Industrial Symbiosis for Circular Economy Transition: Lessons from Global Practices and a Case Study in Türkiye

The transition to a circular economy is crucial for addressing environmental degradation, climate change, and resource depletion. Industrial Symbiosis (IS)—the collaborative exchange or shared use of raw materials, energy, infrastructure, and by-products among geographically close industrial facilities—has emerged as a highly effective tool for accelerating this transition. By converting industrial waste into valuable secondary resources, IS enhances resource efficiency, reduces production costs, and lowers greenhouse gas emissions, thereby boosting both environmental performance and industrial competitiveness. This paper examines the global and national development of IS, with a particular focus on the industrial symbiosis projects of Türkiye. In addition, a case study on the green transformation of an organized industrial zone is presented. The findings indicate that the potential for the industrial symbiosis is high, however, a number of constraints hinder its implementation. The main barriers include organizational and institutional limitations, limited company engagement, financial constraints, insufficient knowledge, and a lack of awareness. Our experiences revealed that both the awareness and engagement of stakeholders in industrial cooperation are vitally important for successful implementation. Furthermore, firms should revise and upgrade their data collection systems to incorporate sustainability indicators such as waste generation, water consumption, recycling rates, wastewater generation, and greenhouse gas emissions. Finally, financial supports (including grants, loan, etc.) which have to be provided to tenants and/or OIZ Directorate are another important factor to facilitate the implementation of industrial symbiosis projects and accelerate the green transition of industry.

Keywords: *Industrial symbiosis, Organized industrial zones, Circular economy, Eco-efficiency, Green industry.*

Introduction

Increasing resource consumption, climate change, and environmental degradation have intensified the need for more sustainable production and consumption systems. The shift toward a circular economy offers a vital strategy for mitigating climate change, resource depletion, and environmental degradation. By prioritizing resource efficiency, reuse, and waste minimization, circular practices significantly reduce greenhouse gas (GHG) emissions and support sustainable industrial development while reducing dependence on virgin raw materials (Ellen MacArthur Foundation, 2013). In this context, the European Green Deal highlights climate neutrality, sustainable production, energy efficiency, and responsible resource management as key priorities for achieving a competitive and sustainable economy (Filipovic et. al., 2022). Similarly, Türkiye has accelerated its sustainability efforts through national policies such as the Turkish Circular Economy Strategy and Action Plan (2025-2028) and related green transformation strategies, which encourage efficient resource use, waste recovery, cleaner production, and industrial sustainability practices. These policy initiatives support industries in adapting to international environmental standards while strengthening their competitiveness in global markets. Among the approaches that contribute to these objectives, Industrial Symbiosis (IS) has emerged as one of the most effective mechanisms for improving industrial sustainability and accelerating the transition toward a circular economy (Chertow, 2007).

Industrial Symbiosis can be defined as the exchange or shared use of raw materials, energy, infrastructure, human resources, and by-products among industrial facilities, preferably located in close geographical proximity (Chertow, 2000; Laatsit & Johansson, 2025). Through collaborative resource utilization, IS enables one company's waste or by-product to become another company's resource, thereby increasing resource efficiency while reducing waste generation and environmental impacts. Numerous studies have demonstrated that industrial symbiosis contributes to lower production costs, reduced greenhouse gas emissions, improved resource productivity, and enhanced industrial competitiveness (Neves et al., 2020). These benefits not only improve environmental performance but also strengthen industrial competitiveness and profitability, making IS an important mechanism for achieving circular economy and green growth objectives. In addition, IS contributes to sustainable waste management by transforming industrial waste into valuable secondary resources that can be reused by other industries, thereby reducing dependency on virgin raw materials and landfill disposal, making it a key enabler of the circular economy (Ellen MacArthur Foundation, 2013; Chertow, 2007).

The best-known and most widely cited example of industrial symbiosis is the Kalundborg Industrial Symbiosis network in Denmark. Beginning in the 1960s through voluntary collaboration between local industries and public authorities, the network gradually evolved into one of the world's most successful industrial symbiosis systems (Ehrenfeld & Chertow, 2002; Faria, E., 2021). Today, the Kalundborg network comprises six industries and three public institutions connected through approximately 25 material and energy exchange flows. The long-term success of this model has attracted global attention and demonstrated that cooperation among industries can simultaneously generate economic, environmental, and social benefits while improving industrial resilience and resource efficiency.

Following the success of Kalundborg, industrial symbiosis initiatives have expanded across Europe, North America, and Asia. Significant developments have been reported in countries including the United States, China, Japan, Canada, South Korea, Denmark, the United Kingdom, Norway, the Netherlands, Sweden, Switzerland, Germany, and Italy (Dolgen & Alpaslan, 2020). In Türkiye, although various national and international policies encourage environmentally friendly industrial practices, large-scale implementation of IS applications remain relatively limited. Nevertheless, some initiatives have been carried out, including the IS Projects in the İskenderun Gulf, Black Sea Basin, the Trakya region, the Bursa-Eskişehir-Bilecik zone, Ankara, Antalya, Gaziantep, Kayseri, Tire, Bagyurdu and İzmir together with the development of the National Industrial Symbiosis Roadmap. These projects have demonstrated considerable technical potential for industrial symbiosis while also revealing important organizational, institutional, financial, and technical barriers to its wider implementation.

Although industrial symbiosis has been extensively investigated internationally, studies examining its practical implementation within organized industrial zones (OIZs) in Türkiye remain limited. Moreover, relatively few studies combine a comprehensive review of national industrial symbiosis initiatives with a detailed case study to identify both implementation barriers and enabling factors. Addressing this gap is particularly important, as OIZs represent one of the most suitable organizational structures for promoting industrial cooperation and resource sharing among geographically proximate industries.

Accordingly, this study evaluates the development of industrial symbiosis practices in Türkiye within the broader international context and investigates their contribution to the green transformation of industry. The study combines a review of national industrial symbiosis initiatives with a case study conducted in an organized industrial zone to identify implementation opportunities, challenges, and critical success factors. Based on these findings, practical recommendations are proposed to facilitate the wider adoption of industrial symbiosis practices and support the green transition of organized industrial zones in Türkiye.

The Evolution of Industrial Symbiosis: From Spontaneous Exchanges to Digital Ecosystems

Industrial symbiosis (IS) has undergone significant transformation over the past six decades, reflecting advances in industrial organization, environmental policy, and digital technologies. A review of global practices reveals that industrial symbiosis can be synthesized into four distinguishable phases as given in Table 1: (i) spontaneous industrial symbiosis (1960–1980), (ii) planned eco-industrial parks (1990s), (iii) policy-driven regional and national industrial symbiosis programmes (2000s–2010s), and (iv) digitally enabled industrial symbiosis (2020s onward). Although the fundamental objective of improving resource efficiency through inter-firm collaboration has remained unchanged, the mechanisms used to establish and manage symbiotic relationships have evolved considerably over time.

Table 1. *Historical Evolution of Industrial Symbiosis*

Phase	Period	Main Characteristic	Representative Example
I	1960–1980	Spontaneous exchanges	Kalundborg (Denmark)
II	1990s	Planned Eco-Industrial Parks	Brownsville (USA), Styria (Austria)
III	2000–2019	Policy-driven programmes	NISP (UK), TEDA (China)
IV	2020–Present	Digital & AI-enabled IS	Horizon Europe Digital Twins, Sharebox

Phase I: Spontaneous Industrial Symbiosis (1960–1980)

The first phase of industrial symbiosis was characterised by spontaneous development, marked by uncoordinated, decentralised, and market-driven growth. During this period, resource exchanges were driven primarily by economic incentives rather than environmental regulations or climate policies. Companies identified mutually beneficial opportunities to exchange of by-products, water, and energy among private companies at the local level occurred entirely spontaneously, without external coordination or any regulatory requirements and climate targets.

The most notable example of industrial symbiosis worldwide emerged entirely by chance during this period. In 1961, the Equinor refinery required access to water, and therefore constructed a system of pipes to extract surface water from Lake Tisso. Subsequently, in 1972, the Gyproc plasterboard manufacturing facility established a pipeline to receive excess gas from the refinery, with the purpose of fueling its drying ovens. Over time, a sophisticated network of resource exchange has gradually emerged between a power plant, a refinery, a plasterboard factory, a pharmaceutical company (Novo Nordisk), and the local municipality Kalundborg. Unlike later industrial symbiosis initiatives, the Kalundborg network evolved incrementally through bilateral agreements rather than centralized planning. The design of Kalundborg was not due to a master plan or government agency. The success of this initiative can be attributed to the close physical proximity of the companies involved, the established trust between them, and their recognition of the potential for one company's by-product to serve as a more economical feedstock for another (Chertow, 2000; Ehrenfeld & Chertow, 2002; Kalundborg Symbiosis, 2025).The Kalundborg experience demonstrated that industrial symbiosis could generate simultaneous economic and environmental benefits while strengthening relationships among participating organizations. However, because its development depended heavily on local circumstances and long-term cooperation, the model proved difficult to replicate elsewhere.

Phase II: Planned Eco-Industrial Parks (1990s)

Inspired by the success of Kalundborg, in the 1990s, the concept of planned green space projects emerged, and a top-down, centralized engineering approach was adopted to build circular ecosystems—generally referred to as Eco-Industrial Parks (EIPs)—from the ground up (Valenzuela-Venegas et al. 2016).

Several pilot projects were initiated during this period. The Brownsville Eco-Industrial Park project, conducted in the U.S. to evaluate planned greenfield EIPs, serves as a suitable model in this regard (Mortensen et. al., 2024; Mohsen, 2011; Heeres et. al., 2004). The objective of the project was to establish an industrial park in which a chemical plant, a textile factory and a plastics manufacturer would be constructed simultaneously and connected to one another via a pre-designed pipeline infrastructure (Dregulo & Brownfields, 2023). In Europe, regional initiatives promoted cooperation among paper, steel, metallurgical, and energy-intensive industries through exchanges of waste heat, secondary materials, and industrial by-products. The Styria region developed one of Europe's most robust regional symbiosis networks (Chopra & Khanna, 2014; Deutze & Lyons, 2008). Researchers mapped more than 50 distinct companies across various sectors. In this context, waste heat from local paper mills and metallurgical plants was redirected to district heating networks. The regional iron and steel industry began utilizing secondary plastic fractions from consumer waste as a reducing agent in blast furnaces, bypassing virgin coke. Prior to the initiation of the National Industrial Symbiosis Programme (NISP) in the UK in the 2000s, regional micro-pilots were established during the late 1990s, a prime example being the Humber Industrial Ecology Project (Islam, K., 2016). These pilots targeted heavy chemical clusters and refineries along the Humber estuary, thereby testing the early database methodologies for identifying corporate needs and resources.

Although these projects demonstrated the technical feasibility of planned industrial symbiosis, the majority of these "greenfield" projects in the 1990s encountered difficulties or were unsuccessful. The more rigid structure inherent in top-down designs, which resulted in the collapse of the entire network in the event of one participant's inability to fulfil their financial obligations, was a contributing factor to this failure. Changes in market conditions, investment decisions, or company closures frequently disrupted planned exchanges, limiting the long-term success of many greenfield eco-industrial park initiatives.

Phase III: Policy-Driven Industrial Symbiosis (2000s–2010s)

In light of the rigid failures observed during the 1990s, a transition towards macro-level, state-driven frameworks occurred in the 2000s and 2010s. It was recognised by governments that the creation of isolated parks was not a sufficient approach; rather, a more effective strategy involved the use of policy, funding, and national strategy to incentivize existing industrial clusters to establish connections.

China became one of the global leaders in this transition by incorporating industrial symbiosis into its national circular economy strategy. The National Circular Economy Strategy of China and the National Innovation and Science Fund (UK) are demonstrative cases in point. In 2008, China initiated a substantial, state-led initiative by mandating the transformation of traditional national economic development zones into EIPs (Borzenko, 2025; Yizheng et. al. 2025; Hongru et. al. 2020). The Tianjin Economic-Technological Development Area (TEDA) represents one of the most prominent examples in this regard (Han et al, 2010). The government provided substantial infrastructure subsidies, tax reductions, and stringent environmental regulations that compelled the electronics, automotive, and chemical sectors to exchange waste heat, treated wastewater, and materials (Chiu & Yong, 2004; Zhungde, 2009).

During this period, a different policy model, the National Industrial Symbiosis Programme (NISP), was implemented in the UK with significant intensity (Mirata, 2004). NISP was a government-funded initiative that functioned as an industrial "matchmaker". Instead of developing new parks, NISP advisors explored existing industrial clusters, collected data on discarded materials, and proactively established partnerships, thereby generating economic value and diverting significant volumes of waste from landfill disposal (Paquin & Howard-Grenville, 2009).

This period marked a significant shift in the philosophy of industrial symbiosis. The emphasis moved from designing industrial ecosystems to creating institutional conditions that encourage voluntary collaboration among industries through supportive policies, financial mechanisms, and dedicated facilitation programmes.

Phase IV: Digital and AI-Enabled Industrial Symbiosis (2020s–Present)

Recent advances in digital technologies have initiated a new phase in the evolution of industrial symbiosis. The limitations that were previously imposed by physical proximity and manual matchmaking have now been transcended. The contemporary era is characterised by the utilisation of cloud computing, Artificial Intelligence (AI), big data, and block chain to establish highly dynamic, cross-industry, and frequently cross-border digital networks (Menny et.al, 2024; Maicon et. al, 2022; Anastasovski et. al, 2025).

Digital industrial symbiosis platforms enable companies to exchange real-time information on available materials, energy, water, waste streams, and infrastructure, thereby significantly improving the identification of potential symbiotic partnerships. In the field of industrial waste management, companies such as Sharebox and Synergie have adopted digital platforms to function as matchmaking services, similar to the Uber model. In accordance with the provisions stipulated within the Horizon Europe framework, the European Union is presently providing financial support to the establishment and operation of digitalised regional hubs. These hubs utilise digital twins (i.e. virtual models of regional industrial inputs and outputs) in order to track real-time flows of carbon emissions, waste heat, and materials. This facilitates the dynamic exchange of resources within digital spot markets, thereby transforming industrial symbiosis from a static local agreement into a dynamic digital economy.

The integration of AI and digital technologies is transforming industrial symbiosis from a relatively static system based primarily on geographical proximity into dynamic and data-driven industrial ecosystems capable of supporting resource exchanges across wider regional and even international networks. Consequently, digitalization is expected to play an increasingly important role in accelerating the transition toward circular and climate-neutral industrial systems.

Overall, the evolution of industrial symbiosis demonstrates a gradual transition from localized and spontaneous exchanges among neighboring firms to coordinated, policy-supported, and digitally enabled industrial ecosystems. While the underlying objective of improving resource efficiency through industrial collaboration has remained constant, the methods used to identify, establish, and manage symbiotic relationships have continuously evolved. These international experiences provide valuable lessons for countries such as Türkiye, where industrial symbiosis is gaining momentum but still faces organizational, institutional, financial, and technical challenges. The following section therefore examines the development of industrial symbiosis practices in Türkiye.

Development of Industrial Symbiosis in Türkiye

Industrial symbiosis practices in Türkiye have developed progressively over the last fifteen years as part of broader efforts to improve resource efficiency, cleaner production, and industrial sustainability. Although the implementation of industrial symbiosis remains relatively limited compared with several European and Asian countries, a number of regional and national initiatives have established an important foundation for future expansion.

The first major industrial symbiosis initiative in Türkiye was the Iskenderun Bay IS Project, launched in 2010 under the Baku-Tbilisi-Ceyhan (BTC) Crude Oil Pipeline Project and financed by the BTC Crude Oil Pipeline Company. The project was implemented by the Technology Development Foundation of Turkey (TTGV) with the objective of introducing the industrial symbiosis (IS) approach into the area of Iskenderun Bay as a mechanism to increase the collaboration and solidarity between companies for the purpose of achieving both environmental and economic improvement in the region, as well as creating a background for a national programme (Dolgen & Alpaslan, 2020). The project yielded a number of potential synergies within the IS network of 51 member companies from 28 industrial sectors for material, energy, and by-product exchanges. Beyond its direct outcomes, the project played a pioneering role in introducing the industrial symbiosis concept to Türkiye and creating the basis for subsequent national initiatives.

Building upon the experience gained in İskenderun Bay, several regional industrial symbiosis projects were initiated through the collaboration of regional development agencies (such as IZKA, TRAKYAKA, BEBKA), organized industrial zones (OIZs), and the Ministry of Industry and Technology (MoIT). Notable examples include projects implemented in the Trakya Region, Bursa–Eskişehir–Bilecik Region, Ankara, Antalya, Gaziantep, İzmir, Tire, and Bağyurdu OIZs. These initiatives were generally conducted within existing industrial clusters and focused on identifying opportunities for resource sharing, by-product utilization, and waste minimization among participating firms.

Among these initiatives, the Industrial Symbiosis and Eco-Efficiency Project implemented by Directorate of Antalya OIZ and TTGV in Antalya Organized Industrial Zone in 2015 represented an important step toward integrating industrial symbiosis with cleaner production and resource efficiency strategies. The objective was to reduce consumption of resources and to implement more productive, eco-friendly production and service processes. This was achieved by preventing waste and reducing it at the source. Similarly, the Gaziantep OIZ project investigated industrial symbiosis opportunities among companies operating in 166 different industrial sectors, highlighting the substantial potential for inter-sectoral collaboration within large industrial clusters.

A summary of major industrial symbiosis initiatives implemented in Türkiye and their associated symbiosis opportunities is presented in Table 2.

In recent years, industrial symbiosis initiatives in Türkiye have increasingly become integrated with broader green transformation and sustainable industrial development policies. One of the most important developments in this regard was the "Green OIZ Framework Development for Türkiye" project initiated by the

Ministry of Industry and Technology (MoIT) of Turkiye, with the support of the World Bank Group (WBG). The main components of the project were to analyze green OIZ opportunities and to develop a national strategy for Turkiye. In this framework, case studies were conducted in four different OIZs, located in the cities of Izmir, Bursa, Adana and Ankara. The potential improvements in energy and water efficiencies were determined by conducting carbon and water footprint analyses in all cases, enabling the identification of priority investment areas and sustainability opportunities.

Table 2. *Major Industrial Symbiosis Projects Implemented in Turkiye.*

Project Title & Year	Focused Region	Potential Projects	Reference
The Iskenderun Bay Project 2010	The area around the Gulf of Iskenderun	• Production of biogas and energy from corn waste and waste from poultry and cattle, • Production of animal feed from fruit pomace, • Production of a bioremediation product from cotton seed waste, • Utilization of soda process waste as a minor additive in cement production, • Utilization of slag and tuff from iron and steel production in fertilizer production; • Utilization of various wastes as fuel in lime kilns	Çıkmak, S. (2025) Alkaya, E. (2021) Dolgen & Alpaslan (2020)
An Investigation of the Potential for Industrial Symbiosis in the Trakya Region 2014	TR21 Trakya Region	• Production of biogas and electricity from organic waste, • Recovery of coal boiler slag and ash, • Recovery of foundry sand, • Recovery of metal and plastic waste,	https://www.kalkinmakutuphanesi.gov.tr/dokuman/tr21-trakya-bolgesi-endustriyel-simbiyoz-raporu/984

Bursa-Eskişehir-Bilecik Industrial Symbiosis Program 2014	TR41 Level 2 Region (Bursa, Eskişehir, Bilecik)	• Industrial wastewater treatment sludge, • Naturally occurring mineral wastes, • Construction and demolition waste, • Iron-based wastes and scrap (non-recyclable).	https://www.kalkinmakutuphanesi.gov.tr/assets/upload/dosyalar/bebkafizibilitesonucweb.pdf
Industrial Symbiosis Opportunities in Ankara OSTİM 2014	Ankara Region	• Utilization of foundry sand in the manufacture of ceramic sanitary ware • Utilization of rubber waste in production of fired clay bricks, tiles, and construction materials • Utilization of scrap glass in production of fired clay bricks, tiles, and construction materials	

The Industrial Symbiosis and Eco-efficiency in Antalya Organized Industrial Zone (Antalya OIZ) 2015	Antalya OIZ	• Utilization of filter cake in fertilizer production • Utilization of fine powders such as limestone, dolomite, etc., in fertilizer and concrete production • Production of new products from byproducts of alcoholic beverage production; production of flavorings from spent distiller's grains; use of liquid distillate waste as a soil conditioner; and production of dry ice and liquid CO_2 from CO_2 generated during fermentation • Utilization of whey or whey powder in alcohol or fertilizer production • Production of amino acids from waste generated by poultry, meat, and fish processing plants • Utilization of wood shavings and broken wood waste from wood processing plants in other sectors • Utilization of broken glass waste as fine aggregate in concrete production • Utilization of fruit pulp waste in fertilizer production • Compost producing from food scraps • Producing compost from park and garden waste and organic waste	Dolgen & Alpaslan, 2023

Gaziantep OIZ 2015	Gaziantep OIZ	• Recovery of used carpets and carpet tile waste • Recovery of used PET materials • Production of Re-PET raw materials • Utilization of polymer-based waste in the production of construction materials • Utilization of polypropylene waste in the production of recycled non-woven fabrics • Utilization of recycled carpet yarn in carpet production • Utilization of organic waste in animal feed production • Utilisation of EVA and polyurethane waste from the plastic footwear and slipper industry • Utilization of waste vehicle tyres in production of outdoor surfaces • Utilization of ash waste in construction materials • Utilization of polymer-based waste and hazardous waste for energy generation	https://gso.org.tr/en/project/gaziantep-industrial-symbiosis-project-13.html
Eskişehir Province Potential Industrial Symbiosis Network 2015	Eskişehir Province	• Utilization of glass cullet waste in glass wool production, • Utilization of sing marble slurry and fragments in the ceramics sector and construction chemicals production, • Utilization of calcite waste in the manufacture of ceramic products, • Utilization of waste silica sand in construction material production, • Utilization of furnace slag in road construction.	https://www.kalkinmakutuphanesi.gov.tr/dokuman/eskisehir-endustriyel-simbiyoz-projesi-raporu/1409

Investigate Industrial Symbiosis Opportunities in the Kayseri Organized Industrial Zone 2017	Kayseri OIZ	• MDF particles and particleboard waste • Food waste (whey, sesame husks, stale wafer dough, cookie waste) • Styrofoam waste/scraps • Sponge waste • Coal slag and various sludges • Textile waste	https://www.kalkinmakutuphanesi.gov.tr/assets/upload/dosyalar/oran-endsimbiyoz.pdf
Tire Organized Industrial Zone Eco-Industrial Park Transformation Project 2020	Tire OIZ	• Conversion of kitchen waste into compost • Using fruit- and meat-based products as fish feed. • Development of new products from fruit waste for cosmetic and/or medical use, targeting specific effects such as antioxidants and anti-inflammatory properties. • Development of products focused on food colouring and/or flavouring additives, such as fruit-based yoghurt and milk-based beverages. • Utilisation of waste products as additives • Production of insulation materials from high-quality plastic waste • Utilisation of slag generated as waste in steam boilers • Production of organic fertiliser from tobacco dust and waste containing elements such as N, K, P, Ca and Mg. • Solvent recovery	Bayram A., et al, 2020

The outcomes of these studies subsequently contributed to the implementation of additional World Bank-supported projects in Türkiye. These projects have mainly two complementary components; (i) supporting the infrastructure for OIZ sustainability, (ii) providing technical assistance, capacity building and project management. First component requires new green infrastructure investments in OIZs, in order to improve energy and water efficiency by renewable energy investments, and advanced water and wastewater treatment facilities. Technical assistance and capacity building support for MoIT and OIZs services are provided by workshops, meetings, and consultancy services.

In this framework, feasibility studies to determine the opportunities on green transformation and industrial symbiosis implementation were also performed by several OIZs such as Izmir Ataturk OIZ, Tire OIZ, Bagyurdu OIZ. . These studies also contributed to the development of a national roadmap for green OIZ certification system in Turkiye (Dolgen & Alpaslan, 2023).

As a result of these developments, the official "Green OIZ Certification Application Guide" has been published by the Ministry of Industry and Technology in partnership with the Turkish Standards Institution (TSE). The certification process has been fully digitalised through the Spatial Management and Digitalisation Project (MEYDİP), which was initiated to modernise the process and make it more efficient. The certification framework evaluates OIZs using 38 indicators, which are divided into four core domain categories: Environmental, Economic, Social and Governance performance. Eligibility requires compliance with several prerequisite criteria, including certification under ISO 14001 (Environmental Management Systems) and ISO 50001 (Energy Management Systems). Green Flags are given to OIZs that pass the baseline criteria and tiers (Bronze, Silver, Gold, Platinum) are then certified based on their performance scores. These certifications are valid for three years, subject to continuous progress audits. The number of organised industrial zones that have been awarded with the Green OIZ Certificate by meeting the environmental, social, governance and economic sustainability criteria set by the Turkish Standards Institute (TSE) has reached 27 as of 2026. Figure 1 presents the distribution of certified Green OIZs in Türkiye.

Figure 1. *Geographic distribution of Green OIZ in Türkiye*

The evolution of industrial symbiosis in Türkiye demonstrates a gradual transition from pilot projects focused on resource exchanges toward integrated approaches supporting green transformation, digitalization, and sustainable industrial development. Nevertheless, important challenges related to institutional capacity, financial resources, data availability, and stakeholder engagement continue to limit the wider implementation of industrial symbiosis practices. These challenges are further explored through the case study presented in the following section.

Case Study: Evaluation of the Industrial Symbiosis opportunities in an Organized Industrial Zone

The IS potential was evaluated in an organized industrial zone (OIZ) located in Izmir, Türkiye. Within the OIZ, there are 106 industrial firms, of which 68 are currently in operation during the study period. The companies located in the OIZ operate in a wide range of sectors, including the food processing, packaging, electrical equipment, energy, construction materials, chemicals, machinery, furniture, automotive, plastics, textiles, medical devices and supplies, tobacco products, and agricultural machinery manufacturing.

The food industry is the most dominant sector within the OIZ accounting for approximately 44% of all enterprises. It is followed by construction materials (9%), plastics (9%), animal feed production (8%), packaging (6%), medical devices and supplies (6%), chemicals (4%), tobacco products (4%), machinery (2%), furniture (2%), automotive (2%), agricultural machinery (2%), and energy (2%).

Since the OIZ represents a mixed industrial structure with a large number of sectors and firms, a sector prioritization approach was adopted to improve the efficiency of the field study in this project. For this purpose data obtained from the OIZ administration (NACE codes, number of firms, firms' parcel and production areas, water usage, electricity usage, and natural gas usage) have been compiled and analyzed.

The sectors were subsequently ranked from largest to smallest based on various factors (criteria), such as the number of firms operating within the sector, parcel and production area sizes, water usage and energy consumption. In order to consolidate the different rankings based on each criterion (factor) into a single list, "criterion/factor weighting" was applied, and the sectors were ranked according to the determined weight ratios. Based on the resulting scores, the food, construction, chemical, medical devices and supplies, plastics, tobacco, animal feed and packaging sectors were identified as priority sectors for industrial symbiosis investigations.

Following the prioritization process, 23 companies operating within the selected sectors were surveyed in detail and interviewed face-to-face. Information was gathered on the raw materials used in production, the product outputs, by-products and waste streams, as well as the existing waste management practices. In addition, site visits were carried out to identify ongoing resource efficiency measures and opportunities for improving material, water, and energy efficiency.

The collected information was evaluated to identify potential industrial symbiosis opportunities among participating companies. Particular attention was given to opportunities for by-product utilization, waste valorization, resource sharing, and circular use of materials within the OIZ. Potential project concepts were subsequently developed by considering both technical feasibility and sectoral compatibility among firms.

The assessment revealed several promising industrial symbiosis opportunities involving organic waste recovery, material recycling, resource recovery, and by-product valorization. The proposed industrial symbiosis projects and their potential stakeholders are summarized in Table 3.

Table 3. *Potential IS Opportunities Identified in The Case study OIZ*

Projects	Potential Partners	Expected Benefit
Conversion of food waste into compost	Cafeterias, green spaces, and food production facilities	Reduced organic waste disposal and production of soil conditioner
Using fruit- and meat-based products as fish feed	Food companies specializing in fruit processing, dairy producers, and companies producing feed and feed additives	Valorization of organic by-products, reduction of feed production costs, and substitution of virgin feed ingredients.
Development of new products from fruit waste for cosmetic and/or medical use with specific effects, such as antioxidants and anti-inflammatory properties.	Food companies specializing in fruit processing and firms operating in the medical sector	Recovery of high-value compounds from waste streams, creation of value-added products, and increased economic return from by-products.
Development of products focused on food colouring and/or flavouring additives, such as fruit-based yoghurt and milk-based beverages	Food companies specializing in fruit processing and firms producing milk and dairy products	Reduction of food waste, replacement of synthetic additives, and creation of new market opportunities for food by-products.
Utilisation of industrial waste as additives in production processes	Chemical industry, construction chemical manufacturers, ready-mix concrete plants, and fertilizer producers	Reduction in virgin raw material consumption, lower disposal costs, and improved resource efficiency.
Production of insulation materials from high-quality plastic waste	Medical device manufacturers and thermal insulation material manufacturers	Reduction of plastic waste disposal, substitution of virgin polymer materials, and reduction in production costs and carbon emissions
Utilisation of slag generated in steam boilers	Companies operating steam boilers and ready-mix concrete and/or	Diversion of waste from landfill, reduction in clinker consumption, and

	cement plants	lower greenhouse gas emissions associated with cement production.
Production of organic fertiliser from tobacco dust and waste containing nitrogen (N), potassium (K), phosphorus (P), calcium (Ca) and magnesium (Mg).	Tobacco product manufacturers, construction chemical manufacturers and fertilizer producers	Recovery of nutrient-rich waste streams, reduction in chemical fertilizer consumption, and support for circular nutrient management.
Solvent recovery and reuse	Packaging companies	Reduction in hazardous waste generation, lower solvent procurement costs, and reduced environmental impacts associated with solvent disposal.

Results & Discussion

The findings of this study confirm that circular economy and industrial symbiosis approaches not only help companies achieve higher levels of resource efficiency in production and minimize potential environmental issues but also enable them to generate economic gains. As competitiveness is enhanced by environmental investments, green approaches are becoming attractive investments that increase profit rather than being a financial burden on industries. Consequently, investments supporting green transformation are increasingly being perceived not as additional financial burdens but as strategic investments that improve long-term profitability and resilience.

In recent years, Türkiye has established a comprehensive policy and institutional framework supporting the transition toward circular economy and industrial symbiosis, particularly as part of the process of aligning with the EU Green Deal and in line with national sustainability goals. The second main heading of the 'Green Deal Action Plan', published by the Turkish Presidency, is 'green and circular economy'. The plan supports the transition to a sustainable, resource-efficient economy, in line with our country's development goals. The green and circular economy is based on 'green (eco) production' at the individual company level and 'EEP' initiatives at a more holistic level, which highlights the importance of the efforts to be undertaken in this context. In this context, administrative mechanisms such as the National Circular Economy Strategy and Action Plan (2025–2028), the Green Deal Action Plan, the Green Organized Industrial Zones (OIZ) Framework, as well as the Regional Synergy Programs of Development Agencies, the Turkey Circular Economy Platform (TDEP), and the green transition support programs offered by KOSGEB and TÜBİTAK have been key initiatives. These initiatives provide an important administrative foundation for the wider implementation of industrial symbiosis practices.

Nevertheless, the findings indicate that the existence of policy instruments alone is insufficient to ensure successful implementation of industrial symbiosis projects. For any green practice that supports the circular economy — particularly industrial symbiosis — it is essential to first collect and analyse reliable data at the company and/or sector level. Although firms routinely collect information mainly related to production activities, many indicators essential for industrial symbiosis assessments—such as waste generation, by-product quantities, water consumption, recycling rates, wastewater generation, and greenhouse gas emissions—are not systematically monitored or recorded. Consequently, improving industrial data collection systems and integrating sustainability indicators into routine reporting practices represent critical prerequisites for future industrial symbiosis implementation.

Financial constraints constitute another important challenge for industrial symbiosis projects. Many symbiotic opportunities require investments in new equipment, infrastructure modifications, material handling systems, or process adaptations before economic benefits can be realized. Therefore, companies must allocate budgets for the research and projects they plan to undertake. Although the number of financial mechanisms supporting green investments has increased significantly in recent years, access to finance remains a major challenge, particularly for small and medium-sized enterprises. In Türkiye, funding opportunities are available through the Ministries of Industry and Technology; Energy and Natural Resources; Development; and Economy; Regional Development Agencies; TÜBİTAK and KOSGEB. In addition to national funding sources, financial support for projects can also be obtained from sources such as the Turkish Sustainable Energy Finance Fund (TurSEFF), the Turkish Mid-Scale Sustainable Energy Finance Fund (MidSEFF), and the International Finance Corporation (IFC). However, financial experts or investors are not always environmental experts. They may therefore struggle to determine whether a project is beneficial to the environment or merely a marketing strategy, known as 'greenwashing'. The recent development of the Turkish Green Taxonomy therefore represents an important step toward improving investment transparency and directing financial resources toward environmentally sustainable projects. Investments in renewable energy, waste management and biodiversity conservation are considered "environmentally sustainable" by the green taxonomy, which uses scientific and clear criteria to determine such investments. This enables funders to ensure that resources are being directed towards environmental protection, and to make informed decisions about whether to support or reject investments.

The study further revealed that awareness and stakeholder engagement are among the most important determinants of successful industrial symbiosis implementation. The transition from a linear production model toward circular resource management requires a fundamental change in the perception of industrial waste—from an unavoidable disposal problem to a potentially valuable secondary resource. It is imperative to facilitate a shift in perception, whereby waste is recognized not merely as a cost to be eliminated, but as a raw material. In contrast to greenwashing, training staff and managers is conducive to the development of scientific and measurable projects that lead to a substantial reduction in the carbon footprint. Furthermore, the dissemination of knowledge to decision-makers within companies (i.e. CEOs, CFOs and boards of directors) will facilitate their comprehension of the fact that such investments will engender a reduction in expenses in the medium and long term, thus preparing the company. In the context of industry and SMEs, it is imperative to raise awareness through practical symbiosis workshops and mentoring programmes. However, it is equally crucial to achieve the integration of academia and the education system to facilitate a comprehensive and sustained understanding of the subject matter.

Finally, the findings emphasize the strategic role of organized industrial zones in promoting industrial symbiosis. Organized Industrial Zones (OIZs) are the ideal environment for the development of industrial symbiosis. The physical proximity of these areas naturally facilitates the sharing of resources, thereby addressing many of the logistical and administrative challenges associated with such collaborative endeavors. The distinct advantages OIZs offer for industrial symbiosis are geographic proximity, shared infrastructure, the trusted "matchmaker" role, cross-industry diversity and access to green financing. Hence, almost all successful industrial symbiosis practices both in the world and in Turkiye have emerged within OIZs or similar industrial clusters. Over the past decade in Turkiye, significant progress has been made through projects led by the Ministry of Industry and Technology. In this context, the recent Green OIZ Certification System introduced by the Ministry of Industry and Technology and the Turkish Standards Institution represents an important opportunity for integrating industrial symbiosis principles into the broader green transformation agenda of Turkish industry. The number of organized industrial zones that have obtained the Green Industrial Zone Certificate upon meeting the environmental, social, governance, and economic sustainability criteria has reached 27 as of 2026, and this number is expected to increase.

Overall, the results indicate that the technical potential for industrial symbiosis in Türkiye is considerable. However, its successful implementation depends not only on the identification of resource exchange opportunities but also on the development of supportive institutional structures, reliable data systems, financial mechanisms, and stakeholder engagement processes.

Conclusions

Industrial symbiosis has emerged as one of the most effective mechanisms for supporting circular economy objectives and accelerating the green transformation of industry. By facilitating the exchange of materials, energy, water, and industrial by-products among companies, industrial symbiosis contributes simultaneously to improved resource efficiency, reduced waste generation, lower greenhouse gas emissions, and enhanced industrial competitiveness.

The international experience reviewed in this study demonstrates that industrial symbiosis has evolved from spontaneous exchanges among neighboring industries toward increasingly sophisticated policy-supported and digitally enabled industrial ecosystems. In parallel with these global developments, Türkiye has made significant progress during the last decade through pilot projects, regional initiatives, Green OIZ programmes, and national circular economy policies.

The case study conducted in an organized industrial zone in İzmir confirmed the existence of substantial opportunities for industrial symbiosis implementation across multiple industrial sectors. Several promising opportunities involving organic waste valorization, secondary material use, recycling, and resource recovery were identified. However, the findings also demonstrated that technical feasibility alone does not guarantee successful implementation.

The main barriers identified include insufficient data availability, limited financial resources, inadequate institutional capacity, and low levels of awareness among stakeholders. Addressing these challenges requires improvements in industrial sustainability reporting systems, increased access to green financing mechanisms, stronger facilitation capacities within organized industrial zones, and expanded training and awareness programmes for industrial stakeholders.

Given their geographical concentration of industries, shared infrastructure, and institutional governance structures, organized industrial zones represent one of the most suitable environments for promoting industrial symbiosis in Türkiye. The continued expansion of the Green OIZ Certification System, together with national circular economy policies and digitalization initiatives, is expected to create favorable conditions for the wider implementation of industrial symbiosis in the coming years.

Future research should focus on the quantification of environmental and economic benefits associated with industrial symbiosis projects, including material savings, greenhouse gas reductions, and life-cycle impacts, in order to strengthen the evidence base for policy development and industrial decision making.

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