Unravelling sustainability in the textile industry: A literature and case study analysis on Industrial Symbiosis initiatives

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Abstract: The textile industry contributes approximately 2 percent of global greenhouse gas emissions and consumes substantial amounts of energy, water, and chemicals throughout its supply chain, leading to relevant environmental concerns. This environmental impact is further compounded by the growing volumes of industrial and end-of-life textile waste generated during manufacturing processes and by consumer habits. Regrettably, only 20 percent of this waste is currently recycled globally, primarily for downcycling applications. To address these challenges and align the textile industry with circular economy principles, industrial symbiosis emerges as a potential solution by transforming textile waste into high-value resources. Over the past few years, scientific literature has investigated the topic of industrial symbiosis within the textile industry, albeit in a fragmented way. To reduce the cloudiness around this topic, a review of existing literature is conducted and the main dimensions describing industrial symbiosis initiatives are pointed out. These are then applied through multiple case studies. Overall, this paper provides an improved understanding of industrial symbiosis initiatives, thus helping textile companies comprehend what is needed to be considered for undertaking this transition.

Keywords: Industrial symbiosis, Literature Review, Circular Economy, Textile industry, Supply Chain

1. Introduction

Circular Economy aims at optimising the use of materials and energy while minimising the use of finite resources through smart employment of materials, products and services (Su et al., 2013). Due to its ambition to decouple economic growth from resource use and consumption, it has been increasingly recognised as an effective avenue for achieving sustainable development (Hofmann, 2019). The adoption of circular strategies can yield positive outcomes both on a macro- and a micro-level (Bressanelli et al., 2022). Industrial Symbiosis has been recognised by literature as a noteworthy circular business opportunity within the "closing loop strategy" (Geissdoerfer et al., 2017). In this approach, waste and scraps generated by one company become raw materials in the production processes of other businesses. Given the projected 70% increase in global waste generation by 2050, with industrial waste currently surpassing urban waste by nearly 18 times, industrial symbiosis emerges as a significant opportunity to address Sustainable Development Goals (Sullivan et al., 2018). In particular, companies can pursue industrial symbiosis to find an application for surplus resources, generating revenue while gaining environmental benefits, such as the reduction of waste generated, a limited use of virgin raw materials, etc.

The textile industry contributes to this negative trend, since quantities of industrial and end-of-life waste originating from both manufacturing processes and poor consumer habits are increasing (Colombo et al., 2022; Saccani et al., 2023; Schmutz & Som, 2022). Unfortunately, only 20 percent of this waste is currently recycled globally, primarily for downcycling applications (Sandvik & Stubbs, 2019). Industrial symbiosis emerges as an effective solution to tackle these challenges and align the textile industry with circular economy principles, by converting textile waste into high-value resources.

Despite the fact that the benefits of its application are now well recognised, industrial symbiosis issue within the textile industry has been investigated in the existing scientific literature in a fragmented way. Therefore, this paper aims to diminish the cloudiness around this topic by following a combined approach. Based on this, the following research question is addressed in the current study: *"Which dimensions can be used to categorise industrial symbiosis initiatives in the textile industry?"*. First, a review of extant literature to find out the main dimensions describing industrial symbiosis initiatives is conducted. Second, these dimensions are subsequently applied through multiple case studies for validation.

The remainder of this paper is structured as follows. Section 2 proposes the theoretical background on how to classify industrial symbiosis initiatives. Section 3 introduces the methodological approach adopted to conduct the study. In Section 4, the results of the systematic literature review on industrial symbiosis initiatives within the textile industry (Section 4.1), the case studies (Section 4.2), and the dimensions describing industrial symbiosis initiatives (Section 4.3) are presented. Finally, discussion and conclusion together with limitations and future developments are reported in Section 5.

2. Theoretical background

The concept of industrial symbiosis has been introduced by Chertow (2000) as an approach that "engages traditionally separated industries and/or entities in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products". It brings significant benefits for companies (Jacobsen, 2006). Hence, in recent years, scholars have tried to devise frameworks for classifying industrial symbiosis initiatives.

Several key dimensions have emerged as pivotal in this endeavour. Drawing on a comprehensive literature review, Fraccascia & Giannoccaro (2020) underscored the significance of comprehending the factors to consider when categorising industrial symbiosis. They delineated three main levels of implementation: at the company level, involving internal synergies among diverse production processes within a single company (Zhu et al., 2007); at the level of industrial symbiosis relationships, involving two companies – one generating and the other utilising it, thereby establishing a symbiotic synergy (Chertow, 2000). These interactions may occur between proximate or distant companies (Fraccascia & Giannoccaro, 2020). Chen et al. (2022) classified industrial symbiosis based on the type of resource exchange: material symbiosis, where by-products or waste from upstream entities serve as raw materials for downstream ones; water symbiosis, aimed at maximising water reuse to conserve resources; energy symbiosis, optimising energy exchange networks for enhanced efficiency; and synergistic symbiosis, involving the exchange of multiple resources. These exchanges may be unilateral or bilateral (Domenech et al., 2019; Domenech & Davies, 2011) and may occur within the same sector or across different industries (Chertow et al., 2008; Mendez-Alva et al., 2021). Additionally, three distinct approaches to industrial symbiosis have been theorised in the literature (Boons et al., 2011; Domenech et al., 2019; Turken & Geda, 2020). The facilitated approach involves a third-party actor coordinating activities and material exchanges, while the self-organised approach emerges from direct interactions among companies without third-party facilitation, typically driven by profit motives in a bottom-up fashion. In contrast, the planned approach stems from centralised planning, often initiated by governments, to organise material exchanges in a top-down manner.

Despite these efforts, relatively few studies have focused on designing comprehensive typologies or taxonomies to characterise industrial symbiosis initiatives, which could potentially aid companies in decision-making processes. Turken & Geda (2020) proposed a taxonomy based on three types of industrial symbiosis (self-organised, facilitated, top-down) and three supply chain decision levels (strategic, tactical, operational), highlighting a scarcity of literature on industrial symbiosis from a supply chain perspective. Albino et al. (2013) developed a structural classification model for industrial symbiosis networks based on physical flows types (material or energy) and internal or external symbiotic relationships, identifying four network configurations. Fraccascia et al. (2019) defined a taxonomy of industrial symbiosis business models based on governance features, categorising four main models according to value proposition, creation, and capture mechanisms. Finally, Zhang et al. (2015) reviewed theoretical and methodological foundations of industrial symbiosis, associating six theories with various types of industrial symbiosis, considering factors such as key species, relationship dynamics, geographical proximity, sector integration, and historical formation. These efforts contribute to a deeper understanding of industrial symbiosis dynamics and may inform future research and practical applications.

Nevertheless, overall, a complete overview of the dimensions to consider for classifying industrial symbiosis initiatives is still missing in literature, especially with a focus on a specific industry such as textiles.

3. Methodology

In this paper, a literature review has been combined with a case study approach.

The scientific literature was initially systematically reviewed on Scopus, the most comprehensive database, by means of the inclusion criteria reported in Table 1. 122 documents were found, by launching the search query for the first time. After analysing titles and abstracts, 26 documents were selected. The final sample is composed of 10 papers focused on industrial symbiosis in the textile industry that have been fully read. Next, through a narrative review, more general scientific literature on industrial symbiosis classification frameworks was scrutinised.

Table 1: Scientific Literature Review Inclusion Criteria

Inclusion criteria	Description
Keywords	("Industrial symbios*" OR "symbiosis" OR "eco-industrial park*" OR "eco industrial park*" OR "industrial ecology") AND ("textil*" OR "garment*" OR "cloth*" OR "apparel*" OR "fashion")
Language	English
Document Types	Article, Conference paper, Review
Source Types	Peer-reviewed journals, Conference proceedings
Subject area	Environmental and Social science, Engineering, Energy, Business, management and accounting, Economics

Second, the case study approach was adopted as it is one of the most effective empirical methodologies for conducting research in operations (Voss et al., 2002). Moreover, this method may help build the theory that explains how industrial symbiosis initiatives can be classified. More in detail, the multiple case study methodology was selected to reduce the cloudiness around the topic under investigation. This choice enabled the authors to ensure a reasonable level of external validity and to reduce the risk of relying on biased information (Voss et al., 2016).

Four case studies were selected through a purposive sampling technique (Patton, 2002). As a context of study, the focus was on Italian textile companies. The Italian context was chosen for the analysis as it is recognised as one of the most significant in terms of employment, income generated and number of companies involved at a worldwide level (European Commission et al., 2021). Specifically, both primary and secondary case study has been used in this analysis. As regards the former, to attain the research goal, data were gathered by means of semi-structured interviews based on a research protocol built on the literature review. Each interview, which lasted between 40 and 70 min, was conducted online by at least two researchers and was recorded to increase the internal reliability of the study (Yin, 2009). For case Beta, the purchasing manager was involved in the case study; while R&D director was consulted for Delta. Furthermore, the data were analysed within and across cases to find significant patterns. First, they were coded and then triangulated with companies' secondary sources such as website and reports to further check the internal consistency of the obtained information (Scandura & Williams, 2000). Consistency of the gathered data and their adherence were assessed independently and cross-checked by the researchers, to minimise biases and reach consensus (Baxter & Jack, 2008). As regards the latter, instead, data on the different dimensions emerging from the narrative literature review were collected leveraging companies' websites and reports. Overall, the unit of analysis is the industrial symbiosis initiative from the generation of the surplus resource to its valorisation. To sum up, Table 2 reports the main characteristics of the analysed case studies.

Table 2: Characteristics of the analysed case studies

Case study	Type of case study	# of employees (2022)	Revenue (mln €, 2022)
Alpha	Secondary	573	131
Beta	Primary	157	45
Gamma	Secondary	2	0.043
Delta	Primary	16	2.4

4. Results

4.1 Systematic literature review on industrial symbiosis in the textile industry

Within the extant body of scientific literature, industrial symbiosis has been applied to the textile industry in a limited and fragmented manner. As a proof of that, only 10 papers have been found through the systematic literature review (Table 3). Three main areas of analysis can be extracted.

First, some papers focused on documenting single case studies showcasing the successful utilisation of non-textile waste in yarn production. For example, Motta et al. (2023) demonstrated that the transformation of chiengora, the canine undercoat, sourced from pet shops, breeders and dog owners into fabric. Another example is provided by Torrisi et al. (2023) who highlighted the case of Orange Fiber Srl, an Italian start-up extracting cellulose from discarded citrus by-products, originally destined for landfills after being deemed unsuitable for food applications. These cases underscore the potential for establishing productive and sustainable synergies through the cross-sectoral exchange of waste.

Second, other articles assumed a more technical perspective, emphasising industrial symbiosis applications in textiles through laboratory experiments. These investigations showcased innovative technologies fostering symbiotic relationships within and between sectors. For instance, Barla et al. (2017) and Voncina et al. (2018) detailed the outcomes of the Resyntex project, focusing on enzymatic processes to convert textile waste into feedstock for the chemical industry. Özüdoğru et al. (2022) presented a more recent technique, developing a carbon-based sorbent from end-of-life tires to absorb dyes in water, addressing challenges posed by the synthetic textile industry. Zoccola et al. (2015), instead, illustrated how green hydrolysis, employing superheated water, could convert waste wool into fertilizers for managing grasslands and cultivations.

A third literature stream took a conceptual approach to industrial symbiosis initiatives within the textile industry, conceptualizing challenges and drivers. Yadav & Majumdar (2023) undertook an investigation into the impediments hindering industrial symbiosis within India's textile domain. Employing a questionnaire, they pinpointed 18 obstacles, subsequently scrutinising their interconnectedness via the WINGS methodology. Yu et al. (2015) explored the drivers propelling industrial symbiosis, concentrating on nine industrial chains situated within a Chinese eco-industrial park. Tseng & Bui (2017), utilising the fuzzy Delphi and factor analysis techniques, explored the fundamental eco-innovation attributes essential for enhancing industrial symbiosis efficacy. Within the Vietnamese setting, they identified "regulation and perception" along with "waste-management synergies" as the most significant components. Oliveira Neto et al. (2024), through a systematic literature review coupled with the Delphi method, advocated for industrial symbiosis as a circular business model tailored to the textile sector. This model recommends textile recycling, repurposing scraps for new product manufacturing, and leveraging innovative technologies to recycle without relying on virgin raw materials. Moreover, it incorporates production processes aimed at recuperating energy and water consumption within the examined firm.

Table 3: Papers on industrial symbiosis initiatives in the textile industry

Authors	Year	Objective
Motta et al.	2023	To describe the Orange Fiber case study, highlighting production processes and technological innovation
Torrisi et al.	2023	To describe Chinegora start-up case study, highlighting production processes and technological innovation
Yadav and Majumdar	2023	To propose an integrated decision-making framework overcoming industrial symbiosis barriers for the textile and clothing industry
Yu et al.	2015	To explore drivers fostering industrial symbiosis, focusing on nine industrial chains located within a Chinese eco-industrial park
Voncina et al.	2018	To present the result of an EU project in which emerged that textile waste can be used as feedstock for the chemical industry
Tseng and Bui	2017	To explore the main eco-innovation attributes essential for enhancing industrial symbiosis efficacy in the Vietnamese context
Oliveira et al.	2024	To support industrial symbiosis as a circular business model suitable for the textile industry
Barla et al.	2017	To present the case study of a textile waste biorefinery
Özüdoğru et al.	2022	To present a technique for recycling end-of-life tires able to absorb dyes in water
Zoccola et al.	2015	To present the possibility to use green hydrolysis as a technology to turn wool waste into organic nitrogen fertilizer

4.2 Case studies

4.2.1 Alpha

Alpha is a leading premium-grade shirt fabrics manufacturer located in Northern Italy, whose mission is to produce superlative fabrics at a superior aesthetic appeal on a global scale since its foundation. The company strongly believes in the power of innovation to achieve this goal. Furthermore, it continuously invests in its industrial sites with the aim of creating an increasingly sustainable reality, fully respecting the environment and the ecosystem. In this vein, in 2019 Alpha established an innovation centre dedicated to addressing environmental sustainability challenges within the textile domain through practical solutions.

Several industrial symbiosis initiatives have been launched within the innovation centre. Among these, there is one involving the exchange of water between Alpha and another Italian company, specialised in the production of rice. Specifically, Alpha directly recovers the water used throughout the hydrothermal treatment for processing a variety of black rice by the other company to produce a natural dye suitable for dyeing textile products. This water, which would otherwise be considered production waste for the company producing rice, becomes a valuable secondary raw material for Alpha. Overall, this industrial symbiosis initiative involves two entities who have voluntarily and consciously decided to collaborate to reduce their environmental impact while simultaneously gaining economic benefits.

4.2.2 Beta

Beta is a leading carpet manufacturer located in Northern Italy, whose mission focuses on technology, know-how and the "Made-in-Italy" values. The company serves several markets, including automotive, aircraft, ships, building, hotels and offices, with products made of synthetic fibres such as polyester and polyamide.

For decades, the company has been involved in an industrial symbiosis initiative in which production offcuts are collected and sold to small companies, which use them for cordage production (i.e., a textile output). Specifically, a local intermediary is needed to recover the by-product from Beta and resell it to cordage producers for two main reasons: first, the quantities involved are not so high (approximately 70 tons per year); second, the exchanged resource is considered as waste by legislation, therefore, to be reused it must follow a specific regulatory path. Overall, it can be claimed that this industrial symbiosis initiative has been voluntarily performed by Beta primarily for achieving economic advantages.

4.2.3 Gamma

Gamma is an innovative start-up located in Northern Italy promoting the use of unconventional materials in the textile industry. Since 2020, it has been committed to innovation and sustainability to respect people and the environment.

The whole production process of Gamma is built upon industrial symbiosis. The company recovers marble powder from the Italian stone industry to manufacture fabrics suitable for apparel, interior, and automotive applications. Specifically, several marble quarries directly supply Gamma with powder with the proper physical, chemical and mechanical properties to be fed into the production cycle. Overall, this industrial symbiosis initiative stems from Gamma's desire to transform a production waste into a valuable secondary raw material, thus reducing environmental impact.

4.2.4 Delta

Delta is an Italian company located in Northern Italy specialised in the dyeing and finishing of textiles composed of every kind of fibres for third-party companies. It has steadily followed the technological evolution of the sector and argues that sustainability is a set of actions, technical and social aspects where each entity contributes to adding value to the entire supply chain.

Delta, within an innovation project funded by the European Union, started an industrial symbiosis initiative involving the recovery of textile waste coming from the garment makers' cutting table with the aim of producing textile accessories and/or new yarns. Specifically, the involved textile waste is a poly-bonded material, which is difficult to recover. Delta is carrying out research and development with a leading Italian university to decouple the metal coating from the polyester substrate in order to recover the latter. This polyester will be subjected to two routes. Either it will be frayed, carded and spun into a new yarn to produce a fabric, or it will be pelletised and subsequently extruded to produce textile accessories.

4.3 Dimensions describing Industrial Symbiosis initiatives

From the combined analysis of scientific literature and case studies, it was possible to define that industrial symbiosis initiatives can be classified according to different dimensions (Table 4). Dimensions are extracted from the literature review on textile (Section 4.1), while configuration options are devised from the case studies (Section 4.2). First, the type of resource exchanged is crucial for distinguishing among industrial symbiosis initiatives (Chen et al., 2022). In particular, the exchange can involve water, as exemplified by Alpha, or materials, as observed in the other cases under investigation. No exchanges of energy have been identified. Second, industrial symbiosis initiatives can be classified according to their sectoriality (Mendez-Alva et al., 2021). In particular, depending on the fact that the exchange of surplus resource can occur within the same sector or across different industries, industrial symbiosis initiatives can be distinguished into within and across sector, respectively. For instance, Beta is within sector because it provides textile waste that are used for other textile applications. The same may be applied to Delta that recovers fabric offcuts to produce new yarns or textile accessories. On the other hand, Alpha and Gamma can be classified as across sector because they leverage non textile waste (water from rice production and marble powder) for textile applications, namely dyes and fabrics, respectively. Third, the number of both supply chain actors and supply chain layers involved are fundamental. The former can be divided into two, when the exchange involves two supply chain actors, or many, when the exchange involves more than two supply chain actors. The latter, instead, can be classified into 2-layer relations, when the interactions involve only two supply chain layers, or multi-layer relations, when the interactions involve three or more supply chain layers. For instance, Alpha involves two actors in its industrial symbiosis initiative, since it has only one wastewater supplier. Contrariwise, Gamma and Delta involve many actors since multiple suppliers provide waste to them. The same may be applied to Beta, even though with a different perspective, as it represents only one supplier of the cordage manufacturer. As regards the number of supply chain layers, instead, Beta and Delta industrial symbiosis initiatives are multi-layered since they need an intermediary to respectively give and receive the textile waste. On the contrary, Alpha and Gamma directly interact with their supplier without needing a third-party collecting the surplus resource. Lastly, the approach with which the industrial symbiosis initiative began is equally important (Boons et al., 2011; Turken & Geda, 2020). Alpha, Beta and Gamma emerged as self-organised initiatives, since they originated voluntarily, without the need of a facilitator. Specifically, Alpha and Beta, which are well-established textile companies, were initially driven by economic rather than environmental benefits. Only Delta followed a facilitated approach because the specific initiative started thanks to the funding received by a third-party public actor that financially supports exchange of resources.

Table 4: Industrial symbiosis dimensions within the analysed case studies

Dimension	Alpha	Beta	Gamma	Delta
Exchanged resource	Water	Material	Material	Material
Sectoriality	Across	Within	Across	Within
Number of supply chain actors involved	Two	Many actors	Many actors	Many actors
Number of supply chain layers involved	2-layers	Multi-layer	2-layers	Multi-layer
Approach	Self-organised	Self-organised	Self-organised	Facilitated

5. Discussion and conclusion

This paper aimed at diminishing the cloudiness around the industrial symbiosis initiatives by describing and identifying the dimensions that characterise industrial symbiosis initiatives. In doing so, some theoretical and practical conclusions may be drawn. As regards the former, this research extends the scientific literature on industrial symbiosis by identifying various dimensions which could be potentially used to classify related initiatives. As regards the latter, the application of the identified dimensions to real case studies improves the understanding of these initiatives, thus helping textile companies comprehend what is needed to be considered for undertaking the transition towards this circular business opportunity. Nevertheless, this work is not exempt from limitations typical of qualitative research. In particular, a larger sample of companies should be analysed to consolidate the achieved findings. In such a context, future research should focus on the analysis of a wider number of primary and secondary cases with the aim of providing a comprehensive classification framework. Moreover, as the research is confined within a specific sector and country, the analysis should be extended to other industries and countries to validate its applicability in – and generalization to – diverse contexts. Lastly, three main research directions can be drawn from this study. First, academics are called to better conceptualise industrial symbiosis initiatives for textiles in the future, developing precise typologies and focusing on the different operational mechanisms. Second, new tools should be developed – or existing ones adapted – to assess impacts and benefits of industrial symbiosis initiatives in textiles. Third, and rooting on the previous points, Decision Support Systems (DSS) should be developed to foster industrial symbiosis implementation in the textile industry.

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