified 3. Scalability: it allows for easier scaling with minimal infrastructure changes.	1. Integrating blockchain into existing systems can be complex. 2. Implementing blockchain requires significant hardware and software investment. 3. Improper blockchain implementation can lead to data leaks. 4. Public blockchains may compromise data privacy. 5. Lack of regulations and outdated legislation can hinder adoption. 6. Some participants may resist adopting blockchain technology	Not specified	Enable fast transactions and facilitate the integration of new participants into the symbiosis network. Also, since every transaction is kept on the blockchain, makes auditing transactions much easier.

Author(s)	Reference	Year	Digital technology evaluated	Advantages	Barriers	N Companies	Drivers
Costa et al.	[181]	2022	Blockchain	1. Increased transparency 2. Traceability of waste materials 3. Potential support for circular economy practices such as reuse, servitization, reverse logistics, and IS.	1. Complexity of blockchain implementation 2. Hardware limitations 3. Challenges related to programming languages	Not specified	Support the identification of the materials and waste management chain, promoting IS. Creation of business opportunities within the industry itself that provide expertise to foster the circular economy such as reverse logistics, servitization, and IS.

Author(s)	Reference	Year	Digital technology evaluated	Advantages	Barriers	N Companies	Drivers
Minde and Bäcklund	[182]	2023	Artificial Intelligence	1.Enhancement of the utilization of waste gases within the symbiotic system by predicting future supply. 2. Diminishment of the dependence on oil to ensure continuous operations. 3. Foresight into future waste gas availability.	1.Necessity of secure, reliable, transparent, and accessible data to guarantee reliable and top-notch data throughout an IS 2. Necessity of tight cross-company cooperation, engaging diverse functions and specialists, to minimize miscommunications, train AI on accurate data, and streamline AI development.	3 symbiotic companies: steel manufacturer, energy producer, and energy utility company	1. Developing an AI in isolation is inadequate for fostering innovation and enhancing the circularity of an IS. Realizing the complete potential of AI within a symbiosis requires collaborative and coordinated efforts among companies 2. IS and digital technologies like AI foster more sustainable and competitive industries

Author(s)	Reference	Year	Digital technology evaluated	Advantages	Barriers	N Companies	Drivers
Bruel and Godina	[185]	2023	Blockchain	1. Facilitation of secure and automated transactions. 2. Improved data management and traceability of materials and resources for IS. 3. Enhanced transparency and trust among stakeholders. 4. Simplification of administrative procedures through smart contracts. 5. Potential for optimizing the operation of IS networks.	1. Technological challenges related to blockchain immaturity, scalability, and energy consumption. 2. Lack of infrastructure for blockchain implementation in some industrial sites. 3. Resistance to change and cultural barriers. 4. Financial constraints associated with initial investment and operating costs. 5. Lack of regulatory framework and incentives from government authorities	Not specified	Need to facilitate data collection, administrative procedures, optimization of financing programs, traceability of information, operational efficiency, security improvement, and fostering trust and transparency among IS stakeholders

Author(s)	Reference	Year	Digital technology evaluated	Advantages	Barriers	N Companies	Drivers
Mallawaarachchi and Jayakodi	[186]	2023	IoT	1. Real-time tracking and monitoring of material needs and availability for IS. 2. Reduced cost of materials through efficient sharing. 3. Integration of construction projects for resource exchange. 4. Reduction in greenhouse gas emissions and construction and demolition (C&D) waste.	Not specified	Not specified	Reduce knowledge and communication gaps between industry partners of the IS network. Assure real-time tracking, record keeping, and communicating material related data among the industry partners who have engaged in the IS network.

3.4.1. Discussion on Table 3

Analysis of Table 3b

Table 3b offers a concise yet comprehensive overview of various research papers that have delved into the role of digital technologies in enabling industrial symbiosis. It's a repository of valuable insights that have been distilled from these studies, providing a roadmap useful to explore and discuss the key findings.

The upcoming discussion will begin by highlighting some of the most noteworthy takeaways from this table, each of which paints a unique facet of the broader picture. By examining these results, it is aimed to offer a deeper understanding of the role digital technologies play in fostering industrial symbiosis and how it has been assessed hitherto in scholarly research.

Regulating the transition of manufacturing companies from their current linear economy ecosystems, towards intrinsically sustainable, innovative ecosystems based on circular economy and industrial symbiosis classifies as a complex task that is currently encountered by modern-day managers, and that is expected to persist and intensify in the future. Under these circumstances, digitalization is crucial in bolstering organizations and business models to navigate this transformation [188]. Indeed, one of its main advantages relies on effectively generating value from vast volumes of data through the timely, efficient, and effective oversight, control, and management of processes by introducing adaptable organizational models and integrated production management systems [188].

As it has been previously noted, one of the fundamental principles behind industrial symbiosis is the fact that the by-products, off-gas, water or energy streams originating from one company can be made productive by other organizations, comprising neighbouring communities as well. However, when the characteristics of these streams exhibit significant variability, such as variations in chemical or physical attributes and energy content, which is common in real-world scenarios, the opportunities for their utilization may fluctuate over time. Consequently, sensing and monitoring devices, which are one of the digital technologies enabling industrial symbiosis highlighted by Table 3b, play a crucial role. This is because they can gather the most detailed data possible about the streams in question, which is fundamental because the processes or systems receiving these streams are likely to be influenced by immediate or short-term characteristics rather than the average ones [188].

As a second, and significant technology that could play a prominent role in the process of industrial symbiosis, Machine Learning becomes apparent. This is due to the fact that, once the information about the relevant streams has been collected, it must be disclosed to the participating parties in a safe and secure way.

One of the primary concerns related to working with Big Data pertains to its veracity. In simpler terms, the existence of outliers, biases, noise, and any other types of irregularities in data can impede their relevance in relation to the problem or feature under observation [188]. This is exactly where Machine Learning proves its utility: it is extensively employed for data cleansing and anomalous data identification. For example, fuzzy inference systems are used to merge different well-known methods for spotting unusual data [189].

Once the veracity of the gathered information, which could be extensive and varied, is ensured, it is then important to interpret said information in a fast and efficient manner. In this context, the field of machine learning offers, once more, an array of tools and methods to extract valuable insights and meaningful knowledge from the data [188]. For instance, the gathered data, along with process knowledge can be further utilized to forecast basic characteristics of the exchanged streams among the parties implementing an IS solution, with the aim of enhancing their utilization [190].

Ultimately, for the benefit of all the employees and stakeholders involved in the symbiosis, the results of the data analyses, interpretations, and various optimization stages must be presented in a pragmatic and easily comprehensible manner, considering that plant managers and technical personnel may not possess specialized knowledge in information and communication technology [188]. With this objective in mind, the most recent technologies, including advanced Human-Machine Interfaces and Augmented Reality (AR), can be harnessed [191].

Through the initial analysis of one of the most noteworthy takeaways from Table 3b, it is possible to assess how industrial symbiosis can be enhanced by exploiting digital technologies. However, since data storage, secure sharing, and exchange of information between the different actors of a symbiosis network are fundamental components of the digitalization process, cybersecurity and its associated risks become a critical issue that must be addressed. This aspect continues to pose a significant obstacle to fully realizing the benefits of the ongoing digital transformation, and that's why considerable efforts will be directed not only towards implementing suitable technological solutions but also towards equipping workers at all levels with the necessary skills [188].

Digital Platforms

Continuing the analysis of the most relevant insights from Table 3b, it is important to mention how some scientific contributions focus on the role digital platforms, alternatively referred to as "collaborative platforms", "online digital platforms" or "web platforms", play on the facilitation of industrial symbiosis.

In the context of industrial symbiosis, digital platforms have the capability to aid in identifying potential collaborations and fostering connections between companies. They achieve this by facilitating the exchange of (real-time) information and aligning resource buyers with suppliers [176].

Indeed, industrial symbiosis digital platforms are primarily designed for information sharing, enabling open electronic markets, and delivering supplementary industrial symbiosis-related services that improve collaboration, involvement, and community awareness [172], [192].

In this context, matchmaking platforms help reduce informational barriers among companies. This is done, for instance, by raising companies' awareness about the availability or demand for a specific waste stream or asset, thereby reducing the expenses associated with seeking, bargaining, and overseeing symbiotic partnerships [193]. This highlights a fundamental advantage of digital platforms since for the correct development of industrial symbiosis networks, it is crucial for participants to timely access to resource and secondary material markets in align with their needs [164].

Digital platforms also aid overcome technical barriers to the implementation of industrial symbiosis: Many companies choose not to engage in industrial symbiosis as it falls outside their core business scope. These firms primarily focus on their production operations to meet market demands, rather than prioritizing resource optimization through collaborative efforts with other industries. Consequently, the technical skills necessary to recognize industrial symbiosis opportunities are not considered to be aligned with their primary business function [176]. In this sense, since expertise in sharing assets and exchanging by-products demands skills that are not the specialized focus of most firms, the involvement of a third party (company behind the digital platform) is seen as a way to facilitate industrial symbiosis given that it could offer user-friendly tools and consulting services to their users.

Furthermore, digital platforms necessitate minimal to virtually no alterations in the physical infrastructure of organizations interested in participating in a symbiosis network [161]. Since implementation faces minimal technical obstacles, companies could be easily drawn to the initiative, especially since it's often a third-party organization developing the interface through which the matchmaking takes place.

However, to make the most of those benefits, it's crucial to overcome certain barriers that could hinder their implementation. Among the most cited ones, it's possible to find that attaining a critical mass of users, on both ends of the platform (supply and demand), is fundamental to effectively support the exchanges in industrial symbiosis [161], [176], as well as the fact that the quantitative and temporal variables of supply side must be in alignment with those of the demand side [157]. Moreover, the lack of cooperation and trust between companies [157], renders the establishment of harmonious social relationships among all the stakeholders engaged in the symbiotic processes even more challenging [172]. Finally, economical implementation efforts, cultural orientation towards sustainability and the prediction of further opportunities for symbiosis network classify as supplementary factors that have also been considered by literature as restraints in the successful adoption of digital platforms [172].

Industry 4.0 – IoT

Another noteworthy finding from Table 3b, regards how Internet of Things (IoT) facilitates industrial symbiosis. A first overview of its application can be evaluated under the umbrella of Industry 4.0, in the sense of a smart digital factory. In this context, the utilization of, for instance, a network of sensors in a production plant, enhances symbiosis practices through the acquisition of real time measures of production processes [162], which, as previously mentioned, is fundamental because the processes or systems receiving symbiotic streams are likely to be influenced by immediate or short-term characteristics rather than the average ones [164].

Additionally, through a smart factory enabled by IoT, the transfer of data from machinery, systems, and sensors to end-user software is simplified [158], [178] and thus, companies are able to easily acquire valuable information on the current characteristics of the streams that flow across their plants, enabling them not only to understand which could be the best symbiosis alternatives, acting either as a supplier or as a customer of a specific material, but also identify waste generation sources that possibly were not acknowledged formerly.

IoT enables tracking how energy and materials are used in real time, and real-time tracking is demonstrated to be an important solution for industrial symbiosis and circular economy, that could enable efficient and timely operations [175]. Furthermore, from the table it was noted that IoT can be used for leveraging the sharing of materials among the construction projects under the concept of industrial symbiosis through a real-time data-driven platform [186]. The information network of IS supports the exchange of symbiosis-related raw data, encompassing details such as the types of materials available for exchange, the quantities to be shared, the frequency of material availability, and the quantities required by other partners in the IS network. Consequently, the authors have developed a model that leverages IoT technology to enable IS for the sharing of construction materials in the construction industry. In this proposed model, IoT is employed to facilitate the sharing of materials among geographically proximate construction projects through a real-time data-driven and smart platform [186].

Moreover, combining waste recognition, gathering, and conversion technologies along with IoT and collaborative platforms has the potential to enable the establishment of a zero-waste management ecosystem [177] which is in alignment with the principles of industrial symbiosis and circular economy. Following this train of thought, the benefits of a smart factory could be further exploited by employing simulation software through which companies are able to test the impact, in terms of performance and cost, of switching from virgin materials to materials coming from a symbiosis agreement. In this way, organizations could profit from experimentations without risk and obtain detailed insights before the actual implementation of the symbiosis practice [162].

In a recurrent manner, barriers arise that prevent the seamless application of Industry 4.0 technologies to enhance industrial symbiosis practices. Among these, the most relevant one regards the IoT network implementation in a traditional manufacturing plant. However, once this obstacle has been overcome firms must still face technological hurdles such as security vulnerability, interoperability, data analysis and transmission, and information technology (IT) and operation technology (OT) convergence [178].

Artificial Intelligence – Machine Learning

A further remarkable insight derived from Table 3b pertains to how Artificial Intelligence algorithms could boost the adoption of industrial symbiosis practices. Initially, AI algorithms like Artificial Neural Networks and Reinforcement Learning could be employed to enhance the value proposition offered by digital platforms. In this way, the stage of IS identification can be significantly accelerated and additional simulation and modelling modules could be integrated [166]. These modules, with the help of system dynamics and/or AI methods, could simulate and model scenarios of optimally used IS systems, considering the best possible connectivity among entities, material/energy flows, and system resilience [166], [168].

Moreover, by leveraging on Machine Learning, which is an application of AI, companies could benefit from the examination of the impacts of specific IS activities and disruptive occurrences, such as the arrival/departure of entities and fluctuating material/energy flows, as well as the simulation of the required adaptability range of flows (minimum-maximum flow) to ensure the IS system functions smoothly [168]. In this way, organizations could start consolidating insights for subsequent decision-making processes and prioritizing IS initiatives.

Here, once again, obstacles arise. Among these, it's possible to classify the monetary and temporal resources required to train the underlying AI algorithm from different IS activity patterns and data obtained from real case studies as one of the most restraining ones. Associated with this, the acquisition of relevant data bases of IS material exchanges, IS measures and structural IS formations for generating templates, along with IS actions with their associated numeric data which the AI algorithms can use for the learning process (training and testing) poses an equally significant challenge for companies interested in this initiative [166]. Finally, and of comparable importance to the aforementioned, the establishment of a global infrastructure of information networks (IoT) becomes imperative so that pertinent data from the actual world can be automatically gathered, interconnected, and shared for subsequent processing through intelligent, adaptive analytical models and machine learning techniques [168].

Blockchain Technology

To conclude the discussion, by analysing Table 3b, it is evident that blockchain technology presents a promising solution for overcoming the challenges associated with the implementation of industrial symbiosis networks, which are vital for achieving a more sustainable and circular economy. The potential of blockchain in supporting IS lies in its capacity to enhance trust, transparency, and efficiency in the exchange of resources, thereby fostering cross-sectoral synergies and promoting environmental sustainability.

Blockchain's decentralized and immutable ledger ensures that all transactions and data related to resource exchanges within an IS are securely recorded [174]. Every transaction is logged in a secure and immutable ledger, reducing the complexity of auditing processes. This transparency enhances trust among network participants and ensures the accountability of all parties involved [180], allowing them to verify the history of transactions and the authenticity of the shared information. Trust is crucial for encouraging companies to collaborate and exchange resources, which is a central aspect of IS. Additionally, the smart contract capability of blockchain further enhances this trust by enabling self-executing contracts, eliminating the need for intermediaries, and reducing the risk of disputes [174], [175]. Furthermore, blockchain's robust security mechanisms also protect sensitive data, fostering a secure environment for transactions [174]. Another crucial advantage is that the blockchain platform can collect and provide real-time data and performance metrics related to resource exchange and material flow. This resource matching is a fundamental aspect of industrial symbiosis, where one organization's waste becomes another's input. This knowledge sharing enables organizations to identify potential symbiotic relationships and align their operations more effectively, promoting a collective approach to resource management [181]. This data-driven decision-making approach empowers participants in industrial symbiosis to make informed decisions, optimize resource utilization, and identify areas for improvement. Also, the immutability of blockchain transactions ensures that data cannot be altered or tampered with. This is particularly crucial when dealing with sensitive and confidential information in industrial symbiosis, such as waste management or resource exchanges [185]. Furthermore, the use of tokens on the blockchain can represent the value of exchanged resources, making the economic aspects of IS more accessible and manageable. Companies can use tokens to facilitate transactions and incentivize resource sharing. Moreover, blockchain's traceability features can help monitor and verify the environmental impact of resource exchanges, which can be particularly valuable for demonstrating the positive contributions of IS to sustainability. This includes reducing waste and lowering greenhouse gas emissions [174]. Additionally, blockchain can provide a reliable record of IS activities, aiding in demonstrating compliance with relevant legislation and regulations [174]. This transparent record can help policymakers and regulatory bodies better understand and support IS, ensuring their growth and success in fostering sustainable IS.

Some barriers that constrain the implementation of the blockchain into the IS, include cultural and social challenges characterized by resistance to change and slow decision-making processes [185]. Participants accustomed to traditional supply chain platforms may resist the adoption of blockchain, requiring educational workshops and tests to promote awareness and acceptance. These organizational barriers emerge from the need for financial and human resources to integrate blockchain, with potential resistance from those accustomed to older systems, highlighting the importance of comprehensive training [185]. Financial aspects pose another challenge, with the costs of consulting, design, development, insurance, and maintenance to consider. Mitigation strategies involve exploring cost-effective alternatives, such as integrating existing platforms or hiring specialized agencies [185]. Moreover, the technological immaturity of blockchain technology raises usability and interoperability issues and addressing them requires external technical expertise. Data security and privacy issues can arise if blockchain implementation is not well-designed, potentially leading to data breaches or privacy violations. Finally, the lack of government measures and incentives represents a political and incentive barrier. Regulatory challenges exist due to the evolving legal landscape for blockchain technology, with a gap between current legislation and blockchain implications within networks [180]. These barriers collectively underscore the need for a thoughtful and strategic approach to implement blockchain successfully in IS networks.

Analysis of Table 3a

The analysis of various research papers has revealed several notable gaps in the existing body of knowledge. As seen in Table 3a, one particularly prominent gap identified in the review pertains to the limited number of real-life case studies. Among the 21 papers analysed, only 9 were found to be dedicated case studies. This finding underscores the scarcity of empirical evidence and practical examples to illustrate the application and effectiveness of digital technologies in fostering industrial symbiosis. The limited number of case studies raises questions about the extent to which these concepts have been practically implemented and it highlights an important avenue for future research. Further investigation and in-depth case studies may provide valuable insights into the main challenges and opportunities faced by businesses and industries in a specific country, as well as the potential benefits of leveraging digital technologies for achieving industrial symbiosis. Addressing this research gap is crucial for a more comprehensive understanding of the subject and for informing policymakers and researchers looking to harness the potential of industrial symbiosis in their respective fields. During the literature review, a diverse array of geographical locations from which the selected papers drew their focus was observed. While some studies offered an international perspective by addressing European countries without specifying individual nations, others were anchored in specific countries such as Italy, Portugal, Greece, Finland, Norway, Sweden, and Argentina. The inclusion of such a broad spectrum of locations confirms the global relevance and applicability of the topic of how digital technologies enable industrial symbiosis. This diversity of focus points towards an increasing area of research with the potential to yield valuable insights and practical applications across a wide range of industrial contexts, both within and beyond the locations explicitly addressed in the reviewed literature. However, it is notable that a substantial portion of the literature did not specify a geographical focus, which may indicate a need for more research and case studies in various regions to fully understand the worldwide implications of digital technologies in industrial symbiosis. As the field of industrial symbiosis continues to evolve, encouraging more in-depth investigations in diverse geographical contexts is essential to ensure that the findings and insights derived from these studies can be universally applied.

Additionally, the comprehensive literature review has revealed a wide array of sectors that have been examined in the context of how digital technologies facilitate industrial symbiosis. These sectors encompass diverse domains such as agriculture, manufacturing, water supply, waste management, industrial parks, peer-to-peer markets, eco-industrial parks, and construction. The presence of such a varied range of sectors demonstrates the versatility and adaptability of the concept of industrial symbiosis and the role of digital technologies in enhancing sustainability and resource efficiency across different industries. Notably, several papers did not specify a particular sector, which could suggest either a broader scope that transcends a single industry or a lack of explicit sector focus in those studies. The absence of sector-specific details in these cases confirms the need for further research to explore the potential applicability and impact of industrial symbiosis in various domains.

Considering the insights gained from the literature review presented in Table 3a, it is evident that a significant research gap exists, particularly concerning case studies. This study aims to address this gap by conducting a series of in-depth interviews of actual case studies that delve into the practical applications and outcomes of digital technologies in fostering industrial symbiosis specifically within the Italian industrial context. By addressing the scarcity of real-life case studies, the research aims to contribute to a more comprehensive understanding of the practical challenges and opportunities associated with industrial symbiosis, and how digital technologies can be harnessed for sustainability in the Italian industrial landscape. The insights gained from the interviews have the potential to inform decision-makers and industry leaders in Italy, offering them practical guidance on how to enhance sustainability and resource efficiency within their organizations, leading to more sustainable practices in various Italian industries, which could, in turn, reduce environmental impacts, improve resource utilization, and increase competitiveness in the global market.

In this context, the following chapters will be developed as follows:

Chapter 4 presents the analysis of the current operational industrial symbiosis practices within the Italian industrial context. This was performed by reviewing and updating the data base constructed by Pavesi M [15] through which it is possible to find the Italian corporations actively participating in the application of industrial symbiosis strategies. After the initial review of this database, it underwent further enhancements by evaluating which cases are employing digital technologies to promote symbiotic initiatives. Therefore, the result of this section is an updated overview of the Italian companies engaged in symbiotic practices, specifying which and how many of these are implementing digital technologies and which types of technologies are being used.

Chapter 5 presents the evaluation of 6 case studies that have applied the most used digital technologies identified in the previous section to foster industrial symbiosis, which is the primary contribution of this research to literature. 4 of these case studies relate to Italian companies, while the remaining regard European organizations, with the aim of providing an international perspective into the analysis. Interviews were conducted as a primary method of data collection to evaluate the selected cases.

Chapter 6 presents a further analysis of the results obtained from the interviews by assessing whether the barriers, advantages and drivers to digital technologies identified in literature align with those encountered by companies in the Italian and European context in the practical implementation of the technologies within an industrial symbiosis framework.

Lastly, Chapter 7 is specifically allocated to the conclusion of the research, encapsulating the main outcomes derived from the assessment of actual case studies that have practically exploited digital technologies in fostering industrial symbiosis. Finally, this section offers valuable insights for prospective studies, providing a foundation for further research in the field.

4 Digital Technologies enabling IS in the Italian Context

4.1. Active IS Practices in the Italian Context

Overview of the Initial Database

As concluded from Table 3a, the preceding literature review highlighted several notable gaps in the existing works. The main one being the lack of real cases present in the studies. Aiming to contribute to this evolving field, this work draws upon the foundational research of Pavesi M [15], whose thesis provided valuable insights into industrial symbiosis within the context of the circular economy in Italy. Pavesi M's work [15] extensively covered legislation, European policies, taxonomy, and case studies, offering a robust basis for the following research.

Pavesi M's work [15] started by providing a literature review to understand the scope of IS, categorizing cases into real and potential IS scenarios. Out of 102 initial papers analysed, 35 addressed IS or potential IS cases, with 18 focusing on real IS cases. The additional 67 articles were used to explore IS-related strategies, barriers, and opportunities. The gathered data was organized into a database, enabling the categorization of cases by taxonomy, sectors, proximity and involved companies. The following steps followed by Pavesi M's research [15] involved contacting the companies, as well as creating a map and analysing the collected data. The Italian Industrial Symbiosis map was constructed along two key axes: proximity (x-axis) and the number of sectors involved (y-axis), with proximity indicating whether IS case partners are within about 30km of each other, and the y-axis focusing on the number of industries involved, rather than individual players. In Italy, geographic proximity is significant, with 71% of the 31 Italian IS cases operating in proximity and collaboration with Public Administration being more achievable in such cases. The most common interaction occurs between the agri-food and chemical-pharmaceutical sectors, for example, utilizing agricultural waste for food supplements or beauty products. Furthermore, it was noticed that Public Administration involvement often focuses on wastewater and waste management for energy production. Additionally, the research classifies Italian IS cases into different types, with Type I involving the purchase of recycled materials or waste to produce new products, Type II involving sharing leftovers within a firm's business units, Type IV focusing on building a network to reduce waste, and Type V involving a central authority facilitating connections between firms over a larger geographic distance. The absence of Type III, the Eco- Industrial Park, indicates room for expanding the range of sectors involved, especially when considering successful examples from other European countries such as Denmark, Sweden, and Austria, where eco-industrial parks collaborate with various sectors and industries.

After doing the respective interviews, the study discusses a comparison between barriers identified in academic literature and those confirmed through real case managers and entrepreneurs in the context of industrial symbiosis. Among the discrepancies found by Pavesi M [15] it was found that in academic literature, it's noted that limited awareness and understanding of IS can be a barrier to its implementation, nevertheless, the interviews with real case managers and entrepreneurs confirm that knowledge is essential, but they also emphasize that the commitment of business leaders and managers is a more critical driver for IS, rather than knowledge alone. Also, academics associate the lack of technology and R&D projects with low economic support, but interviews suggest that such actions should be placed in the Legislation and Policy cluster, highlighting the critical need for technological support, such as software and databases, to quantify waste, a fundamental step for IS. These technologies can facilitate intercompany communication and simplify the process of identifying partners capable of giving or receiving waste materials. To address the challenges stemming from a scarcity of accessible technology, governments should increase their investments in research and development, focusing on technological advancements. This should involve closer collaboration with research teams from universities and business associations [15]. The conclusions drawn from this study highlight the significance of the research in the context of digital technologies for industrial symbiosis. The findings emphasize that digital platforms and programs can effectively address various barriers in the implementation of industrial symbiosis, enabling better collaboration and the identification of potential partners for waste exchange. Furthermore, the study underscores the necessity for increased government investments in research and development to advance technological innovations in support of industrial symbiosis. These conclusions underscore the timeliness and relevance of the present study, which aims to explore and promote the role of digital technologies in facilitating more sustainable and efficient industrial symbiosis practices.

Review of the Initial Database

Providing an insight into the contributions given by Pavesi M's work [15] was fundamental since the data base developed by said study served as the starting point for the evaluation of the active IS cases in the Italian context. As previously mentioned, the database consisted of 31 IS cases, which was constructed in 2022. The database was first reviewed with the aim of ascertaining whether the cases listed continued to exemplify ongoing industrial symbiosis practices within their respective industries. The assessment started by evaluating the main source cited and was subsequently completed through trustworthy sources of information such as scholarly articles, company websites and primary sources of information like phone calls and emails with relevant contact points of each case under study. As a result of this first evaluation, the field "Development stage" was added to the database. Through this field, it was possible to categorize each case as "Practice", "Case Study" or "No Longer a Practice". In this sense, "Practice" identifies all the instances that classify as cases where companies are actively adopting industrial symbiosis practices within their operations. "Case Study" refers to the scenarios that developed industrial symbiosis synergies specifically for scientific research or projects programmed to last a finite duration. Finally, "No Longer a Practice" notes industrial symbiosis initiatives that were stopped or put on standby.

As a result of this review, out of the 31 initial cases presented, it was assessed that 1 could be eliminated, since it constitutes a project that mainly promotes an informative guide to enhance citizens' understanding of how the waste they produce is treated once it reaches the dedicated facilities for its management, and more specifically, its recovery. Then, out of the remaining 30 cases, 8 were classified as Case Studies, 2 as No Longer a Practice and 20 as Practices.

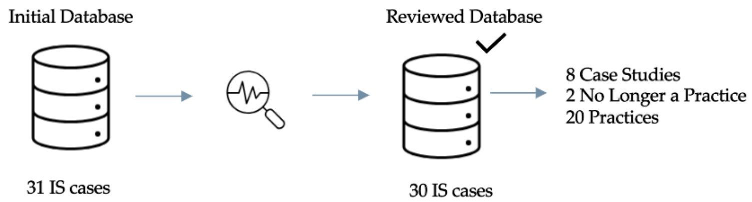

Figure 14. Results of revision of Initial Database.

"No Longer a Practice" Cases Overview

In this context, before delving further into the analysis of the initial data, it is now aimed to outline the factors that led the two cases that in the original database were reported as active industrial symbiosis practices, to stop or put in stand-by their operations.

1) The first case regards a company working in the Italian agri-food industry, specializing in the production of almonds, pistachios, and hazelnuts. The industrial symbiosis initiative consisted in employing the residual almond material to recover the 'hull' for the creation of supplements, one of the primary product offerings of a not cited company operating within the Italian chemical-pharmaceutical industry. The project was stopped due to technical reasons: it was not possible to find a machinery supplier that could provide the equipment that met the requirements for the process of water extraction and cleaning of

the almond waste material within the desired time. This information was obtained from a primary source, specifically from an interview with a Quality Department worker at the primary company under consideration, whose name cannot be disclosed for privacy reasons.

2) The second instance concerns a company which operates in the chemical-pharmaceutical sector within the Italian context. This organization is an innovative agricultural company primarily dedicated to complete natural cycle heliciculture for gastronomy and cosmetics. They not only market snails, already cleansed and ready for the kitchen but also produce a cosmetic line utilizing the mucus from the snails obtained through entirely cruelty-free processes. At the core of the industrial symbiosis initiative was the utilization of fruit and vegetable scraps as feed for the snails, provided by various companies operating in the Italian agri-food sector. Furthermore, the subsequent waste generated by this process would be repurposed within the company for the creation of vermicompost. This vermicompost, a nutrient-rich organic fertilizer, would then be reused to restore and enhance field fertility, completing the cycle of sustainable resource use within the company's operations. However, the initiative was put on standby due to the minimal amount of waste suitable for composting, making it unsustainable even at minimal production levels. Indeed, apart from a few scraps designated for composting, almost all the material was effectively consumed by the snails. The insights presented were acquired directly from a primary source, namely through email correspondence with an employee at the principal company under examination. The disclosure of its name is withheld to ensure privacy.

Update of the Initial Database

Once the initial cases presented in the database were reviewed, a further evaluation was developed to delve deeper into the examination of the Italian context and update the database accordingly with active cases implementing industrial symbiosis practices that had not been previously included.

This subsequent review was produced by searching information not only through scientific search engines such as ScienceDirect, Scopus and Google Scholar but also through the EcoCamere webpage, a project developed by the Italian Chambers of Commerce, per which it's possible to find best practice cases driven by the ESG (Environmental, Social and Governance) criteria, and thus serves as a valuable source of information when exploring the Italian context and trying to find active cases practicing industrial symbiosis. The Ellen MacArthur Foundation website was also visited since it offers the most comprehensive and relevant information on the circular economy and case studies that are implementing circular practices like industrial symbiosis.

This assessment resulted in the identification of 8 new active cases that were consequently added to the database and for which each field was respectively filled. These cases are constituted by: Gruppo Caffè Vergnano, Prato industrial district, Circularity, Versalis, L.M.A. s.r.l., the Aretusa Consortium, iZ precious and Piattaforma di Simbiosi Industriale ENEA. The company mentioned is the reference point of the case, since of course, industrial symbiosis instances require more than one participant.

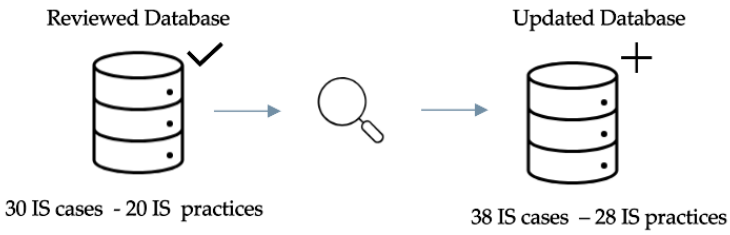

Figure 15. Results of updating the reviewed Database.

4.2. Digital Technologies enabling Active IS Practices in the Italian Context

Once the database was reviewed and updated, all the cases under the "Practice" category were further assessed to address from a practical perspective the primary research question of this study: how digital technologies enable industrial symbiosis, within the Italian industrial landscape. In prioritizing practical cases, the intention was to discern and highlight the disparities and alignments between theoretical constructs identified in the existing literature and the tangible realities observed in real-world industrial symbiosis scenarios. Extensive efforts were made to engage with authors and companies associated with each case, aiming at gaining insights about the strategies, challenges and outcomes related to the integration of digital tools within these industrial symbiosis contexts. Survey responses from companies revealed a diverse outlook in the adoption of digital technologies. Some of the most mentioned ones included: Cloud Technologies for Internal Business Management, use of cloud-based management systems and emails, use of Google Drive for archiving, matchmaking digital platforms and blockchain technology and artificial intelligence also in the context of a digital platform. Cloud technologies for internal business management emerged as a relatively common digital practice among the respondents. However, its application is often limited to general business processes rather than specifically enhancing industrial symbiosis. Among other findings, a trend towards the implementation of digital platforms for industrial symbiosis purposes was identified. Some findings of these sort of platforms include iZ Precious which integrates blockchain technology to facilitate resource exchange between dismantling centres and recovery plants, particularly in the luxury industry. The Circularity platform also stands out as a main character in fostering symbiotic relationships between manufacturers and waste management entities, by connecting manufacturers with companies and producing by-products, acting as a dynamic marketplace. Furthermore, the ENEA symbiosis platform function by cultivating synergies among manufacturers operating within the Italian industrial landscape. Finally, another innovative platform found revolves around the fusion of a digital marketplace and Artificial Intelligence within the operations of Atelier Riforma. The integration of a digital marketplace and AI showcases a sophisticated approach to industrial symbiosis, emphasizing the role of cutting-edge technologies in optimizing the recovery and utilization of resources within the fashion and textile sector. These conclusions are consistent with the information presented in Table 3b, where it was observed that digital platforms possess the capacity to assist in identifying prospective collaborations and nurturing connections among companies, by enabling the seamless exchange of real-time information and aligning those seeking resources with potential suppliers [176].

Despite the diversity in responses, a considerable number of companies did not provide insights into their digital practices, signalling potential challenges in obtaining a comprehensive overview. Moreover, another significant number of companies revealed that they are not currently leveraging digital technologies for these practices. Instead, traditional methods such as emails, contracts, and in-person interactions remain prevalent, especially among smaller establishments. Figure 16 below presents an overview of these findings.

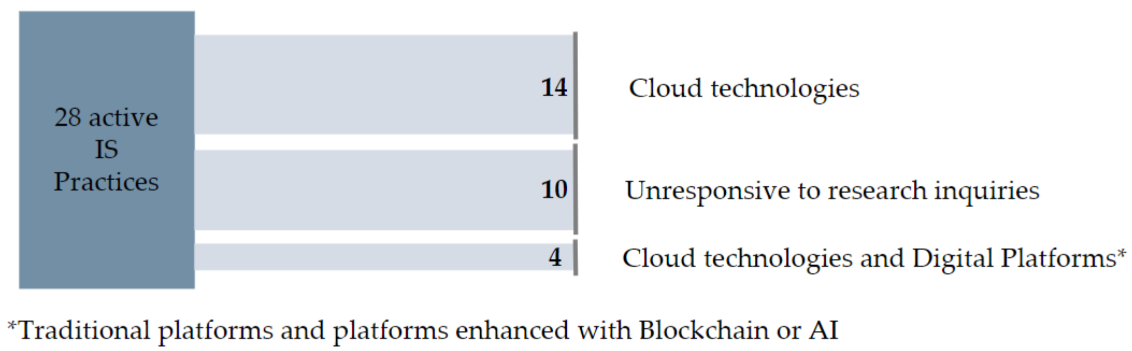

Figure 16. Digital technologies enabling IS practices in the Italian context.

As a final summary of the findings previously presented, encompassed by Figure 16, it's important to highlight that Italian companies have a limited level of digitalization, with the predominant use of cloud technologies. It was observed thar the companies' digitalization efforts are primarily directed at internal business management software systems, emails, ICT, search engines and fundamental digital tools necessary for everyday business operations. Nevertheless, it's not unexpected to confirm that in the examined cases the choice is limited to the use of cloud technologies, as according to Eurostat, a mere 42% of Italians aged 16 to 74 possess basic digital skills, positioning behind the EU average of 58%, which significantly impacts the use of digital services. In the European context, Italy ranks the lowest in terms of internet usage, with 17% of individuals aged 16 to 74 having never accessed the internet—nearly double the EU average of 9%, based on Eurostat's 2019 data. Additionally, the statistics indicate that only 1% of Italian graduates hold an ICT qualification, placing Italy at the bottom within the EU. Despite the gradual increase in the percentage of ICT specialists in Italy, reaching 3.6% of total employment, it still falls below the EU average of 4.2% [29].

Additionally, among the digital technologies discussed, Figure 16 shows that Digital Platforms emerge as the most widely adopted of the technologies within the real business landscape of Italy. This phenomenon is backed up by the literature review developed in Table 3b, where approximately 33% of the papers discussed appeared to include digital platforms in their domains. Following these findings, the focus of this research will be emphasized on understanding and leveraging digital platforms for IS.

5 Case Studies implementing Digital Technologies to enable IS within the Italian and European Context

This section presents the findings of 6 real case studies that have implemented digital technologies to promote industrial symbiosis, constituting the main contribution of this research to the existing body of literature. Among these cases, 4 pertain to Italian companies, while the remaining cases involve European organizations, offering an overview also from an international perspective. In the pursuit of a comprehensive understanding of the case at hand, interviews were conducted as a primary method of data collection. These interviews served as a means to directly engage with individuals closely connected to the case, facilitating the extraction of firsthand information.

By interacting with professionals working in the context of industrial symbiosis and digital technologies, the research aimed to gather multiple perspectives, uncover unseen details, and delve into personal experiences that may not be apparent through other data sources. In this context, the interviews will be presented by initially providing a description of the case, followed by the challenges, advantages and drivers that the professionals have experienced while implementing digital technologies to enable industrial symbiosis. Finally, relevant additional information supplied by the interviewees will be disclosed.

5.1. Italian Findings

The four practical Italian cases evaluated regard the most relevant findings of the updated database discussed in the previous section. These practices can be classified as the most relevant ones since the digital technologies employed represent the most advanced ones within the database evaluated: **Digital Platforms and Blockchain and AI within the scope of a digital platform**, and are composed by: Atelier Riforma, iZ precious, Circularity and Piattaforma di Simbiosi Industriale ENEA. Consequently, by prioritizing the most up-to-date cases, this evaluation aims to provide a comprehensive and contemporary analysis, ensuring that the insights derived are reflective of the forefront of technological innovation within the dataset.

5.1.1. Interview 1 – Atelier Riforma

Atelier Riforma is an innovative startup founded in 2020 with a focus on promoting circular fashion and social inclusion. The company operates as a platform that connects a network of tailors, designers, and social tailoring workshops across Italy. Their mission involves transforming and upcycling discarded clothing, adding value to the garments, and reintroducing them into circulation through a dedicated marketplace. This platform has become a pioneering force in the circular economy, relying on a multifaceted technological approach, including online platforms, artificial intelligence (AI) and algorithmic logic. In the interview with the CEO, a deep dive was taken into the innovative technologies employed by Atelier Riforma and the challenges and advantages encountered in their journey.

The CEO began by emphasizing the crucial role of their online platform and AI in fostering collaboration within the circular economy. Beyond these, additional algorithms, such as a pricing algorithm based on garment characteristics, have been integrated to streamline processes. The platform operates as a transparent B2B digital marketplace, connecting entities and businesses to efficiently trade wholesale unused garments, promoting circularity in fashion. The AI, crucial for classification and digitization, analyses garment images and labels, extracting vital information for enhanced valuation. Atelier Riforma adopts a proactive approach to engagement, reaching out to potential B2B partners through networking events, social media, and email campaigns. Simultaneously, businesses express interest independently, drawn to the potential of integrating their operations into Atelier Riforma's circular ecosystem.

Barriers

Addressing barriers, the CEO highlighted the hurdles of venturing into an entirely new technological domain without prior expertise. Collaboration with experts, engineers and data scientists played a crucial role in overcoming these challenges. Fundraising was also an initial obstacle, requiring a strategic approach to garner support. The development process involved creating an embryonic version of the platform, manually cataloguing garments and extensive training of the AI algorithm. Discussing potential areas for further development in digital technologies for industrial symbiosis, the interviewee highlighted challenges within Italy's regulatory landscape concerning the sale of used garments. Simplifying these regulations could significantly enhance circular processes. Additionally, the technology adoption gap within traditional entities involved in garment collection poses a considerable hurdle, necessitating extensive training and information dissemination.

Advantages

The interviewee also outlined key advantages stemming from their technological innovations. Automation accelerates and systematizes processes, but the most significant advantage lies in creating a tool accessible to diverse entities globally. By providing this technology beyond internal use, Atelier Riforma envisions scaling its positive impact on circular models worldwide. Metrics for measuring impact were also discussed. Key indicators include the quantity of garments diverted from landfills, promoting reuse and recycling. Additionally, the platform enables substantial resource savings by utilizing existing materials, a metric derived from reputable online studies and scientific documents.

Drivers

Exploring the drivers compelling Atelier Riforma's digital platform, the CEO highlighted the significance of enabling communication between entities that would otherwise struggle to connect. Identifying major players and evaluating compatibility emerged as key drivers for utilizing the platform. This underscores the dynamic role that technology plays in reshaping industrial relationships in the pursuit of sustainability. The emphasis on communication and networking, facilitated by digital solutions, reflects the transformative power of technology in reshaping industrial relationships in the pursuit of sustainability.

Security measures for data sharing were addressed, emphasizing transparency in basic company information for transactions. Garment information, being shared openly, undergoes a meticulous process, with each item being plastic-coated to convey comprehensive details from the seller to the buyer. Finally, the interview concluded with the interviewee acknowledging the presence of other platforms and startups in Italy focusing on waste exchange and circular models. Notable examples include Sfrido and Circularity, addressing various waste types beyond textiles. Mainstream consumer-to-consumer platforms like Vinted and Depop were also recognized, though their impact on sustainability remains challenging due to the one-item-at-a-time nature of transactions.

5.1.2. Interview 2 – iZ Precious

iZ precious is an Italian based platform startup, supported with blockchain technology, created with the aim to support luxury brands in their journey towards sustainability. More in detail, through the iZ platform, jewellery, watches and fashion accessories brands can access to precious metals made using materials recovered from the electronics recycling industry (through dismantling centres and recovery plants) in a certified reverse supply chain that respects the ethical principles of social sustainability and embraces industrial symbiosis [194]. Indeed, iZ precious aims to turn the Urban Mines problem into an opportunity for the fashion and jewellery industry: the possibility to use an alternative and sustainable source of gold, silver, and palladium. Through the development of a digital platform and the creation of a certified and traceable supply chain, iZ Precious provides brands with a valuable story that resonates with a new consumer.

It was possible to communicate with iZ Precious' Chief Executive Officer to gain essential firsthand knowledge vital for comprehending the significant role this platform and the creation of a traceable supply chain play in enabling industrial symbiosis practices in Italy within the luxury sector.

As a starting point, the interviewee expressed how this tool supports industrial symbiosis practices by declaring: "Within the iZ supply chain, there is a partner engaged in the procurement and trade of gold and precious metals. This partner acquires gold from iZ-certified facilities and subsequently sells it to certified brands. In this sense, iZ suppy chain consists of disassembly centers, recovery plants, buyers of gold, and those who use it on the brand's end. However, it is important to emphasize that iZ's role is to ensure the certification of the entire supply chain, which, at present, lacks cohesion. This certification can be done thanks to digital tools like the platform and blockchain, which contribute to enhancing a narrative that currently does not exist".

Drivers

The interviewee was then inquired about the drivers that could motivate companies to utilize this tool, to which it was assessed: "As of today, what any brand can declare is whether they use gold from mining or recycled gold. Whether it comes from jewellery waste, electronic waste, or dental recovery is not currently recorded. Therefore, iZ aims, in a way, to prompt brands to address the issue of electronic waste" In this context, it was then further added that: "We're addressing a problem that is now everyone's concern because we all have a cell phone, a PC, or a smartwatch. In this sense, we can satisfy the appetite for sustainability stories to tell in the luxury world. Currently, there isn't a brand, certification scheme, or platform for this, which is why iZ was born. For example, with iZ Gold, when we talk about gold, we mean gold that comes from electronic waste through a certified, sustainable supply chain committed to social projects".

Advantages

When asked about the advantages that could be obtained by leveraging on this tool, the interviewee stated that: "Beyond the drivers previously mentioned that can also be seen as benefits, we are developing the idea to employ blockchain to address traceability, which makes part of the value proposal of iZ. The process we have devised with our industrial partners involves creating an NFT (Non-Fungible Token) for the metal to balance the quantity of precious metal within the luxury industry. Let me provide a simple example: a mobile phone cannot yield 1 kg of gold. To regulate this, we employ blockchain technology throughout the entire supply chain. Thus, the NFT for precious metal can only be generated if specific conditions within the supply chain are met. This mechanism ensures, for the luxury world, that if a facility is selling iZ gold, it is because it has adhered to certain parameters within the supply chain. These parameters are verified transaction by transaction, enhancing the concept of trustiness, which is a process that is currently absent in the luxury industry".

Furthermore, it was added that: "On the other hand, it also provides companies the opportunity to demonstrate to the market that they are truly transparent businesses, which could turn into a competitive advantage today. Indeed, at that point, it can give rise to a premium price. The iZ gold costs more, but it's not an expense; it's an investment that can be redistributed within the supply chain to fund social and sustainable projects."

Barriers

Conversely, when inquired about the barriers to the implementation of this tool to promote industrial symbiosis, the interviewee stressed that: "As of today, the challenge lies more in the sharing of data than in technological barriers. An example I often use to discuss this model is that we are currently in a situation like the Internet in the 1990s when people were reluctant to put certain data, like bank account details, online. Nowadays, paying with credit cards online is common, and even cars can be purchased. However, in the 1990s, it was not the case".

As a final query, it was asked which indicators are being used or were considered to employ to measure the effectiveness of the process, specifically for industrial symbiosis, to which the interviewee stated: "Mainly, as of now, the indicator is the number of transactions, meaning the number of NFTs we will generate" The interviewee then highlighted how for the generation of these NFTs, they rely on assistance from another company, mainly because "it's challenging to find people nowadays. Therefore, we have leaned on the expertise of other companies.

5.1.3. Interview 3 – Circularity

Circularity also operates in the context of industrial symbiosis. The company employs an algorithm embedded in its platform, which serves as a facilitator for collaboration among diverse enterprises, including manufacturers, recycling facilities and end-users who incorporate recycled materials into their processes. Communication with Circularity's Chief Executive Officer provided essential firsthand insights crucial for comprehending the significant role of this platform. This sophisticated platform accommodates distinct categories of businesses, comprising producers, recycling plants and end-users. These entities register on the platform and furnish essential information through a comprehensive questionnaire, elucidating the types of materials they handle, the nature of their waste materials and their specific requirements for finding new suppliers or integrating recycled materials. The algorithm within the Circularity platform then allows matches between these companies, categorizing materials meticulously to ensure precise links. The platform goes beyond mere matchmaking, delving into environmental impact metrics. It calculates metrics such as the CO2 emissions saved by opting for one partner over another, thereby offering a holistic view of the ecological benefits associated with different collaborations. The configuration of the resulting supply chain involves companies inputting details about their existing suppliers. This approach allows the platform to measure the current environmental impact of their supply chain. Furthermore, it enables companies to compare this impact to the potential environmental benefits that could be realized by choosing new partners. This comprehensive approach allows the tracking of waste materials from their point of origin to their final destination, providing an encompassing understanding of the waste management process.

In terms of geolocation, Circularity deploys algorithms integrated with Google Maps to locate businesses on the map, enhancing the platform's usability and accessibility. Additionally, the company is at the forefront of technological advancements, developing artificial intelligence capabilities to verify the authenticity of uploaded documents. This feature ensures that users provide accurate and reliable information, adding an extra layer of credibility to the platform. To quantify circularity, the platform utilizes indicators such as the performance of recycling facilities, measuring the amount of material recycled compared to the material entering the facility and associated CO2 emissions. The platform introduces a "circularity assessment," enabling participating companies to evaluate their circularity percentage.

Barriers

However, the implementation of such a groundbreaking initiative did not come without its share of challenges. Regulatory hurdles proved to be a significant barrier, with convincing companies to embrace new waste management paths proving challenging due to legal implications and potential penalties associated with waste management practices. Additionally, the lack of publicly available databases of facilities in the waste treatment sector complicated information gathering, necessitating extensive efforts to register new facilities on the platform.

Advantages

According to the CEO, the benefits of Circularity's platform extend beyond individual companies, contributing valuable data for community-level insights into circularity. By offering data that companies can include in their sustainability reports, Circularity provides a valuable metric that enhances their sustainability profiles. The platform empowers businesses to make informed decisions based on both environmental impact and cost considerations, addressing a crucial information gap in the industry. Circularity's implementation of industrial symbiosis has a transformative impact on the economic performance of participating companies. As businesses explore alternative waste management methods and focus on waste reduction, they experience economic benefits, especially concerning by-products, which can be leveraged as valuable assets rather than treated as liabilities. The company also ensures that information within the platform remains confidential, with companies retaining control over what they choose to make public. Upholding user privacy, Circularity utilizes private data solely to assist companies within the platform.

Drivers

The interviewee highlighted how the drivers for Circularity in adopting digital technologies include the facilitation of connections among diverse businesses in the waste management sector. These technologies enable a transparent and efficient supply chain, allowing businesses to find suitable partners for recycling and waste utilization. Additionally, the platform looks to contribute to sustainability by measuring and optimizing the environmental impact of waste management practices and calculating CO_2 savings, aiming to enhance resource efficiency, reduce waste and promote a more sustainable industrial ecosystem.

Looking towards the future, Circularity envisions the development of a blockchain to trace the waste value chain and carbon credits associated with CO_2 savings. The company aims to utilize blockchain technology to enhance transparency and accountability in waste management processes. Additionally, Circularity contemplates potential integrations with the Internet of Things (IoT) for real-time data collection using sensors or cameras. While not directly providing sensor technology, the company explores partnerships with existing IoT providers to enhance data accuracy and efficiency in waste management processes.

5.1.4. Interview 4 - Piattaforma di Simbiosi Industriale ENEA

The Italian National Agency for New Technologies, Energy and Sustainable Economic Development, ENEA, stands at the forefront of fostering sustainable practices through innovation. One of their notable initiatives is an industrial symbiosis platform designed to connect businesses and facilitate resource sharing. A representative of

ENEA's Sustainability Department provided comprehensive insights into the platform's functionality and impact. The platform initiated in 2011 and operationalized around 2012, emphasizing its continual evolution over the past decade. Companies engaging with the platform can register at different levels, each unlocking specific features tailored to their needs. The interviewee detailed the synergy search tool, an advanced functionality available to companies at higher registration levels, allowing them to explore potential matches by entering specific resource-related keywords. A notable aspect is the incorporation of what ENEA terms as "arcs", these arcs represent pathways defined by ENEA researchers within the platform, outlining specific potential synergies between different resources. This unique approach adds a layer to the matching process, facilitating more precise and context-aware connections between companies.

While artificial intelligence was not directly integrated into the platform, the representative revealed that its development was outsourced to an external company. Technical challenges were encountered in aligning the platform's capabilities with ENEA's specific requirements, emphasizing the importance of integrating ENEA's know-how to create a platform focused on more sophisticated searches than conventional keyword associations. ENEA's role as a facilitator for collaboration, rather than a profit-driven intermediary, sets its platform apart. It was emphasized that ENEA's commitment was put into fostering communication between companies for mutual benefit, in contrast to commercial marketplaces.

Barriers

Among the obstacles faced during the platform's development, technical complexities, and the challenge of effectively conveying ENEA's needs to an external development team were highlighted. Navigating Italy's regional regulatory landscape, particularly concerning waste and by-products, emerged as a formidable barrier. The interviewee stressed the importance of revising regulatory frameworks to create an environment conducive to industrial symbiosis.

Advantages

Addressing the benefits for participating companies, potential economic advantages were mentioned, including reduced waste disposal costs and optimized resource utilization. It was emphasized by the interviewee the economic impetus that serves as a fundamental driver for companies engaging in industrial symbiosis. Additionally, in terms of data security, the platform offers companies the option to remain anonymous, ensuring sensitive information remains confidential unless explicitly made public by the concerned company.

Drivers

In the interview, the representative outlined the driving forces behind ENEA's industrial symbiosis platform. The primary motivation is to foster collaboration among companies, enabling them to identify and engage in synergistic relationships for more sustainable resource management. The economic benefits act also as drivers, where companies stand to gain from reduced waste management costs and potential efficiencies in their supply chains. The platform's goal is to leverage the advantages of proximity among businesses, ensuring that the economic benefits outweigh transportation costs in waste exchange. Ultimately, the company's motivation lies in creating a circular economy, where waste materials become valuable resources, aligning with the broader objectives of sustainability and environmental responsibility.

5.2. European Findings

Since the evaluation of the digital technologies employed to foster industrial symbiosis within the Italian context resulted in the identification of digital platforms as the most spread one, when evaluating the European context, it was decided to focus as well on this type of technology with the purpose of providing a comparable and extended evaluation of Italy's national situation. In this sense, information was gathered about relevant practices not only through scientific search engines such as ScienceDirect, Scopus and Google Scholar but also through The Ellen MacArthur Foundation website and the section of Business Innovation Observatory of the European Commission online page. As a result of the research, two leading platforms were identified: iNex Circular, which also exploits simulation software, and Online Brine Platform, with headquarters in France and in The Netherlands respectively. The findings from the interviews are presented below.

5.2.1. Interview 5 – iNex Circular

iNex Circular is the first European platform for the implementation of circular economy synergies to optimize waste and raw material management. With a substantial presence of 30,000 registered enterprises spanning France, Belgium, and Spain, the platform serves over 100 clients across Europe [195]. Its headquarters are located in France, and it was possible to contact its Chief Executive Officer to obtain invaluable firsthand insights crucial for the understanding of how digital technologies, and in this case, digital platforms, enable industrial symbiosis practices. As a starting point, the interviewee detailed the functionality of the platform. It was stated that the platform operates by simulating waste flows from various entities, such as companies, farms and the public sector. The interviewee highlighted how the simulation is developed to both waste producers and waste takers, where sorting centers are distinguished from transformers. Sorters prepare materials without transforming waste, while transformers, such as bio companies or manufacturers, convert waste into new materials. The platform supports both sorting centers and transformers by simulating their waste needs, although the models for waste transformers are less robust and comprehensive compared to those for sorting centers.

When inquiring further about the core activities of iNex Circular as a platform, the interviewee assessed: “The technology primarily revolves around simulating resource wastage. However, our service differs slightly. Our main focus lies in assisting the recycling industry, which constitutes the core of our business. We also engage with local authorities to identify potential synergies between waste producers and waste takers, operating not only in France but also in other countries. However, this collaboration contributes to only about 20% of our total revenue. Most of our turnover is generated from our extensive work within the industry”. Subsequently, in order to get a clearer picture of how the technology enabled industrial symbiosis, the interviewee was requested to provide additional information on the process of identification of potential synergies, to which he responded= “The process involves identifying the waste producers and takers by scraping open data. Subsequently, these actors are quantified by evaluating their activities and sizes. The third step regards the waste flows simulation, with the tool, and finally, potential synergies are identified. Based on this, consultancy firms are going to work on potential synergies. We don't work on the implementation of the symbiosis. It's consultancy firms that are going to work on that.”

Barriers

When inquired about the barriers encountered in the implementation of the digital platform to foster industrial symbiosis, the interviewee expressed that initially, they believed it would be feasible to simulate the required resources for every industry type. However, as they gained practical experience in the field, they discovered that this approach is not effective. The potential recipients are actually quite limited. Although there are various entities such as sorters, actors, and businesses that may seem abundant, the specific factors for each material type are considerably constrained. Consequently, they have narrowed their focus to 10 types of materials, including biowaste, plastic, wood, textiles, construction, demolition waste, and more. Concluding with: “that's how we perform the synergies, it's not resources needs vs resources waste. It’s more about understanding the recycling schemes, understanding the types of materials you work with.”

The interviewee further included that another crucial challenge lies in the actual implementation of synergies since the platform is “just a means to an end”. He stated that the main goal is to actively create projects that conserve resources, but that in France, the methodology for fostering industrial symbiosis is often inefficient. He highlighted how workshops are organized where stakeholders gather to discuss resources and waste after the platform indicates a potential synergy. However, often, significant synergies with substantial volumes of waste transformation do not emerge from these efforts from the public sector.

Advantages

On the contrary, when the interviewee was questioned about the advantages obtained through the platform, it was stated that: "Most of the benefits of the platform are actually being seen when we work for the industry, when we work directly for an industrial company. They're very pragmatic, so they use our tool to source waste for a specific recycling plant or project, for example. And it is implemented. When we work for the authorities instead, it depends on the project, and as said before, not significant synergies emerge from these efforts."

Drivers

The interviewee was then interrogated about which could be drivers that compelled companies to employ the platform, to which it was answered: "From the tool, our clients can identify the major actors, the top players and they can evaluate if they could be a match" In this sense, it was highlighted that how the platform facilitates the communication between enterprises that could not be possible otherwise.

As a final comment, the interviewee gave some insights on the indicators used to measure the impacts of the synergies enabled through the platform, expressing that: "We monitor the amount of waste recycled for government projects. However, when dealing with industrial projects, we don't specifically track the waste quantity. This is due to the complexity of distinguishing between the quantities originating from the iNex tool and those from other tools".

5.2.2. Interview 6 – Online Brine Platform

The Online Brine Platform is a matchmaking platform developed by the National Technical University of Athens in the framework of ZERO BRINE project, initiative coordinated by the Delft University of Technology in the Netherlands with the purpose of promoting business model solutions within the circular economy framework to minimize industrial saline wastewater streams by recovering and reusing the minerals and water from the brine in other industries, thus 'closing the loop' and improving the environmental impacts of production [196].

Drivers

It was possible to reach out to the project developer to acquire essential firsthand insights critical for grasping how this platform plays a pivotal role in enabling industrial symbiosis practices in the Netherlands. The first comment expressed by the interviewee regards the drivers that compel companies into employing the platform. In fact, it was stated that: "there needs to be a good business case. As always, money is important, so the better the business case, the more interested companies are in engaging in industrial symbiosis. So, in any industrial symbiosis case, if it can save costs, the more costs it can save, the better, the more interesting it is". Beyond monetary considerations, the interviewee also expressed how regulatory requirements, such as new environmental mandates prohibiting certain types of pollution, can prompt companies to engage in symbiotic practices through the platform, irrespective of their immediate financial appeal. The interviewee highlighted that EU regulations and policymakers aim to drive such regulations, mandating companies to enhance sustainability but that achieving a balance between regulatory mandates and economic interests is essential in this context.

Barriers

When questioned about the challenges faced in implementing the digital platform to promote industrial symbiosis, the interviewee emphasized that a strong barrier they have encountered is the hesitancy to share information driven by the sensitivity of the data. Indeed, he explained how when there's no compelling business case or necessity to share information, companies are reluctant to do so, as they fear potential misuse of the shared information. Furthermore, it was added: "While we can provide data security assurances, ensuring that the information remains within the system and isn't made public, there persists a reluctance due to the perceived risk of sensitive data being exposed or ending up outside their company's walls."

The interviewee stressed that this is a big barrier by pointing out: "the platform by definition has to be connected to others. Data from others are combined. The platform cannot run on their own premise with only their data. It needs to be matched with the data from others. So, the data from the company always has to leave the company and go to the server where the matching is done."

In this context, the interviewee mentioned how technologies that help ensure confidentially and transparency like Blockchain could be relevant to exploit and enhance as much as possible the benefits currently provided by digital platforms within the framework of industrial symbiosis, but that "It's always a bit conceptual, so it's difficult to grasp exactly how it is feasible to apply to industrial symbiosis and matching, but that would be innovative".

Advantages

In contrast, when asked about the benefits derived from the platform, the interviewee mentioned that: "We did notice that the more companies that registered and entered their data, the more matches there were. Potential matches. Let's say potential because the program identifies for example, one brine producer and one salt buyer that could collaborate by one using the salt, the minerals from the other. It's potential because once the platform makes the suggestion, they would have to take it offline, to speak and discuss bilaterally, confidentially to identify whether or not it is technically feasible, economically feasible. In this sense, it has led to quite some potential matches. So that is promising."

To obtain a better understanding of the role of the platform in the actual implementation of the symbiosis practice, it was inquired if the Online Brine platform helped the companies in engaging with each other, in tracking the process after the match was done, to which the interviewee answered: "That's a process left to the companies by themselves".

As a closing remark, the interviewee stated how: "the best business cases reached for symbiosis is when companies are co located, or not too far from each other. Because otherwise the transportation of the by product or waste product adds up to the costs and that puts pressure on the business case. So, that's why with Zero Brine, the focus are industrial clusters as much as possible. In the Netherlands there are five big industrial clusters and that's where we focus on"

6 How Digital Technologies enable IS: Theoretical and Practical comparisons.

This section aims to present a further analysis of the results obtained from the interviews by evaluating whether the barriers, advantages, and drivers for digital technologies identified in literature coincide with those faced by companies in the Italian and European contexts during the actual application of these technologies within the framework of industrial symbiosis.

The literature findings were presented in chapter 3, specifically in the subchapter 3.4.1, through the overview of Table 3b, and thus, the comparisons that will be performed make reference to those scientific contributions previously analyzed. Additionally, it's relevant to mention how although the results of subchapter 3.4.1 assess different digital technologies, the focus here will be narrowed to Digital Platforms and AI and Blockchain technology in the scope of a digital platform, which were the technologies appraised through the interviews.

6.1. Barriers to digital technologies within IS.

The following emphasis will be directed on exploring whether the challenges described in the literature hold true in the real-world scenarios analyzed.

An overview of these findings is presented in Figure 17 below. The blue elements are the barriers identified in literature that are confirmed by the Italian and European findings. Instead, the orange elements regard the barriers highlighted by academic research, that were not verified by the practical findings. Finally, the green elements concern the barriers that are present in the working field, that were not assessed in the evaluated literature. The following discussion will provide an analysis of each of these scenarios.

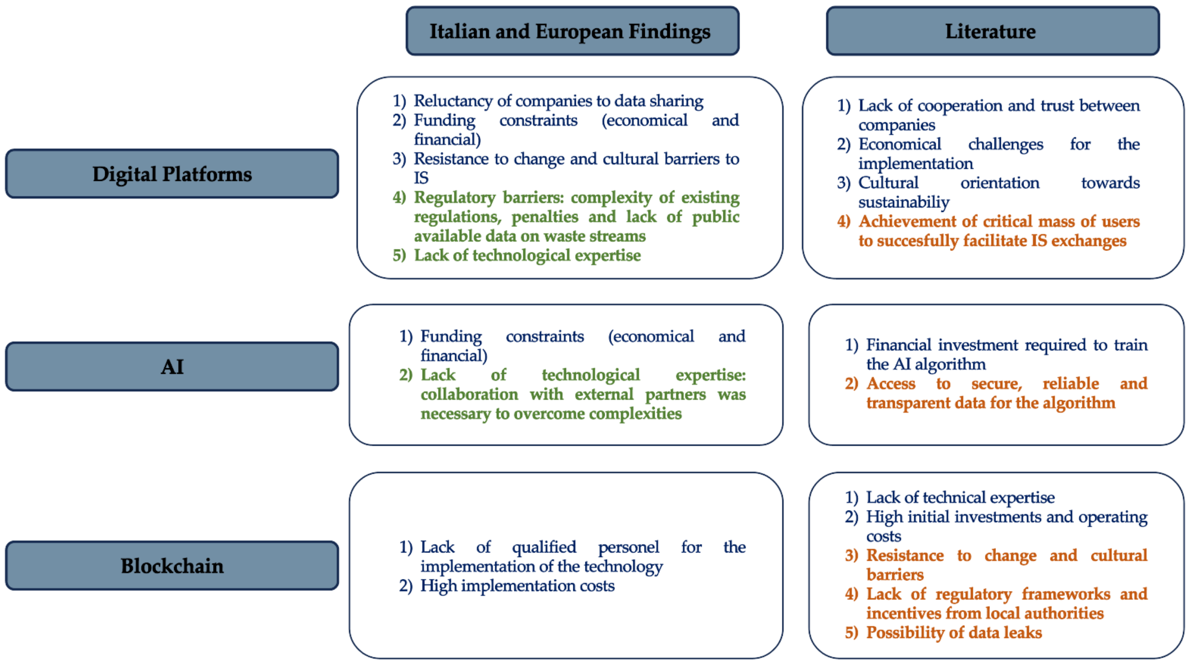

Figure 17. Barriers comparison summary.

Across the interviews, a common challenge emerged regarding the **hesitancy among companies to share data**, presenting a significant obstacle in the implementation of platforms aimed at promoting industrial symbiosis. The interviewees highlighted that the primary hurdle, in the current context, revolves more around data sharing than technological barriers. There is a prevalent reluctance among companies to share information, driven by concerns about potential misuse, even when assurances of data security are provided. This shared challenge underscores a broader issue in the adoption of digital platforms for industrial symbiosis, where the delicate balance between the advantages of data sharing and the perceived risks becomes a central concern (iZ Precious, Online Brine Platform).

Connecting these challenges with those discussed in the literature review reveals a striking alignment. The reluctance among companies to share data, as highlighted in the interviews with iZ Precious and the Online Brine Platform, resonates especially with the literature's findings on blockchain technology. [174] underscores the "persisting lack of trust in technology," attributing it to complexity and a deficient understanding among decision-makers. This mirrors the hesitancy observed in the interviews, where concerns about potential misuse and security vulnerabilities contribute to the reluctance to share information. Similarly, [178], while not explicitly using the term "Data Sharing Hesitancy," points to challenges related to technology, including security vulnerability and the need for synchronization between IoT platforms and blockchain architecture. These concerns strongly imply reservations about data sharing and security, aligning with the challenges voiced by the interviewed companies. Moreover, [180] adds another layer to the literature's perspective by mentioning challenges such as the participants resisting adopting blockchain technology. Lastly, [157] from the literature review underscores the challenge of 'lack of cooperation and trust between companies'. This resistance may encompass hesitancy toward sharing data, echoing the sentiments expressed in the interviews. The convergence between the literature and the interviews outlines the accuracy of the insights in the context.

Another challenge evident in one of the interviews centers around **funding constraints** (Atelier Riforma). The exploration of a new technological domain, especially within the context of circular fashion and technology-driven processes, demanded a strategic approach to secure the necessary support. Consequently, [176], focusing on digital platforms, notes challenges related to achieving a critical mass of users and the difficulty in implementation due to low standardization, implying financial obstacles. Likewise, [172], discussing online digital platforms, emphasizes economic challenges during implementation and the need to measure platform-generated value, indicative of financial considerations. [166], which centers on a digital platform with system dynamics and AI algorithms, also underscores the resources, both temporal and monetary, required to train AI algorithms, highlighting financial constraints. Additionally, [182], focusing on Artificial Intelligence, mentions the necessity of financial investments for achieving secure and transparent data, and tight cross-company cooperation. Furthermore, [180], centered on blockchain, explicitly outlines financial constraints associated with initial investments and operating costs, emphasizing the significance of funding challenges in the adoption of this technology, which is corroborated through the practical case of iZ precious, whose interviewee highlighted how an "iZ gold" costs more due to the traceability enhanced by the NFTs. These parallel findings emphasize the consistent theme of financial constraints in both practical application and academic discourse, underlining securing adequate funding for the successful implementation of technological platforms.

Across the interviews, **resistance to change** and the pressing need for extensive educational efforts was also observed. In the context of Circularity, there is a notable resistance to altering existing waste management practices within the company, indicating a broader industry-wide challenge of embracing change. This resistance is accompanied by the recognized imperative for widespread education, especially crucial in an ecosystem where entities, often represented by older individuals, may lack familiarity with emerging technologies like e-commerce and artificial intelligence tools (Atelier Riforma). In alignment, [172] with focus on digital platforms, emphasizes a barrier associated to the cultural orientation towards sustainability. Additionally, [174] from the literature mentions resistance arising from the complexity of technology, while [185] emphasizes resistance to change and cultural barriers. Notably, it's pertinent to highlight that these last two were predominantly discussed in the literature within the context of blockchain technologies.

Furthermore, key insights from the interviews highlight that **regulatory barriers** for digital technologies and industrial symbiosis represent significant challenges. One prevalent issue was the complexity of existing regulations, particularly those pertaining to the sale of used garments and waste management practices. For instance, navigating Italy's regulatory landscape, both at a national and regional level, posed substantial barriers for companies involved in circular fashion and industrial symbiosis platforms (Atelier Riforma). The intricacies of these regulations hindered the development of circular processes, requiring a call for simplification and revision of regulatory frameworks. Another recurring challenge was the difficulty in convincing companies to adopt new waste management paths, a task complicated by legal implications and potential penalties associated with such practices (Circularity). Moreover, the lack of publicly available databases in the waste treatment sector added an extra layer of complexity, underscoring regulatory challenges in data availability. The overarching theme across the interviews was the necessity to strike a delicate balance between regulatory mandates and economic interests, with EU regulations and sustainability-focused policymakers playing a significant role in influencing companies to embrace symbiotic practices (Online Brine Platform). In summary, the challenges spanned regulatory intricacies in sales and waste management, the regional regulatory landscape, and the broader imperative to harmonize regulatory requirements with economic considerations. This resonance is particularly notable in literature references specifically related to blockchain technologies, such as [174], which mentions the "Uncertainty regarding legislation and regulations in support of ISN initiatives and blockchain adoption in specific regions." Similarly, [185] points out the "Lack of regulatory framework and incentives from government authorities," while [180] notes that "Lack of regulations and outdated legislation can hinder adoption." From this analysis, it is crucial to emphasize that these challenges are not exclusive to blockchain technology, as identified in the literature, but also extend to digital platforms in Italy, as observed in the real-life scenarios discussed in the interviews.

Continuing with the challenges, some companies collectively highlighted many barriers related to **technological expertise** in different contexts with some focusing on technology adoption and others on technical development and alignment. One aspect involved venturing into new technological domains without prior experience, leading to hurdles in adoption and integration. For instance, in the case of adopting AI and algorithmic logic for the circular fashion platform, collaboration with external experts, engineers, and data scientists was necessary to overcome complexities (Atelier Riforma). Another facet involved technical challenges in aligning industrial symbiosis platforms with specific requirements, requiring collaboration with external experts (ENEA). In a broader industry context, challenges in finding skilled personnel were noted, prompting reliance on external expertise for specific tasks related to the blockchain (iZ Precious). These challenges also align with findings from the literature review, particularly in [174] that focuses on blockchain technologies. This source emphasizes the challenge posed by a lack of technical expertise among potential participants, contributing to uncertainty and barriers in the adoption of Information Sharing Network (ISN) initiatives and blockchain. The challenges faced by companies (Atelier Riforma, ENEA, iZ Precious) mirror the broader industry concerns outlined in the literature, where the absence of technical know-how hinders the successful adoption and integration of advanced technologies. As previously noted, this also demonstrates that these challenges, as outlined in the literature, are not confined solely to blockchain technology. Instead, they extend beyond to encompass also digital platforms operating in Italy.

In analyzing the interviews, it becomes evident that while certain challenges may not neatly fit into the predefined categories of specific digital technologies, the overarching themes resonate with the most prevalent barriers identified in the existing literature. Notably, challenges related to data security, trust issues, and technological hurdles consistently emerged in both the literature and the interviews. This alignment underscores the universality of certain barriers in the adoption of digital platforms.

6.2. Advantages to digital technologies within IS.

The focus will now be on investigating whether the advantages outlined in the literature align with the observed realities in the analyzed real-world scenarios.

An overview of these findings is presented in Figure 18 below. The blue elements are the advantages identified in literature that are confirmed by the Italian and European findings, which represent most of the evaluated aspects. Instead, the orange element regards the advantages highlighted by academic research, that were not verified by the practical findings. Finally, the lack of green elements, which concern the advantages that are present in the working field, that were not assessed in the evaluated literature indicates a thorough evaluation conducted by academic research in this area. The upcoming discussion will provide a further analysis of each of these scenarios.

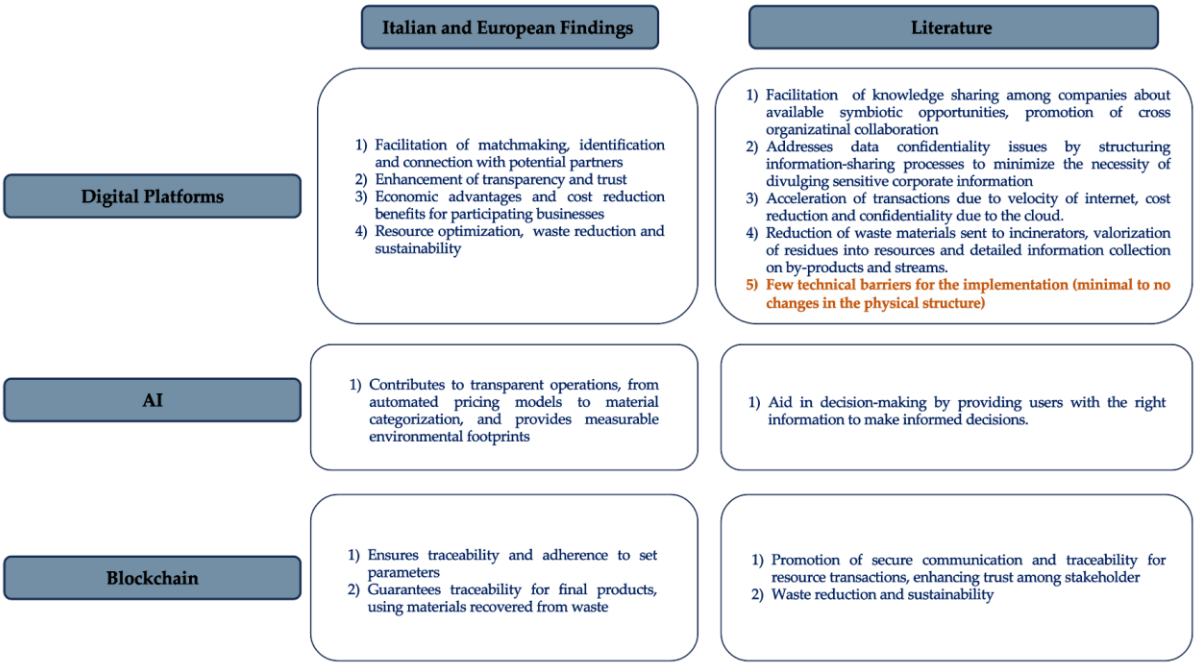

Figure 18. Advantages comparison summary.

In analyzing the interviews, a recurring observation emerged regarding a shared advantage across various digital platforms—the notable capability of digital technology in facilitating **matchmaking and the identification of potential partners**, particularly for industrial symbiosis. The interviews consistently highlighted how these platforms enable companies to efficiently connect, assess compatibility, and explore potential collaborative relationships, underscoring the role of digital solutions in enhancing the matchmaking process for industrial symbiosis initiatives (Online Brine, Circularity, ENEA). Building upon the exploration of real-world scenarios, a notable parallel emerges in the literature, specifically in [172] and [177]. These references discuss online digital platforms and highlight key advantages that resonate with the findings. The literature points towards the facilitation of knowledge sharing among companies about available symbiotic opportunities, a concept congruent with the recurrent observation in the interviews. Additionally, they mention that digital platforms can support the synchronization of material, energy, and product flows across diverse production systems, fostering collaboration between different organizations. Moreover, the reduction of information asymmetries, as outlined in the literature, also aligns with the emphasis on efficient connectivity and compatibility assessment noted.

Continuing with the analysis, a consistent theme emerged across various digital platforms—the substantial advantage of providing **transparency and trust**. Blockchain technology, a key feature in one of these platforms, ensures traceability and adherence to set parameters, fostering transparency and accountability in the business processes (iZ Precious). The incorporation of AI and algorithms to these platforms further contributes to transparent operations, from automated pricing models to material categorization, and provides measurable environmental footprints (Atelier Riforma, Circularity). This commitment to transparency not only appeals to socially responsible companies but also stands as a competitive advantage within the digital landscape. In the context of industrial symbiosis, various references of the literature review regarding blockchain technologies, such as [174], [178], [180], [181] consistently highlight the critical role of trust and transparency. [178] emphasizes seamless data interchange and real-time monitoring, promoting secure communication and traceability for resource transactions. Similarly, [174] underscores transparency and immutability of transaction records, enhancing trust among stakeholders. [180] focuses on quick, auditable transactions and scalability, ensuring transparency and adaptability in an urban IS network. [181] explicitly mentions increased transparency and traceability of waste materials, reinforcing the commitment to clear documentation and trustworthy material reuse. These references collectively affirm that trust and transparency are foundational in optimizing industrial symbiosis, fostering reliability and openness in collaborative processes. Additional papers with a focus on digital platforms also mention these characteristics. [176] emphasizes the potential of digital technology in overcoming informational, cooperative, and technical barriers to industrial symbiosis. It specifically addresses data confidentiality issues by structuring information-sharing processes to minimize the necessity of divulging sensitive corporate information. This approach indicates a strategic effort to enhance trust and transparency within the IS network by prioritizing data security.

Furthermore, during the interviews, the companies provided significant **economic advantages and cost reduction benefits** for participating businesses. Circularity for instance, enhances economic performance by offering insights into potential partners based on environmental impact, leading to informed decision-making. Additionally, it contributes to cost reduction through waste reduction and the identification of valuable by-products that can be sold. Similarly, ENEA, designed for circular economy practices, directly addresses cost-related concerns. It minimizes disposal costs by facilitating the matching of waste or by-products with potential users. Participating companies benefit from reduced waste disposal expenses and potential savings in raw material procurement. Moreover, access to a network of potential partners supports cost-effective collaborations, contributing to enhanced sustainability performance. The platform's focus on internal efficiency and external valorization of resources further underscores its economic advantages for companies. While [164] mentions cost reduction as an advantage of digital platforms, it's noteworthy that the literature doesn't extensively emphasize the cost reduction and economic advantages associated with these factors.

Lastly, another of the most relevant benefits mentioned in the interviews were associated with **resource optimization, waste reduction and sustainability** across diverse industries. In the luxury metal sector, blockchain technology ensures traceability for iZ gold, using materials recovered from the electronics recycling industry. Aligning with this, [181] emphasizes the potential advantages of blockchain related to waste reduction and sustainability. It highlights traceability of waste materials and the platform's potential support for circular economy practices such as reuse, reverse logistics and industrial symbiosis. Consequently, digital platforms like Circularity significantly enhances companies' sustainability initiatives by providing a concrete environmental footprint for comprehensive sustainability reports. The technology also plays a pivotal role in reducing waste, achieving cost savings, and identifying valuable by-products for economic gains. ENEA, on the other hand, excels in minimizing disposal costs and optimizing resource utilization. Companies engaging with this platform enjoy advantages, such as reduced waste disposal expenses and potential savings in raw material procurement. This, in turn, elevates their overall sustainability performance by supporting both internal efficiency and external valorization of resources. In the literature, references [161] and [164] both align with the insights from these interviews, underscoring the role of digital platforms in waste reduction. [161] highlights the advantage of minimal technical barriers for digital implementation, focusing on reducing the mixing of waste materials sent to incinerators. Meanwhile, [164] specifies several ways in which a digital platform supports industrial symbiosis, including the valorization of residues into resources and detailed information collection on by-products and streams.

6.3. Drivers to digital technologies within IS.

The focus now shifts to examining whether the drivers that compel companies into exploiting digital technologies to foster industrial symbiosis identified in literature are validated in actual real-life scenarios.

An overview of these findings is presented in Figure 19 below. The blue elements are the drivers identified in literature that are confirmed by the Italian and European findings. Instead, the orange elements regard the drivers highlighted by academic research, that were not verified by the practical findings. Finally, the green elements concern the drivers that are present in the working field, that were not assessed in the evaluated literature. The subsequent discussion will offer an assessment of each of these scenarios.

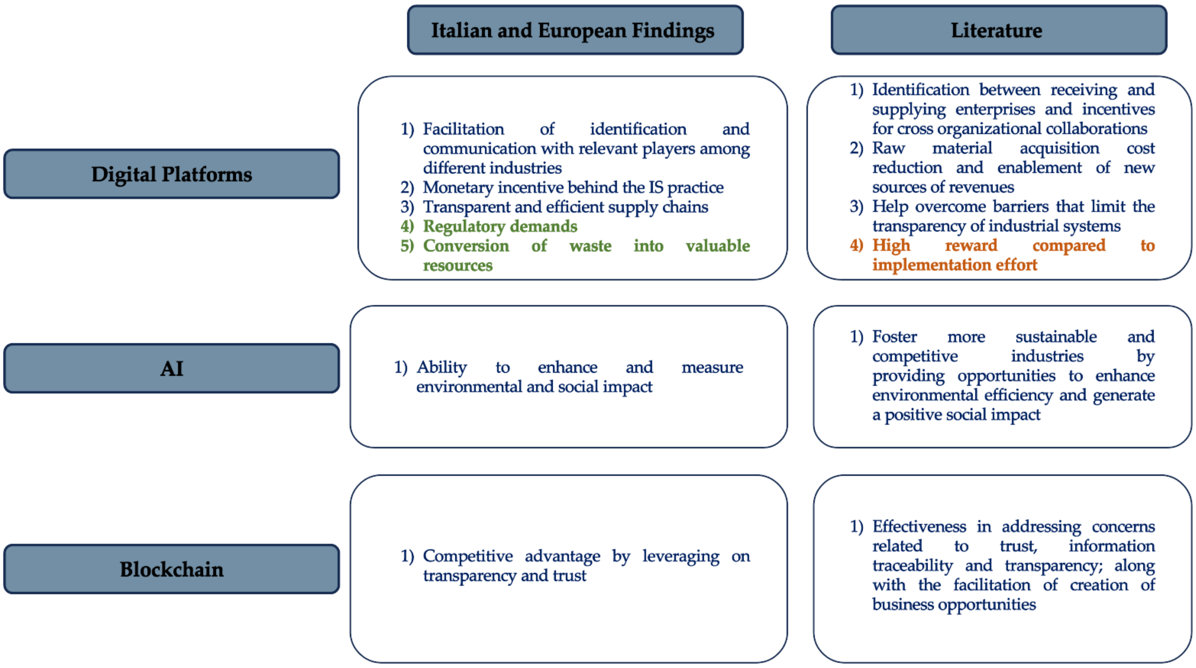

Figure 19. Drivers comparison summary.

As previously noted, the most common digital technology evaluated in the field regards digital platforms. In this context, some of the most relevant findings from the interviews assess how a key factor for the motivation of companies to embrace and engage in both a traditional digital matchmaking platform and one that additionally leverages AI, regards the possibility of being able to identify the mayor actors, the top players in a desired industry and evaluate the likelihood of compatibility regarding demand and supply. In this sense, the interviewees highlighted how companies are drawn to employing digital platforms as they **facilitate communication between enterprises** that would not be possible otherwise, promoting transparent communication and collaboration among entities that may face challenges connecting through traditional means. Indeed, it was stressed that these platforms play a crucial role in reshaping industrial relationships. (iNex Circular, Atelier Riforma, Circularity, ENEA). When evaluating the literature, it's possible to find research that supports this idea. In fact, [177] validates the practical findings by stating that an incentive for companies to engage in collaborative platforms regards the "promotion of cross-organizational collaborations among companies to achieve a competitive advantage through the exchange of materials, energy and other resources" Furthermore, [178] additionally reinforces this notion by expressing how "platforms allow all stakeholders, to provide data regarding material, energy, and waste flows. These data can be used for identifying receiving and supplying enterprises."

Another compelling factor influencing companies to engage into digital platforms pointed out by the interviewees concerns a **compelling financial rationale**: there must be a strong business case with a clear monetary incentive. Indeed, it was emphasized how companies exhibit greater interest in participating in industrial symbiosis when the business case is robust and provides high-cost savings potential. This typically occurs when the economic advantages outweigh not only transportation costs in waste exchange but also the costs associated with sourcing virgin materials (Online Brine Platform, ENEA). Academic research also targets this point. Indeed, [157] exposes how a driving force for the adoption of digital platforms concerns the reduction of raw material acquisition cost and/or the enablement of new sources of revenues.

Switching the focus towards blockchain technology, one key factor emphasized in the interviews was the potential for a company to gain a competitive advantage by leveraging the **transparency** facilitated by blockchain technology. Through the creation of NFTs enabling clients to trace the origin of materials used in their final products, a company's sustainability narrative becomes verifiable. This certification enhances trust levels with clients, allowing companies to establish a credible reputation and reducing the risk of engaging in greenwashing practices (iZ precious). This driver is corroborated by existing literature. Indeed, [174], [180], [181] [185] affirm this claim, asserting that companies are motivated to embrace blockchain technology due to its perceived effectiveness in addressing concerns related to trust, information traceability, and transparency among stakeholders in industrial symbiosis.

The transparency incentive was also related to digital platforms strengthened by AI algorithms. Indeed, it was stated that this tool allowed a transparent and efficient supply chain not only by facilitating businesses in discovering suitable partners for recycling and waste utilization, but also by providing companies with a measurable environmental footprint for their sustainability reports (Circularity). This is again endorsed by academic research. In fact, [172] highlights how companies are compelled to employing this technology since “the breadth and depth of real-time information accessible through web platforms help overcome the conventional barriers that limit the transparency of industrial systems concerning resource extraction and environmental emissions.”

From the practical evidence, it was also possible to conclude that companies may be stimulated to participate in symbiotic practices through a digital platform due to **regulatory demands**, such as new environmental directives that prohibit specific forms of pollution, even if these practices do not offer immediate financial benefits (Online Brine Platform). As to the scientific research evaluated in this study regarding online platforms, regulatory demands were not mentioned among the driving factors for companies to adopt this technology to enhance industrial symbiosis. This reveals an aspect that was not previously examined in the assessed literature.

Regarding digital platforms empowered by AI tools, interviewees pointed out a significant incentive for companies to leverage these services which regards the ability to **enhance and measure their environmental and social impact,** which aligns with the current societal and corporate emphasis on sustainability (Circularity). Scientific research also draws attention to this point. Actually, [182] expresses that IS and digital technologies like AI foster more sustainable and competitive industries and this is recognized as a pivotal factor propelling companies to integrate the technology.

As the last driver highlighted by interviewees in real-life cases, the fundamental motivation for industrial symbiosis becomes evident: the utilization of reused and recycled materials, promoting the **conversion of waste into valuable resources,** ultimately resulting in a reduction of a company's overall environmental footprint, which is enabled by digital matchmaking platforms (ENEA). While the direct use of reused and recycled materials is an outcome of engaging in industrial symbiosis, the literature did not assess this as a motivating factor for companies to leverage digital platforms.

As a closing remark, it’s pertinent to draw attention to how one of the drivers mentioned by the literature was not appraised in the practical cases. Specifically, this pertains to the high reward obtained compared to the low implementation effort of collaborative platforms for IS [161].

6.4. Relevant insights “from the field”

This final subsection is dedicated to spotlighting valuable insights shared by the interviewees. These insights, not falling under the categories of barriers, advantages, or drivers, are presented as contributions that serve to enhance the comprehension of the practical implications associated with the implementation of the assessed digital technologies for enabling industrial symbiosis.

One initial apprehension is the one concluded from the interview regarding iNex Circular, where it was noted that the potential synergies identified through the platform are not performed by strictly analyzing resources needs vs resources waste. Actually, it was assessed that “It’s more about understanding the recycling schemes, understanding the types of materials you work with.”

Furthermore, regarding the scope of digital platforms, two practical cases stressed that these tools serve as detectors of potential synergies. In essence, when a potential match is identified, the subsequent evaluation and potential implementation are either conducted by a consultancy firm or are left for the companies to handle independently (iNex Circular, Online Brine Platform). Moreover, when assessing the major barrier regarding the reluctancy to data sharing within digital platforms, it was noted how technologies that help ensure confidentially and transparency like Blockchain could be relevant to exploit and enhance as much as possible the benefits currently provided by digital platforms within the framework of industrial symbiosis, but that “It's always a bit conceptual, so it’s difficult to grasp exactly how it is feasible to apply to industrial symbiosis and matching, but that would be innovative” (Online Brine Platform). This draws attention to how although there’s knowledge about tools that could help assess one of the most significant barriers to the adoption of digital platforms to foster IS, the practical execution is not entirely evident.

Finally, the necessity for clearer regulations to facilitate symbiosis was emphasized. While technologies serve as enablers, policymakers assume a critical role not only in establishing regulations that promote symbiosis practices but also in ensuring their clarity. The importance of this clarity is evident when a company wishes to participate in the initiative, ensuring they are not hindered by a lack of understanding. This principle also extends to organizations functioning as technology providers or platform enablers. Understanding the type of material, they receive and the technical conditions for its reuse is pivotal in developing a tool that maximizes the potential of the technology. Certainly, while the technology's availability is a key factor, its proper utilization is essential for achieving the intended results (Atelier Riforma).

7 Conclusions

This thesis explored the synergies between digital technologies and industrial symbiosis, with a primary focus on the Italian context. The research unfolded through an examination of policies, a literature review, an analysis of digital technologies in Italy and real case studies within the Italian and European context, systematically addressing gaps in real-case evaluations and providing both theoretical and practical insights. The literature review focused on assessing the primary research question: "How Digital Technologies Enable Industrial Symbiosis? "played a foundational role by leading to the identification of 30 initial articles (Table 2) from 2015 onwards, underscoring the novelty of the research. These articles were then narrowed to 21 by solely analyzing the research effectively evaluating digital technologies within an IS framework, and not solely assessing circular economy broadly. Presented in Table 3, the structured literature review categorized research papers based on the dynamic interactions between digital technologies and industrial symbiosis. The ensuing discussion highlighted key takeaways, emphasizing the pivotal role of digitalization in transitioning toward sustainable business ecosystems, with specific emphasis on technologies such as digital platforms, sensing devices, machine learning and blockchain.

Practical insights, derived from the case studies, significantly contributed to understanding the drivers behind the adoption of digital technologies in IS. The prevalence of Digital Platforms, often enhanced with Blockchain or AI, emerged as a crucial finding, showcasing their predominant adoption in Italy. Companies were driven by financial rationale, regulatory demands, and the desire to measure environmental and social impact. The exploration of under-explored literature aspects, such as the low implementation effort of collaborative platforms, enriched the understanding of practical considerations. The study revealed notable gaps and missing information that manifest in real-world cases but are conspicuously absent in the existing literature. Challenges, including financial constraints, resistance to change, regulatory barriers and technological expertise, were identified, while advantages encompassed efficient matchmaking, transparency, economic benefits, and sustainability initiatives. This detailed analysis provided an important understanding of the complexities and opportunities associated with the integration of digital technologies in IS, aligning in most cases, theoretical expectations with real-world challenges.

The detailed examination of digital technologies, covering advanced interfaces such as, digital platforms, IoT, AI and blockchain, emphasized their potential to optimize IS practices. However, challenges such as cultural resistance, financial constraints and technological immaturity require for strategic solutions to work on. The discussion also highlighted the need for more in-depth case studies, emphasizing the scarcity of real-life examples in the current literature. This could involve conducting more extensive field studies, collaborating closely with companies engaged in symbiotic practices and incorporating a broader range of industrial sectors and geographical locations. Furthermore, the research community could benefit from exploring the long-term impacts and scalability of digital technologies in industrial symbiosis. Investigating the sustained effectiveness of these technologies over extended periods, considering diverse industrial settings, will contribute to a more robust understanding of their role in fostering sustainable and circular practices. Additionally, given the dynamic nature of technology and industrial practices, continuous monitoring and assessment of emerging digital tools and their applicability to industrial symbiosis are crucial. Future studies should stay attuned to technological advancements, evaluating their potential integration into symbiotic frameworks and assessing their impact on resource efficiency, economic viability, and environmental sustainability, keeping an emphasis on the need for clearer regulations and the role of policymakers.

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Acronym	Description
IS	Industrial Symbiosis
IE	Industrial Ecology
EIPs	Eco Industrial Parks
EU	European Union
CE	Circular Economy
ICESP	Italian Circular Economy Stakeholder Platform
ENEA	"Ente per le nuove tecnologie, l'energia e l'ambiente"
SUN	Symbiosis User Network
ICT	Information and Communication Technology
IoT	Internet of Things
AI	Artificial Intelligence
SMEs	Small and Medium Enterprises
R&D	Research and Development
SLR	Systematic Literature Review
ERP	Enterprise Resource Planning systems
NLP	Natural Language Processing
SD	Sustainable Development
CBM	Circular Business Models
WM	Waste Management

DT	Digital Technologies
BT	Blockchain Technology
ML	Machine Learning
BDA	Big Data Analytics
DP	Digital Platforms
I4.0	Industry 4.0

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