EVALUATE THE FRAMEWORK OF INDUSTRIAL SYMBIOSIS IN INDIAN INDUSTRIAL AREAS

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ABSTRACT

The research discusses an industrial symbiosis framework in Indian industrial areas using a scalable three-level approach with Industry 4.0 technologies. It tries to optimize resource sharing through facilities, machinery, water, energy, materials, and human expertise with digitalization. At the local level, it would focus on residual energy and collaboration on water and energy efficiency. This not only reduces operational costs but also increases sustainability due to the utilization of the indigenous human skills and local infrastructure. Geographical proximity in this level makes it easy for the industries to share production plants, warehouse capacities, and waste treatment units easily, which makes the concept of industrial symbiosis economically viable.Intermediate levels are expanded, based on recycling processes of material and energy through various industrial sectors, to larger geographic scales. Greater coordination and exchange of resources beyond the local scale will be a focus in these levels. There will be deployment of digital technologies and AI-driven decision-making for the support of communication and collaboration within the interlinked supply chains. These technologies enable real-time data exchange, what-if analysis, and decision support systems; more relevant to a larger industrial operation. This level can better tackle the scaling-up issue of industrial symbiosis. Further, a more resilient supply chain is facilitated with reduced impacts through material re-use and energy efficiency.The framework will venture into a global level of digital collaboration using human capital, which is the most important component for developing the level of resilience in the supply chain. It is in line with Industry 5.0 where advanced digital technology used along with knowledge from the human capital. This, therefore, marks a transition from old, age-old industrial practices towards more people-friendly and stakeholder-centered engagement that fosters inter-cooperation, and knowledge exchange beyond geographical boundaries. Global Level ensures that compliance is integrated with local, national, and international laws and that sustainability parameters are met regarding proper waste management, resources used, and supply chain efficiency through implementing the best practice around the world. This approach is in line with international sustainability goals and promotes the transition toward a circular economy. This scalable three-level framework would make Indian industries achieve sustainable industrial practices and promote their competitiveness and resilience in the global market.

Keywords: Industrial Symbiosis, Industry 4.0, Digitalization, Resource Sharing, Sustainable Industrial Practices, Government Regulations, India.

I. INTRODUCTION

Industrial symbiosis is the synergistic use of facilities, water, machinery, energy, materials, and human expertise by several industries in a way to maximize efficiency and minimize waste. The underlying basic idea behind this concept is that the sharing of unused or underutilized resources between businesses might otherwise become waste. The businesses, however, might gain from it economically, environmentally, and socially. Industrial symbiosis not only promotes sustainability by reducing the environmental footprint of industrial activities but also fosters innovation through cross-sector collaborations. The integration of digitalization further amplifies the benefits of industrial symbiosis through real-time data exchange, advanced analytics, and automated decision-making processes.

Digitalization as an enabler of Industry 4.0 plays a critical role in the evolution of industrial symbiosis, which enables effective resource management and coordination across interconnected supply chains. Internet of Things (IoT) devices, cloud computing, artificial intelligence (AI), and blockchain technologies will be fully integrated to contribute to the development of a more transparent, responsive, and resilient industrial ecosystem. These technologies help in tracking and streamlining the flow of materials and energy while allowing for predictive maintenance and waste reduction, along with real-time decision-making, which helps in achieving sustainable industrial practice. This is, in brief a strategic way to solve and handle the problem and demands put forth by less resources on supply, the regulatory constraint placed upon and competition increasing inside the global market arena: digitalization plus industrial symbiosis.

This paper deals with the three-level industrial symbiosis framework that integrates Industry 4.0 technologies to be context-specific for the Indian industrial areas while digitalization can help in developing the system for enhancing synergies at the local, intermediate, and global geographical scales toward sustainable growth in industries. Here, the scope is to optimize resource use through digital monitoring and collaboration at the local level. On the middle level, wider material and energy exchanges have been studied. Industry level, as in the Industry 5.0, will integrate human experience with the advanced digital technology to allow for a holistic, sustainable industrial landscape. "The introduction lays a background from which to understand how digitalization can play a great role in advancing industrial symbiosis to achieve long-term sustainability goals."

II. REVIEW OF LITERATURE

Bain et al. (2010). The recovery, reuse, and recycling of industrial byproducts, sometimes seen as trash, are prevalent in India and other developing nations mostly owing to reduced related expenses. Certain wastes are repurposed inside the originating plant, others are used by adjacent industrial establishments, and others are processed via official and informal recycling marketplaces. Direct inter-firm reuse is fundamental to the concept of industrial symbiosis, whereby companies collaborate in the interchange of material and energy resources. This research used material flow analysis to examine the recovery, reuse, and recycling of industrial residuals in an economically varied industrial region in South India. It measures the waste production from 42 firms, including items transferred between facilities and those that are recycled or discarded. This research examines a company cluster in Mysore, Karnataka, and is the first study in India to comprehensively analyze material flows to discern existing symbiotic relationships inside an industrial zone. The businesses in this industrial region produce 897,210 metric tons of waste residuals yearly, recovering 99.5% of this total, with 81% being reused by the originating enterprises, mostly by a sugar refinery that processes the majority of this trash. Geospatial data indicate that activities within a 20km radius of the industrial zone get more than 90% of residuals departing from facility gates. Two-thirds of this sum is allocated directly to other economic entities for reutilization. This research significantly contributes to the literature by differentiating the various methods of material reuse, examining the

geographic scope of symbiotic activities, and highlighting the crucial role of the informal sector in industrial waste management within industrializing countries.
Yap, Nonita & Devlin, John. (2016). Industrial symbiosis (IS) refers to the process of revalorizing and exchanging by-products across different corporate units. Literature indicates that information systems may provide financial, social, and environmental advantages to both companies and society. Analytical tools have been created to reveal information systems configurations and recommendations for developing information systems when they are not yet established. Notwithstanding the proposed advantages and the availability of these technologies, few planned information systems arrangements have effectively come to fruition, with significant exceptions in East Asia. Comprehending the emergence, expansion, or decline of IS networks requires both macro- and micro-level investigation. Certain explanatory aspects have been thoroughly examined in the IS literature, particularly the significant function of coordinating organizations. However, the examination of enterprise-level activities and plans, together with the external environmental factors affecting firms and their networks, is little explored. The article presents an analytical framework that incorporates findings from studies on cleaner production, corporate social responsibility, innovation diffusion, and the state's role in development. The approach aligns with the perspective that the development of IS networks is defined by ‘equifinality.’ Diverse networks may get IS via various combinations of elements. No comprehensive theory of Information Systems success or failure is proposed, since such a theory is unattainable. The origin, evolution, and disruption of IS are examined as a sociohistorical analytical issue. Analytical frameworks provide a shared explanatory foundation for such occurrences, although lack forecasting capability.

Boons et al. (2016). Industrial symbiosis (IS), a fundamental concept in industrial ecology, has proliferated globally as a method that mitigates the ecological effect of industrial operations among groupings of enterprises. This paper presents a novel perspective on the study issue, leveraging the significant progress achieved in the last 15 years in comprehending the emergence of IS. We present a conceptual and theoretical framework for addressing the problem of global comparative analysis. This necessitates formulating a strategy to resolve the issue of equivalence: the challenge of comparing instances of IS across diverse institutional settings. The suggested framework highlights Information Systems (IS) as a process and seeks to overcome challenges in comparative analysis by (1) defining vocabulary for examining IS variations, (2) offering a typology of IS dynamics, and (3) establishing essential research objectives to guide future inquiry. Our thesis is founded on the shared experiences of collaborative research initiatives in North America, Europe, and Asia, as shown in recent literature reviews.
Chertow, Marian, et al. (2019). This work formulates an algorithm using lifecycle assessment methods to ascertain a city's industrial symbiosis potential, defined as the aggregate of wastes and byproducts from local industrial firms that might feasibly function as resource inputs for other regional industrial operations. This study, unlike many prior papers that report on private benefits to firms, emphasizes public benefits to cities by estimating the capacity of municipal infrastructure preserved through the maximum recoverable resources from local enterprises, specifically in terms of landfill space and water demand. The findings herein evaluate this innovative methodology for the district of Mysuru (Mysore), India. The assessed industrial symbiosis potential, derived from the examination of inputs and outputs of around 1,000 urban firms, corresponds to 84,000 tons of industrial waste, exceeding 74,000 tons of CO_2e, and 22 million gallons of wastewater each day.

This technique illustrates how industrial symbiosis connects private output with public infrastructure to enhance a city's resource efficiency by expanding public infrastructure capacity and yielding public health co-benefits.
Boom et al. (2022). Industrial symbiosis (IS) facilitates the use of resources within a production chain via cooperation across enterprises, identifying methods to repurpose one entity's waste as inputs or raw materials for another. IS aims to foster environmental sustainability, optimize resource use, and provide social, environmental, and economic advantages via the physical exchange of trash, residues, and materials, yielding multiple benefits for enterprises and ecological gains for society. Extensive research has been undertaken globally regarding the implementation of Information Systems (IS) in business environments and case studies in economically robust nations; however, no studies mapping IS research in emerging and frontier markets have been identified, and academic literature on this subject in such countries remains limited. This research entails a comprehensive literature review of information systems cases in emerging and frontier market nations, aimed at equipping future researchers with insights into the similarities, weaknesses, strengths, and considerations necessary for addressing the topic and bridging research gaps in the field. A mapping was conducted on the development of studies about IS, categorized by country, economic activity, journal distribution, publication year, used methodologies, hurdles and drivers in case studies, and the significance of this issue within the contemporary academic landscape. In Asian and emerging nations, the amalgamation of enterprises and economic activity occurs inside industrial parks, which are supported by laws and governmental rules that facilitate industrial symbiosis. Conversely, in the United States and Africa, the integration of diverse resources such as electricity, water, coal, and waste within industrial settings is in its nascent phase, with prospects being recognized to foster industrial symbiosis among enterprises. This study appeals to a diverse audience, including investors, regulators, politicians, and academics focused in promoting industrialization and economic growth in emerging and frontier market nations via information systems.

Akhtar et al. (2022). Industrialization is essential for socio-economic advancement but has significant consequences for resources and the environment. As a result, partnerships based on industrial symbiosis are increasingly acknowledged as an effective approach to managing resource use to alleviate environmental suffering. Nonetheless, such synergistic alliances are more common in developed areas and are associated with bigger enterprises. Indeed, such collaborative partnerships are less prevalent in developing countries and small to medium-sized firms (SMEs). This necessitates exploring the possibilities for synergistic collaborations among small and medium-sized industrial organizations in emerging countries. Consequently, the research aimed to discover, evaluate, and investigate the potential for symbiotic cooperation among SMEs in Pakistan. Furthermore, the suggestions are equally pertinent for cultivating and enhancing productive partnerships in emerging areas. Data on inputs and outputs was gathered from sixty-one (61) SMEs via a field survey conducted in 2019. The data was processed and evaluated to identify current and prospective synergies among SMEs. The key results revealed that most collaborative relationships are bilateral and aimed at maximizing economic benefits. Nonetheless, informal networks of recyclers and the lack of a rigorous regulatory framework characterize the reality in emerging or transitioning countries. These variables adversely affect the process of official and informal communications between businesses. Moreover, the lack of knowledge and impulsivity among SMEs, together with the irregular supply of by-products, pose as obstacles to such collaborations in developing nations. It requires proactive involvement and support from governmental entities via policy tools. The study targets a diverse audience including manufacturers, investors, policymakers, and scholars involved in Information Systems studies. Furthermore, the inputs will catalyze eco-industrial advancement in emerging places like Pakistan.

III. RESEARCH METHODOLOGY

The research paper provides a framework for industrial symbiosis that utilizes Industry 4.0 enabling technologies and is scalable to a global level. A three-tiered structure is presented, illustrating the relevant Industry 4.0 technologies at each tier. The suggested symbiosis framework and the advancement of Industry 4.0 technology-based design demonstrate the potential for enhanced cooperation and expedited attainment of sustainability objectives. The literature suggests the horizontal integration capabilities of industrial symbiosis. The present industrial comprehension and implementation maturity are derived from the examination of digitalization tools and platforms relevant to industrial symbiosis. The study advances Industry 4.0 research and its expansion to the fifth generation, emphasizing human resource knowledge exchange as its central focus.

IV. INDUSTRIAL SYMBIOSIS FRAMEWORK AND ARCHITECTURE

The suggested three-level information systems architecture is predicated on the sharing of idle or underused resources in services (facilities, equipment, storage capacity), water, energy, materials, and human resource knowledge and skills via digitalization. Industrial symbiosis has been used locally for the utilization of leftover energy. Economic, technological, environmental variables, and governmental regulations/policies influence the development of industrial symbiosis. The cement industry in India utilizes slag from the steel sector and fly ash from thermal power plants. The resurgence of interest in industrial symbiosis is driven by governmental restrictions and initiatives. In the last two years, as a consequence of the Paris Agreement, the Indian government has mandated several companies to disclose their implementation of extended producer responsibility. Consequently, companies across many sectors in India are pursuing cooperation with one another and research institutions to develop strategies for using each other's trash in compliance with government rules and policies. Figure 1 illustrates the symbiosis structure, with each level representing synergies according to geographical size.

Three level Industrial symbiosis framework

First level – Local level: The innermost level is the most implemented symbiosis relation where resource utilization is bound by geographical proximity. The level deals with the service-based synergies like sharing of production facility, warehouse capacity and waste treatment plants (recycling units). Due to the geographical proximity the costs of infrastructure are low, depend on indigenous human skill and promotes water and energy-based collaborations. The water resource sharing targets to reduce the consumption of fresh water and promotes for recovering wastewater. In

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the energy cascading, the byproducts like heat and steam are used by the collaborating industry thus reducing the overhead costs. Due to the limited geographical coverage, the dynamic decision on the prospects of synergy depends on the availability of real time data that can be processed locally.

Second level – Intermediate level: The interim level deals with the interactions between the industrial symbiosis districts where the synergies are between industries located in a wider geographical scale and are not bound by the limitation of proximity. The material and energy interactions are dealt commonly at this level. The recycling and reuse of material wastes are the most diffused and widely implemented among the industries. The waste resources can either be utilized as input substitution or can be used as a byproduct. The energy-based synergy aims for fuel replacement and waste-to-energy production and thus are not infrastructure dependent. The effective digitalization in this level targets for wider opportunities and distribution of resources in terms of human involvement. Efficient communication is important with decision making capability between intertwined supply chains as it caters to a wider geographical boundary. The data processing system and the subsequent control systems should be capable to perform what-if analysis and function as a decision support system for wider collaboration among the industries.

Third level – Global level: The outermost level in the framework is the global level where the interaction is among the industries which are not bound by any geographical confinement. In this level global supply chain becomes important, but the symbiotic relationship at this level is less explored. Primarily the digitalization of the human resource knowledge and collaboration of human expertise is given importance in this layer.

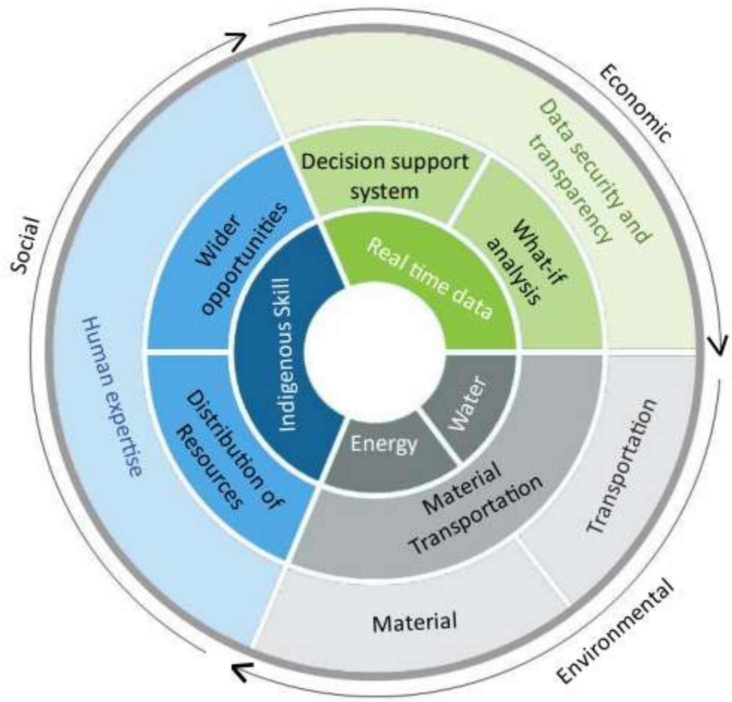

Figure 1: The proposed three-level industrial symbiosis framework

The symbiotic connection aims to enhance manufacturing processes, maintenance, and cognitive decision-making, therefore bolstering supply chain resilience. The global paradigm is human-centric, progressing towards Industry 5.0, where human knowledge and Industry 4.0 technology are

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emphasized alongside data protection. The suggested three-tier digital IS structure offers companies the flexibility to integrate new interactions on a broader scale.

Industry 4.0 based symbiosis architecture for a practical case scenario

The architecture is derived from the suggested framework and incorporates I4.0 technologies at each level of implementation (table.1). Some technologies may be used at all levels of implementation, despite being classified under a particular level. Figure 2 illustrates the implementation architecture for the wine business, sugar industry, and other related sectors. The digitization of industrial processes and the discovery of collaborative opportunities across industries improve interoperability across the levels outlined in the framework. Effective communication from the primary level to the global level will enhance the potential for further synergies.

Table 1: Industry 4.0 technologies/tools for Industrial Symbiosis

	Local level	Intermediate level	Global level
Synergies	Water	Material Energy	Human expertise and knowledge, Material
	Services		
	Energy		
Technologies	Edge computing	Fog to cloud computing	Artificial intelligence
	Internet of Things	Data analytics Simulation	Blockchain Cloud Computing
Requirements	Quick processing	What-if analysis	Human action digitalization
	Real time data	Decision support Systems	Data security
Tools	Real time sensor-based tracking	Digital twin/Shadow	AI model development
		5G/6G network communications	Digital platforms
	Embedded controllers	Data driven models (ML/DL)	Posture detection

The industries are presumed to be distributed throughout a geographical region and may be classified as intermediate level. The fundamental symbiotic connection depends on the accessibility of real-time data and its capacity for local processing. The wine and sugar industries mostly depend on agricultural products for their basic resources, with some commodities being imported. The availability of material data facilitates the scheduling of downstream operations and the effective sharing of facilities. Nevertheless, in primary sector sectors, data availability continues to depend on human interaction, which is susceptible to mistakes and is time-consuming. The difficulties related to data availability may be alleviated by digitizing the data collection process. It is crucial to guarantee that the execution of the digitization method does not lead to elevated total expenses. Retrofitting equipment and converting old machines to Industry 4.0 compatible systems are approaches that may facilitate cost reduction and link current facilities into the communication network. "The efficient sharing of resources is enabled by real-time data derived from agricultural production." The facility is used for both local products and foreign commodities. Consequently, access to IoT-derived data from both international and local supply chains is essential for effective material storage. The sensor-based agricultural field data is crucial for identifying the suitable soil nutrients to be applied. The sugar business mostly manufactures sucrose-based sugar and ethanol. Both items are marketed and exported. Nonetheless, the pricing and demand-supply dynamics in the home market are very volatile. To adeptly manage these variations, it is crucial to use a data-driven decision-making framework that bolsters resilience.

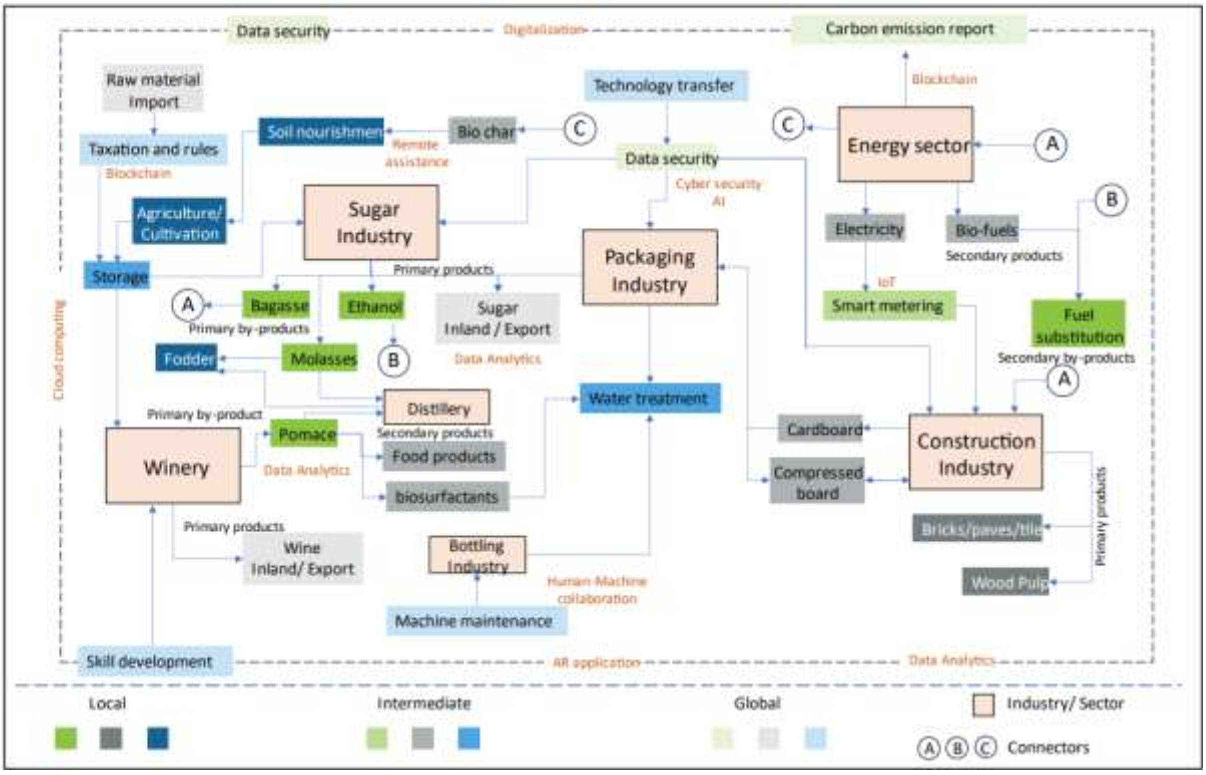

Figure2: Industry 4.0 technologies-based symbiosis architecture for a practical case scenario

It intends to address the multifaceted problems involving resource utilization, waste management, and regulatory compliance in this new industrial symbiosis framework by involving digitalization at all its levels. The framework hence encourages not only local but intermediate and global industrial collaborations while upholding sustainability and economic gains.

Economic Factors: It reduces the cost significantly at the local level, by sharing production facilities and waste treatment plants. By using indigenous human skills and the local infrastructure, it will maintain the cost-effectiveness at all times. The wider material and energy exchanges at the intermediate level can reduce the costs further by recycling and reusing the waste products. Digital platforms and AI-driven decision-making at the global level enhance supply chain resiliency and thus reduce the costs associated with supply chain disruptions.

Technical Factors: Integration of Industry 4.0 technologies such as AI, IoT, cloud computing, and blockchain across the different levels of the IS framework allow for easy data exchange and real-time decision-making along with what-if analysis. This technical base helps support efficient communication and collaboration, minimizes mistakes and inefficiencies, and provides a platform for error-free operations. Digital twins and sensor-based tracking of operations will help track events in any industry, thus reacting promptly to changes in any situation.

Environmental Factors: The IS framework minimizes environmental pollution through optimal usage of resources and minimum wastage. At the local level, water and energy partnerships minimize the consumption of fresh water and waste heat. Intermediate levels minimize further environmental effects through material re-use and recycling. On a global level, it transitions towards digital collaboration and data sharing, thus allowing a circular economy transition to occur, thereby minimizing industrial processes' impact on the environment.

Government Regulations and Policies: The government regulations in India are the primary drivers for the adoption of industrial symbiosis. These include the effects of the Paris Agreement and the extended producer responsibility mandate. These policies encourage industries to collaborate on waste utilization and resource sharing to meet sustainability goals. The three-level IS framework aligns with these policies by providing a structured approach to resource optimization and regulatory compliance.

Challenges and Opportunities: Legacy systems integration into a digital IS framework has challenges like data availability and retrofitting machinery costs, but these can also be reduced by employing superior digital technologies and ensuring that increased overall costs are not incurred upon implementation. Even with the adoption of IoT and AI, it might enhance the accuracy of data and its ability to make decisions, thereby enabling industries to navigate uncertainty and fluctuations in demand and supply.

In conclusion, the proposed three-level IS framework can be considered a holistic approach toward digitalization for the attainment of sustainable industrial practices. This framework opens up various opportunities for industries to cooperate in optimizing their resources and, consequently, meeting the requirements of the regulatory system toward a more resilient and sustainable industrial future.

CONCLUSION

In order to enhance the production process and related services, digitalization in the I4.0 environment is now essential. The manufacturing sectors are being pushed to embrace a more circular value chain strategy by the growing demand for sustainability, which is influenced by both external forces like strict government laws and internal considerations like rising prices and decreasing resource availability. Achieving a circular economy is one of the primary goals of the IS. The use of Industry 4.0 technologies to expand the use of IS in improving human-industrial symbiosis relationships was the focus of this article. The suggested three-tiered framework is scalable thanks to its design built using I4.0 technologies, which allows it to transcend geographical limitations. The theoretical foundation and justifications for putting the suggested framework into practice are the work's limitations. Dealing with the shift from data-centric to human-centric industrial symbiosis will be the focus of future study in this area.

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