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Research

Assessing industry 4.0 readiness: a TOE-P framework for the sugar industry in developing economies

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Abstract
Industry 4.0 concepts have recently significantly supported transparency and reliability in every industrial sector. Organizations must adapt their traditional paradigms and approaches to align with market demands. Hence, developing a framework that can change these conventional approaches with fresh ideas is essential. The Industry 4.0 (I4.0) readiness model presents a creative concept that holds promise for the entire organizational and industrial value chain. Existing research focused only on technological, organizational, and environmental aspects. However, in process-extensive industries, like the sugar sector, the process is critical and considerably impacts the business. So, providing a strong framework for such sectors is necessary. The novelty of this paper is putting a process dimension in the TOE framework, which is critical for sugar industries. The study develops the extended framework to assess readiness. Experts have validated the framework as the study enhances it by adding process dimensions. Practitioners can apply the modeling concept to study the readiness framework in various sectors. Consequently, essential findings and recommendations drive the discussion forward. The study highlights opportunities for cross-disciplinary research across sectors.

Keywords Industry 4.0 · Food sector · Technology-Organization-Environment · Sustainability · Supply chain

1 Introduction

Industry 4.0 modernizes traditional manufacturing by integrating advanced technology [21]. Smart manufacturing enhances supply chain flexibility through automation, shared business planning, alternative routes, and supplier diversification [49]. It supports managing stakeholder engagement, improving operational flexibility, and resource management efficiency [10]. It also provides effective data management solutions [28]. This progression builds upon Industry 1.0, 2.0, and 3.0, with emerging technologies transforming design, manufacturing, and transport, driving wider industry adoption [45, 50, 62].

Industry 4.0 enhances productivity, efficiency, and sustainability in a dynamic world. Its technologies support its integration into manufacturing, fostering competitiveness in the digital transformation journey [34]. However, small and medium-sized enterprises (SMEs) drive the sugar industry in developing nations. Their inclusion in Industry 4.0 and sustainability initiatives strengthen supply chain resilience and economic sustainability [48]. Identifying the proper requirements for adopting new technologies and aligning them with organizational culture remains challenging. Ensuring market competitiveness also requires mitigating the negative impacts of industry-wide adoption [36].

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Organizations often struggle with integrating cutting-edge technologies, particularly within Industry 4.0. Managing these innovations demands expert knowledge, while high initial hardware, software, and training costs pose additional barriers [23]. SMEs, in particular, may find these expenses prohibitive. Despite Industry 4.0's potential to drive growth, process industries struggle to fully capitalize on it due to a lack of empirical evidence and frameworks [47].

Industry 4.0 applications [8] could maximize resource efficiency and productivity in sugar manufacturing. However, the high cost of implementation remains a challenge [31]. Financial constraints are a significant barrier to adoption [43]. Studies have identified twelve key barriers to Industry 4.0 implementation, including organizational culture, leadership, management challenges, and the absence of standardized reference architecture [13, 14, 25, 46, 55].

This research focuses on developing economy nations. India is a developing economy where Industry 4.0 can transform key industries like sugar production. The agriculture-driven economy of India makes it an ideal case for studying Industry 4.0 adoption in traditional industries like sugar. This study examines how Industry 4.0 can enhance efficiency and sustainability in India's sugar industry.

The present research seeks to address the above-mentioned gaps in the extant literature by addressing the following research questions:

i. What are the different aspects of I4.0 adoption in the sugar industries of developing nations?
ii. How can the sugar sector assess an industry's readiness for I4.0 adoption?
iii. How can it support transforming the sugar sector in India?

2 Literature review

Industry 4.0 offers opportunities and challenges across industrial sectors. Technologies like IoT (Internet of Things), BDA (Big Data Analytics), DT (Digital Twin), AI (Artificial intelligence), and Robotics can help industries optimize costs and strategic alignment [6, 54]. However, there are also a few challenges, like training and development of resources, resource optimization, and sustainability. Agriculture is critical in many developing economies like India and supports significant industries. Sugar industries are among the industries that mainly depend on agriculture. Despite its economic significance, the Indian sugar industry faces various challenges, including a shortage of crops as raw material, a lack of infrastructure, and weak supply chain management. Integrating Industry 4.0 into this sector is vital for business and sustainability (water conservation and energy efficiency). It can also provide the scope of rural development. Thus, adopting the global concept of Industry 4.0 can support the Indian sugar industry's sustainable growth. So, thinking globally and acting locally will significantly develop the economy and sugar industries.

However, in the literature review, it was found that support technology implementation, like the Technology Acceptance Model (TAM), the Technology-Organization-Environment (TOE), and the Unified Theory of Acceptance and Use of Technology (UTAUT). The TOE framework supports the implementation of technology and its development; it also explains the organizational ecosystem and the complete ecosystem of the business environment [39], [42], [41]. TAM & UTAUT focused on internal factors driven by attitudinal factors (TRA; [2]). This framework supports user perseveration (TAM; [12])but neglects the ecosystem approach [61]. Therefore, considering the ecosystem approach, the TOE is more suitable for technological adoption [18]; (Hossain and Quaddus 2011; [40].

Furthermore, one of the theoretical frameworks extensively used in the context of technology adoption in different sectors is the Technology-Organization-Environment (TOE) framework. This framework provides a systematic approach to identifying and analyzing the primary dimensions that influence decisions on technology adoption. By using this framework, organizations can make well-informed decisions about adopting and implementing new technologies, enhancing their competitive edge. However, none of the studies have used the TOE framework to analyze the integration of I4.0 technologies in firms. As the market became increasingly competitive, the company's leadership is realizing the importance of embracing the technologies and practices of Industry 4.0 to maintain its edge. However, industries are facing a challenge—the lack of a comprehensive framework to assess their readiness for Industry 4.0 [63].

However, a comprehensive framework is lacking to measure the I4.0 adoption readiness of different firms. Further, most studies have not used any theoretical framework to understand the intricacies of I4.0 adoption in firms. Hence, there is a limited understanding of the different facets of I4.0 adoption. For a swift transition, organizations can perform the readiness check in various dimensions, providing direction for the transformation process and ease of implementation [15]. Some studies have addressed different dimensions of I4.0, but research investigating firms' readiness toward

I4.0 adoption is limited. To answer the posited research questions, the present study aims to propose a comprehensive and business-ready assessment framework to measure firms' readiness for I4.0 adoption. A detailed systematic literature review on I4.0 readiness and adoption is performed to determine the relevant aspects.

Moreover, the detailed analysis shows that the existing Technology-Organization-Environment (TOE) framework offers a holistic approach. However, it does not adequately address the challenges faced by process-intensive industries, such as the sugar industry. In such sectors, processes play a critical role [54]. Therefore, the process is to be incorporated into this framework to ensure sustainable development and satisfy the unique needs of such sectors.

A study was done in developing nations on one of the essential sectors, the steel industry, considering its massive contribution to the country's development [52]. The outcome of the study is quite encouraging as it suggests focusing on the following process-related frameworks for industry 4.0:

i. Prioritize actions to enhance operational efficiency.
ii. Develop an ecosystem mindset.
iii. Support manufacturing system to adapt to uneven production demands, availability of system, and meet market expectations.
iv. Push for adaptability on new or upgraded systems of process.

So, the research extends the TOE framework by including the process dimension (TOE-P) specifically for the I4.0 context to understand the different aspects involved in the I4.0 adoption. The proposed TOE-P framework will provide a systematic process for sugar firms to assess their readiness, make informed decisions, and effectively navigate the complexities associated with Industry 4.0 adoption. This method also considers the interaction of numerous components involved in the sugar sector process dimension.

2.1 Theoretical background

Industry 4.0 readiness is key to organizational value, maturity, profitability, flexibility, and productivity. Assessing readiness and adopting new technologies are essential for navigating Industry 4.0 complexities.

This section examines existing literature on Industry 4.0 readiness dimensions and related factors. It consists of two subchapters, with the first analysing studies on Industry 4.0 readiness. This review identifies key factors influencing readiness and establishes foundational insights. However, the third phase details the TOE Framework (Technological, Organizational, and Environmental) derived from the literature review. This framework systematically links technological advancements, environmental factors, and organizational dynamics to assess Industry 4.0 readiness. Industrial transformations have occurred in distinct phases, each with unique characteristics. The latest phase, "Industry 4.0," emerged from a 2011 German government initiative to enhance production automation [28].

Since 2015, extensive research has explored Industry 4.0. While its adoption offers significant benefits, organizations face challenges, primarily resistance to learning and system adaptation for automation [11, 30]. The significant benefits are leveraging big data, fostering a data-driven culture, and managing complex stakeholder relationships through cyclical processes [38, 44]. However, these benefits exist in intense competition at all levels. The traditional manufacturing process is undergoing significant transformation with new technologies like Additive Manufacturing (AM), Big Data Analytics (BDA), Cybersecurity (CS), Internet of Things (IoT), Cyber-Physical Systems (CPS), Blockchain (BC), and Robotics [45, 50, 62].

Smart IoT sensors can enhance sugarcane farming by monitoring soil moisture, weather, and crop health while tracking equipment data for improved uptime. Blockchain ensures contract security, quality traceability, and compliance in financial transactions. Additive manufacturing enables faster, cost-effective innovation, while robots assist with loading, unloading, and packaging. Cybersecurity protects sugar plants from digital threats. These technologies drive sustainability, cost optimization, higher yields, and improved plant uptime. New technologies transform conventional factories into digitized, automated "Smart Factories" [9]. A study applies fuzzy techniques to assess Industry 4.0 in benchmarking [63]. Prior research enhances human resource capabilities for digitizing logistics and developing a readiness index framework [22]. A mixed-method study identifies barriers to Industry 4.0 adoption in Indonesian SME manufacturing supply chains [17]. A study explores the development of a Quality 4.0 Maturity Index to improve operational performance and efficiency [37]. Research also examines cloud-integrated architecture to enhance delivery commitment in smart manufacturing through technological integration.

2.2 Challenges of adopting industry 4.0

The digital transformation of manufacturing is complex, requiring strong leadership that emerges from a deep understanding of its challenges. The economic factor and cost of implementation or transformation are also significant challenges in Industry 4.0 implementation. So, experts are needed here to guide the complete process and define the phases or steps to make the transformation economical. Cyber risk is a challenge in I4.0 in disrupting manufacturing and enterprise management. A comprehensive risk mitigation and compliance plan should be in place before implementation. After carefully examining the literature review, it is observed that adopting Industry 4.0 is entirely novel in a developing economy context. Although there are many studies in various industrial sectors, very few studies are available in the sugar industry. Moreover, it is the first study discussing the sugar industry's TOE framework.

The sugar industry's vulnerability to climate change makes Industry 4.0 (I4.0) adoption more urgent than in many other process industries. Sugarcane, its primary raw material, depends on rainwater, climate, and seasonality and is prone to pest attacks. It deteriorates rapidly after harvesting, losing sucrose content. Seasonal labor dependency affects productivity. Due to agricultural reliance, perishability, resource intensity, and supply chain challenges, digital transformation is crucial for this industry. The change management strategies to overcome challenges are listed as follows:

I. Existing phase

   i. If the company's manufacturing setup is still at the industry 2.0 or 3.0 level, transitioning directly into the industry 4.0 implementation will be challenging.
   ii. Legal challenges
   iii. Once businesses transform, meeting legal and compliance requirements becomes challenging, demanding expertise and determination to navigate successfully.

II. Unlearn & Relearn

   i. Suppose manufacturing locations have a legacy; learning new things from the entire workforce is easier. A complete framework is needed for unlearning to relearn, and adequate training and coaching should be provided.
   ii. Inhouse fallacy
   iii. Most businesses focus on driving the complete transformation through their internal team.
   iv. However, the existing team needs more expertise, which creates hurdles and failure in the entire transformation process.

III. Focus on Self

The traditional business process always focuses on everything that the businesses themselves should develop. Once businesses transform, meeting legal and compliance requirements becomes crucial. However, a lack of expertise and internal delays often slow market responsiveness. A shift in mindset from "MINE TO OUR" is essential to overcoming these challenges.

2.3 TOE framework

The Technology-Organization-Environment (TOE) framework is a well-established conceptual framework within innovation management and technology adoption. The examination and interpretation of the adoption and assimilation of new technologies within organizations are facilitated by understanding the intricate relationship between technology, organizational elements, and the external environment. TOE typically refers to the Technological, Organizational, and Environmental aspects that may affect the use of the latest technologies and activities related to strategic digital transformation in the context of Industry 4.0 or I4.0. Alternative prevalent theories on technology

adoption, such as the technology acceptance model (TAM) [12], emphasize individual-level technology adoption, while the theory of planned behavior [1] explores behavioral intentions. TOE illustrates the mechanism at the organizational level. TOE posits that technological, organizational, and environmental factors influence a firm's technology adoption. The technological dimension represents the properties of technological innovation (for example, industry 4.0 technology), whereas the organizational dimension represents the characteristics of a firm. The environmental aspect encompasses operational contexts such as government regulations and market competition [58]. This comprehension aids researchers and practitioners in comprehensively analyzing and elucidating this process. Industry 4.0 technologies, such as 3D printing, blockchain, and cloud computing, have significantly changed how supply chains are designed and managed [5]. Researchers who acknowledge the disruptive changes occurring in today's supply networks emphasize the need for scholars to proactively identify and explore pertinent problems in the supply chain business [65]. The disruptions have contributed to the heightened volatility observed in contemporary global supply chains and posed significant challenges.

The technology dimension of the TOE framework supports the sugar industries' production process, supply chain, and farming activity. IT/OT integration can support resource optimization and inventory control. The organizational dimension can support policy and strategic alignment, change management, and scalability. Moreover, SMEs are vital to this sector, so collaboration among the same industry, other sectors, and interdepartmental sectors will support long-term sustainability. The environmental dimension provides the ecosystem effect influencing technological adoption and transformation in the sugar sector.

Researchers and practitioners frequently employ the TOE framework to examine and comprehend the factors influencing the adoption of Industry 4.0, including the drivers and barriers. Still, it is probable that in several cases, the literature or organizations place a perceived—or actual—lack of emphasis or attention on these factors [60].

3 Research methodology

A meticulous process was followed to select papers for the review process. The review was conducted in two phases. In phase one, Industry 4.0 was focussed, and in the second phase, the papers related to the TOE framework were identified.

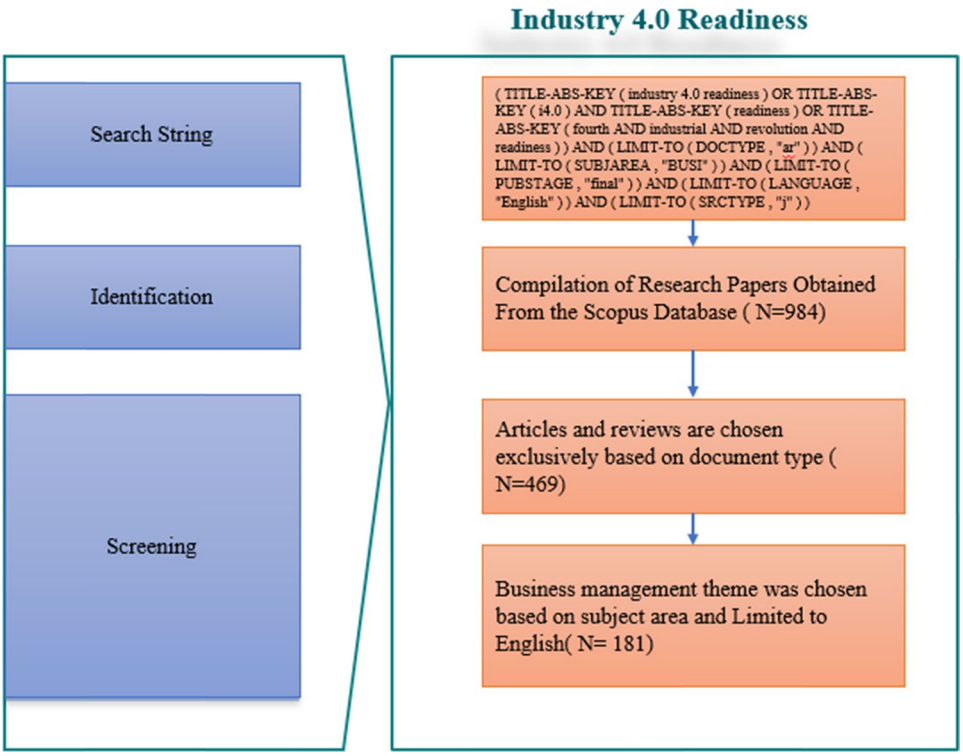

Fig. 1 The screening process of papers for the readiness of Industry 4.0

3.1 Screening process of I4.0 related papers

In Fig. 1, the selection procedure for I4.0-related papers is explained. A total of 984 documents were initially identified after applying search strings containing all pertinent information about Industry 4.0 preparedness. By narrowing the focus to management-related areas and exclusively English-language journal articles, the dataset was refined to 181 articles. This final collection of 181 articles was thoroughly evaluated to conduct the literature review.

3.2 The screening process of TOE framework-related papers

The process for choosing research that is relevant to TOE is shown in Fig. 2. After including all relevant details about the TOE framework in the search queries, 160 papers were found. Subsequently, options for corporate management and accounting were selected. Following this phase, 139 papers were obtained. After limiting the scope to management-oriented fields and solely English-language journal publications, finally 48 papers were assessed.

3.3 Data collection process

The mode of data collection was the interview method. The team established formal communication after selecting experts. The team finalized an interview slot after checking the expert's availability. In order to collect data for its advancement, a comprehensive questionnaire has been designed. The overview and objective of the study were shared. The details of the TOE framework were also included in the objective and overview document. The data based on feedback from each expert was captured. Some of the feedback was the following:

According to the management of one of the sugar industries, "Sugar Industries are seasonal and heavily depend on sugarcane crops and farmers, but farmers supplying sugarcane are reducing day by day because of low yield.". One of the other experts stated, "The government needs to focus on sugar for policy framework and sustainability. Developed countries are talking about it now. The government should also introduce some incentives to drive sustainability in this sector". The experts championed the establishment of a novel variable, which was ultimately designated as "process." In addition to offering comments and validating the framework, their efforts encompassed assisting in the validation process of the framework.

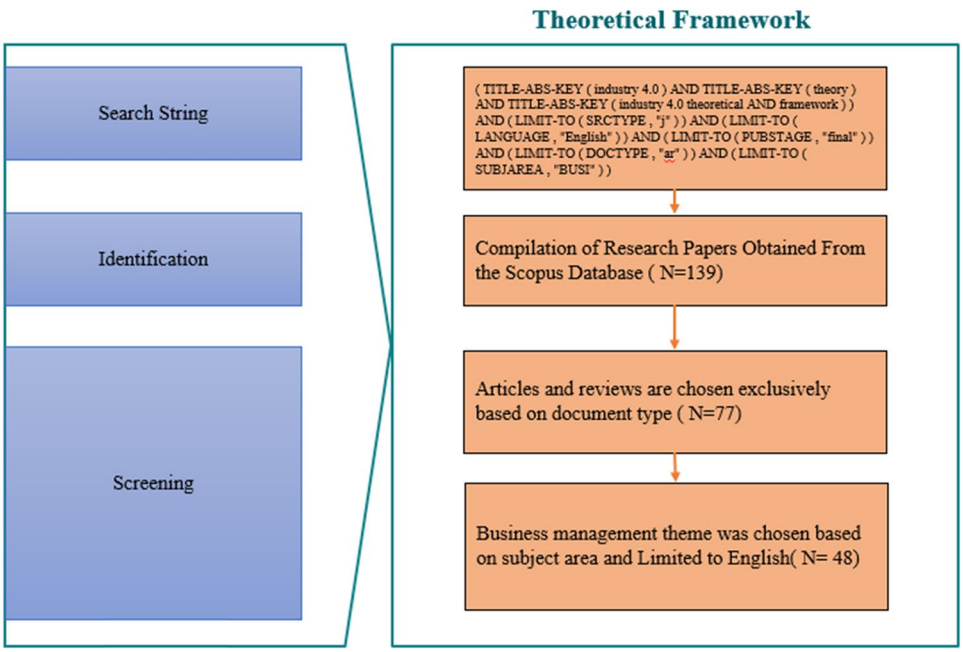

Fig. 2 The screening process of papers for the TOE framework

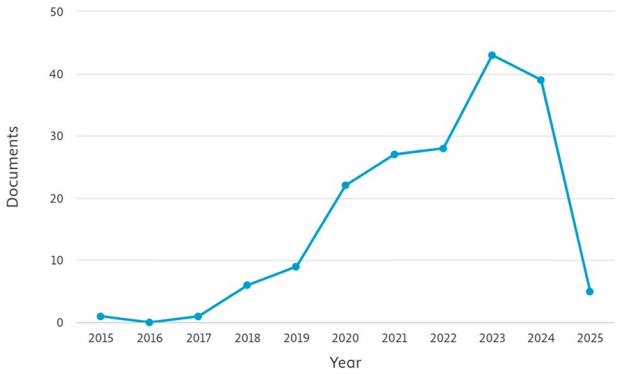

Fig. 3 Document published year on year. *Source:* Scopus

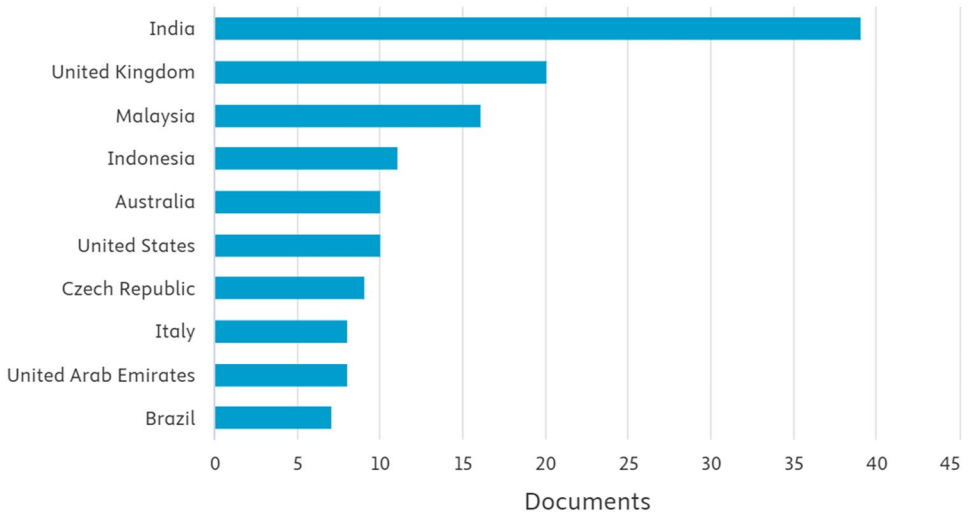

Fig. 4 Document published by various countries. *Source:* Scopus

3.4 Expert consultation process

Experts from the industry were consulted to determine the next course of action as soon as the readiness framework was prepared. Technology experts have chosen from sugar and other sectors based on their expertise in implementing I4.0 technologies like automation, IoT, Digital Twin (DT) co-generation, and renewable energy. In the second lot, consultants were selected based on their experience in supporting the installation of new sugar plants or the technological transformation of the sector. The third lot included top leaders, policymakers, financial institutions, and sustainability experts from various industries for interviews.

4 Analysis of results and key findings

The analysis of results and key findings are discussed as follows:

4.1 Descriptive analysis

The publication attained its Pinnacle in 2022 and 2023, meaning it peaked during those years. Figure 3 shows the rise in publishing popularity in 2017 and forward till 2024. Although there was a minor decline in publications in the first half of 2024, it will acquire momentum, given its growing popularity in the following years. The country-wise contribution of papers is presented in Fig. 4. It is abundantly evident in this text that the readiness of Industry 4.0 is well-known worldwide. There is a significant level of interest in the subject matter in developing economies, as Indian authors have

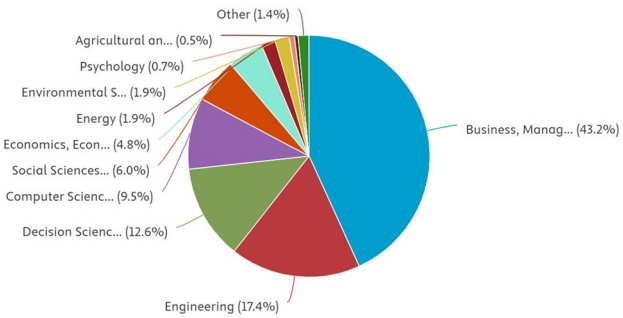

Fig. 5 Documents by subject area. *Source:* Scopus

authored a total of 39 papers on the subject. In addition, the United Kingdom has published twenty publications. As depicted in Fig. 4, the authors from Malaysia have shown a significant degree of interest, as it has generated 16 publications. In contrast, the authors from Australia and the United States have published only 10 papers. It shows that developing economies such as India are aggressively moving towards the adoption of I4.0 technologies.

Researchers in different management areas have taken an interest in and published papers across the field, as shown in Fig. 5. Business, Management and Accounting have topped the list by publishing 43.2% of the published article. Engineering takes the second position with 17.4% publications, followed by Decision science in the third position with 12.6% contribution. Overall, the topic is growing interest among the different fields of study.

4.2 I4.0 readiness framework: A TOE perspective

The term "readiness" for Industry 4.0 refers to the degree to which a sector or organization has assessed the concepts of the standard and taken steps to conform to them. Several factors contribute to this condition, including technological infrastructure, organizational adaptability, process optimization, product innovation, policy and law compliance, staff skill development, behavioural changes, strategic planning, and consideration of environmental and social impacts [26]. A recent study suggests that strategic leadership, market dynamics, governmental influence, and decision-making facilitation regarding technological innovations closely drive the integration of Industry 4.0 technology [3]. It is essential to have a comprehensive and proactive strategy for transformation, as each dimension is vital in making sure the business can reap the benefits of Industry 4.0.

Moreover, the sugar industries should make significant financial arrangements for the I4.0 transformation. This sector faces seasonal and supply chain challenges, so the sugar sector should also embark on the implementation phase. This initiative can be scalable for small and medium-sized enterprises (SMEs) in sugar industries and can become essential to sectoral transformation [35]. The article on I4.0 readiness is growing, however, some gaps remain in sector-specific

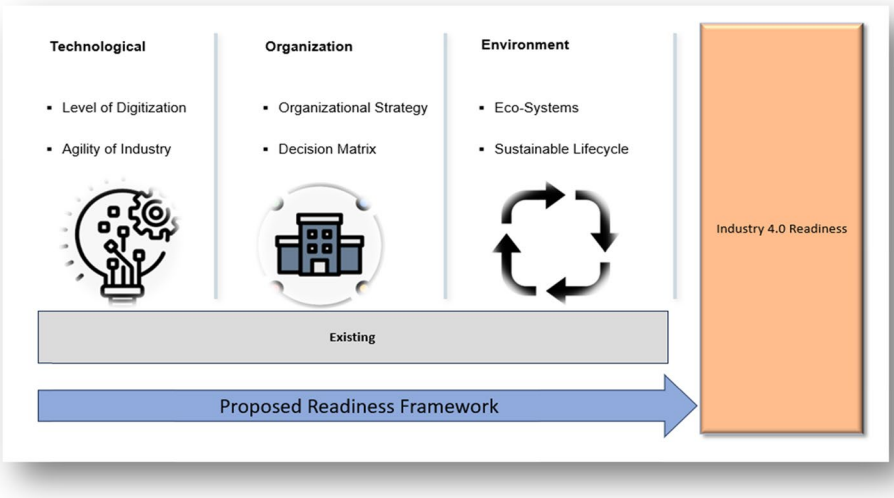

Fig. 6 Proposed readiness framework (author's own work)

focus studies, like the sugar industry and integration of (SMEs), because this sector plays a vital role in developing the economy [30].

However, to overcome the challenges of I4.0 adoption in the sugar sector, there is a strong need for a theoretical framework, and the Technology-Organization-Environment (TOE) framework is quite suitable for it. This framework (Fig. 6) provided a solid foundation for assessing their readiness and making well-informed decisions about adopting and implementing novel technologies [7]. Organizations can embark on a journey to create a theoretical framework for Industry 4.0 readiness, expanding upon the established TOE framework and incorporating components specifically designed to be ready for Industry 4.0. The proposed assessment methodology needed to be broad and encompassing, covering various dimensions of readiness. The aim is to enhance the sugar sector's technical competency, sustainability, and competitiveness.

4.3 Technology readiness

For the sugar sector, being "technologically ready" means assessing the existing plant capabilities, integration possibilities with new equipment, and the status of the ecosystem. Being tech-ready also includes coordinating new technology with the business's long-term objectives and day-to-day operations. The ability to learn and use new technologies, knowledge of handling data, measures to protect sensitive information online, and access to necessary programs and hardware are all crucial for sugar industries. I4.0 technologies such as the IoT, AI, and robotics sugar sectors can enhance their process, increase yield, and support supply chain development.

a. Level of Digitization of the OrganizationIt is essential to check the degree to which the sugar sector company's operations, processes, and supply chain can influenced by digital technologies [20, 26]. The sugar sector can align its strategy to boost productivity and create scalability.
b. Agility of Industry 4.0 InfrastructureThe agility of the Industry 4.0 infrastructure of the sugar sector refers to its management capability toward new technologies [16]. It covers several essential components like ease of use, scalability, connectivity, security, and adaptability.
c. Risks associated with cyber securityIf sugar industries are implementing the I4.0, cyber security risk is essential, and mitigation measures are imperative to reduce the impact of cyberattacks [4, 59]. Employee training and awareness across sectors are essential for risk assessment and mitigation plans for data protection and incident response.
d. Data generation capabilityCritical data related to sugar industries, such as the boiler's pressure and temperature, sugarcane juice's boiling parameters, and the chilling of crystals, should be gathered, aggregated, stored, and managed safely and securely [32]. Once the sector develops data analytics capabilities, such data can be used for more significant insights.

4.4 Organization readiness

The term "organizational readiness" in sectoral refers to the sugar industry or factory ready to implement and adapt the technologies associated with the new industrial age. Some of the significant variables are as follows:

a. Developing Organizational StrategyThe sugar sector's organizational strategy for readiness towards Industry 4.0 comprises various essential alignments of vision, mission, objective, strategy, and action plan. The action plan should be assigned to the leadership with a clear responsibility matrix. Sectorial benchmarking can be performed to determine the KPIs for regular monitoring purposes to ensure effective implementation [35].
b. Effective Decision MatrixDecision-making capability is an important aspect of change management in any organization. This capability is critical for the sugar sector as a seasonal business and depends more on the weather. So, effective controlling is essential and critical for Industry 4.0 implementation. Depending on the organization's size and business volume, a centralized or decentralized decision matrix can be decided and implemented accordingly.
c. Leadership EngagementLeadership is essential for any change and strategic implementation across the organization [24]. Considering its remote location and weak supply chain, it is a transformative and visionary topic for the sugar sector. So effective team management and clear communication will support the transformation of the sugar sector.
d. Organization StructureSince the visionary leadership team drives the industry 4.0, a practical implementation also requires the proper organizational structure. [19]. The structure of sugar industries is adopted based on business requirements. It can be of different types, such as projects for SMEs, matrices, or mixed structures for large sugar

organizations. However, the core team should be empowered and supported and report directly to the top management to ensure speed and effective change management implementation.

4.5 Environmental readiness

The environmental aspect is critical for the sugar sector of developing nations due to the measures of resize, business volume, and geographic location [56]. The team should perform an extensive exercise to consider the context of Industry 4.0 and prepare a detailed business plan for further implementation.

a. EcosystemsThe sugar sector should focus on changing people's mindsets to adapt to the ecosystem. Partner ecosystems (like farmers, technology providers, and other vendors) should be created and integrated into the value chain. A robust digital ecosystem always supports leveraging the capabilities of the latest technologies, enhancing productivity, and driving innovation, and it will support the sugar sector [33].
b. Sustainable LifecycleThe sugar sector is a high-power consumption and agri-dependable sector. Sugarcane requires higher irrigation water. With the help of I4.0, sensor-based irrigation mechanisms can reduce water consumption. Co-generation and using renewable power can reduce the carbon content in manufacturing. AI and data analytics can reduce power consumption. Overall, new technologies support integrating sustainability in the complete life cycle of industries [29].
c. Legal frameworkThe legal and compliance framework requires improvement in the sugar sector. Creating a legal framework for sectors and industries will safeguard the sector's long-term prospects. So, industry 4.0 implementation should meet all legal aspects, considering local and global requirements [30].
d. CollaborationThe sugar sector is highly dependent on stakeholders—farmers as raw material suppliers, skilled workforce for manufacturing, and regulators for controlling the price. Collaboration across the sector value chain is critical for transformation. I4.0 can provide a platform for all stakeholders to collaborate and progress towards digital transformation for growth and innovation.

4.6 Process readiness requirement

Process readiness in sugar industries means checking the existing process capability of the plants to adopt in4.0 technologies. For example, if the plant is not automated, the leadership team can take action accordingly. The sugar industry operates on agri-based raw materials, which farmers transport to the factories. So, there is no proper framework for supply chain integration. With the help of a process readiness framework, the sugar sector can optimize the process, enhance the supply chain capability, and integrate sustainability.

a. Technology enablementThere is a requirement in the global food sector regarding the traceability of food products. The sugar industry is also a significant supplier to the food and beverage industries. With the help of digital twins, the sugar industry can create a virtual replica of the complete process, which will help to enhance process capability and blockchain support in complete traceability. Developing nations' sugar industry can gain an edge and become a market leader [57].
b. Upgradation of the production systemIndian sugar industries and quit the old sector. This industry still operates on various outdated machines. Such machines break down during peak manufacturing season, creating financial losses for the industry. Implementing automation, sensor-based IoT, and big data analytics will enhance productivity and avoid breakdowns. I4.0 adoption will support the complete transformation of the sugar sector [27]

5 Validation of I4.0 readiness framework: an extended TOE-P perspective

5.1 Selection criteria

The sugar industry is vital to the developing economy as it is one of the largest agro-based industries supporting rural employment development. It is also helping millions of farmers who are cultivating sugarcane. However, there are several challenges in the sugar industry, such as raw materials, supply chains, and sustainability. To provide support in solving these challenges makes the sector an ideal sector for this study. In addition, the sugar sector is driving its

aligning industries, such as co-generation, production of ethanol, and renewable energy, to support economics and sustainability strategy. The outcome of this study will help other sectors like food, dairy, pharma, or other industries facing similar challenges.

The four companies have been selected based on annual turnover, industry leadership, customer feedback, operational model, number of skilled and unskilled employees, and geographical location.

5.2 Potential biases

While the study covers the broader perspective, industry-specific challenges might limit the wider applicability of the findings. Some of them are as follows:

I. Sugarcane crops are seasonal, which can influence business strategies and may not be suitable for year-round industries.
II. The sugar sector depends on sugarcane, which is agri-based. Some findings may not apply to industries that are diverse or mining based.
III. Sugarcane crops are highly dependent on rainfall, so findings related to weather challenges do not apply to industries that are not weather-dependent.
IV. Few developing countries' governments provide subsidies and control the industry's pricing. Related findings may not be unsuitable for those countries or sectors with no subsidy or pricing controls.

5.3 Case illustrations

Four case industries, with profiles below, have been chosen for the existing study.

5.3.1 Company 1

A1 Limited established its operations in 2012. It has an annual turnover of INR 20 million to 30 million. The company has a strength of over 200 skilled and unskilled employees. The company produces the best quality of sugar and ensures the crating of the solid brands into the international market. The company is also maintaining global standards, following substantial compliance with business ethics, and working towards empowering its employees. A1 Limited is located in the southern part of India. The company believes combining people and industry 4.0 technologies can create a state-of-the-art manufacturing setup to create a competitive advantage.

Challenges: Fluctuating sugarcane supply and farmers' pending dues due to negative cash flow. government policies.
Existing Process: Implemented the automation technology and IoT sensor.

5.3.2 Company 2

A2 Limited started in 1933 as a sugar mill in northern India in the most significant state of Uttar Pradesh. It has an annual turnover of INR 50 million to 60 million. The company has a strength of over 750 skilled and unskilled employees. This company is doing business in co-generation power and biofuel. The company has 50. The company is trying to create direct/indirect employment by taking sugarcane from neighbouring villages to ensure the growth of farmers and their families. The company wants to create an ecosystem of suppliers, customers, and employees using industry 4.0 technologies. A2 Limited's vision is to be a technology-driven company in the sugar industry that can make value for its shareholders and deliver the best quality products to its customers.

Challenges: Aging infrastructure, change of mindset of employees and farmers, lack of supply chain integration, location, lack of process integration, fluctuating supply of sugarcane, lack of government policies.
Existing Process: Implemented IoT sensors for the process and infrastructure.

5.3.3 Company 3

The A3 Limited is in Maharashtra, the western part of India. This company was founded in 1932. The majority of shareholders of this factory are farmers. The farmers sounded near the factory, growing sugarcane to supply the factory. This factory also has a co-generation facility, which is self-sustaining in power consumption. This company has a turnover of INR 40 to 50 million. The factory has 450 direct/indirect employees. The company is focusing on digital transformation to become a market leader. This company wants Industry 4.0 to support sustainability and productivity through an ecosystem. This company tried to drive technological advancement by supporting them in industrial water intake and safety measures for machines and employees, which can enhance their performance and create a competitive edge.

Challenges: Aging infrastructure, change of mindset of employees and farmers, lack of supply chain optimization, process integration issues, fluctuating supply of sugarcane, lack of government policies, Cyber issues.
Existing Process: Using Distributed Control Systems (DCS) and supervisory Control and Data Acquisition (SCADA), implemented sensor-based irrigation system, Digital twin for critical process, AI implementation under progress for a small section of plant.

5.3.4 Company 4

A4 Limited established its operation in 1989. The company is in the tribal and rural areas of Madhya Pradesh, which is a central part of India. Their annual turnover is INR 40 to 50 million. The factory has 600 direct and indirect employees. This company wants Industry 4.0 to drive the transformation of the business and support it in becoming a factory at global standards, which should make the factory self-sustainable and deliver values to society, customers, and shareholders. This company also wants technological advancement for the factories and the farmers, considering their essential stakeholders. The company believes it will help them safeguard their crop and enhance their yield.

Challenges: Frequent policy changes by the government for co-generation and renewable power, lack of Skilled workforce, slower technology adoption by employees and farmers, low sugar recovery from sugarcane compared to other geographic locations, lack of process integration capability, fluctuating supply of sugarcane, government policies.
Existing Process: Using IoT sensors, Distributed Control Systems (DCS), Supervisory Control and Data Acquisition (SCADA), implemented sensor-based irrigation system, Digital twin for critical processes.

6 Discussion

The survey on newly added process readiness, a dimension in Industry 4.0, highlights its significance in enhancing process effectiveness, supply chain, and sustainability in the sugar sector. Sugar factory machines can install IoT sensors for automation and data collection, BDA for predictive maintenance, and cybersecurity to avoid cyber-attacks. Integrating operations and machine readiness is crucial and requires connectivity, interoperability, and secure partner ecosystems for the sugar business. Process flexibility of existing processes is critical for adapting to new technologies, and change management supports mitigating risks for sugar manufacturing facilities. Finally, value chain integration readiness underlines the need for the sugar sector to effectively incorporate digital technologies from production to customer service, enhancing agility and supply chain resilience. These aspects collectively drive developing nation sugar organizations toward Industry 4.0 readiness, enabling them to remain competitive in a rapidly evolving global market.

As an output of expert interviews and analysis by addressing process readiness within the context of Industry 4.0, sugar factories can improve operational efficiency, supply chain resilience, and sustainability. It can ensure continuous operation of the sugar factory during the entire season. The newly added dimension, process readiness, is shown in Fig. 7. The study suggests that with the help of I4.0, industries can establish machine capabilities to enhance productivity. Machine data can be utilized for predictive maintenance. It can optimize existing sugar manufacturing operational processes to ensure continuous operation during the entire season. Process readiness plays a crucial role in enabling machines to

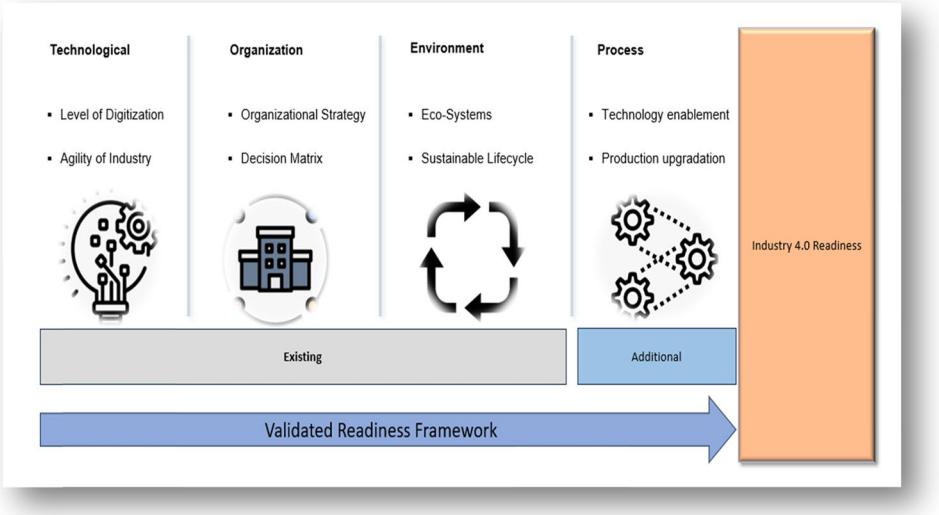

Fig. 7 Validated readiness framework (author's own work)

integrate with the latest technologies like the Internet of Things (IoT), sensors, Digital Twin (DT), and artificial intelligence (AI). Robust cybersecurity (CS) integration of machines in the sugar sector ensures safety and security from cyber-attacks.

Sugar plant operational systems and machines are essential to Industry 4.0, and successful integration is imperative to success. Due to limited funds and resource availability, the integration process can be performed in a phased manner. In the first phase, businesses can prioritize connectivity, compatibility, interoperability, partner ecosystems, and cybersecurity. In the second phase, the critical production process can be integrated. In the rest phase, a business can complete the rest of the transformation of the plant. Process flexibility of sugar plants is essential for their survival. Before implementing I4.0, industries must conduct a detailed analysis based on the return on investment. The implementation process should be phased to ensure smooth adaptability and faster returns. Process capability analysis plays a vital role in finding a risk and mitigation plan to reduce the adverse effects of process modifications of sugar plants. Developing modular concepts and scaling them from one plant to another is better.

The sugar sector value chain is very complex. So, integration of I4.0 with its value can be a tedious task. The implementation phase must be defined based on the availability of budget and the readiness of technology, organization, and environment. It will take a longer time to integrate I4.0 into the complete value chain. So, businesses must be patient.

After the detailed study, it is worth highlighting the various dimensions of Industry 4.0: Technological, Organizational, and Environmental. So, all dimensions can support the organization. Technological dimensions can provide critical aspects like the level of Digitization of the Organization, Agility of Industry 4.0 Infrastructure, Risk associated with cyber security, and Data Structure Capability, which ensure the technological elements are mature enough to take the journey to the next level. Organizational readiness provides the complete view of developing organizational strategy, which can support an effective decision matrix, ensure the full engagement of organizational leadership, and support the creation of an effective structure to drive the transformation process. Environmental readiness provides the complete understating of Digital Ecosystems, which can help the product life cycle and put all legal frames in place to drive collaboration with all stakeholders and customers. The last added dimension, process readiness, provides information regarding the capability of machines for the integration of new processes and the preparedness of processes with machines and provides the detail of process flexibility, which supports the integration of the organization's value chain with the industry value chain. This study focused on Indian sugar industries and found that the challenges related to their digital transformation and the lack of information and readiness checks can create problems and unnecessary investments. Therefore, the theoretical framework was provided for Industry 4.0 readiness and integrated all dimensions accordingly. Considering this, the TOE framework was the most suitable, evaluating its suitability and closeness in supporting the adaptability of new technologies. After integrating the TOE framework with related dimensions of Industry 4.0, complete dimensions were discussed with industry experts. A common understanding came during a detailed interview that the process plays a vital role in any implementation in sugar industries, considering its nature and essential dimension of the manufacturing sector. So, the process dimension added to overall readiness for Industry 4.0. The TOE framework also expanded to integrate this dimension, and a new framework became TOE-P. The expanded and improved Technology-Organisation-Environment (TOE) framework marks a significant advancement in an organization's ability to predict the impact of

various aspects on the readiness of various dimensions and the overall readiness of the organization. This paper allows us to assess the impact of new technology and concepts on many aspects of readiness and, as a result, the overall state of readiness. The study covers the readiness of I4.0 for the sugar industry with socio-economic and addresses the policy challenges. These dimensions play a vital role in supporting I4.0 adoption.

6.1 Socio-economic factor

Socio-economic challenges of sugar are crucial, and study supports to address it as follows:

- Farmers take loans to cultivate the sugarcane and supply it to sugar factories. It is crucial for their survival. Lower yields of sugarcane crops are a huge challenge and create a problem in farmers' return on investment. Some farmers are committing suicide due to their loan burden and inability to repay. Agri-based NGOs, academia, and sugar industry experts educate farmers and provide I4.0 technologies for the field and other required support to solve such problems.
- The location of the sugar industries creates significant challenges for this sector. Industries need continuous power and high-speed internet to adopt the I4.0. Co-generation, renewable power, and rural data connectivity will help to solve these problems.

6.2 Policy factor

- There is a lacuna of clear policies and governance for sugar industries. SMEs in this sector need funds to support transformation. However, a lack of firm policy and governance creates low credibility in the sugar sector and does not allow financial institutions to support them. Strong policy governance can provide confidence to financial institutions and enable the complete I4.0 transformation.
- The sugar sector in India lacks a firm policy of sustainability-driven incentive schemes. Introducing new incentive schemes on sustainability will drive the adoption of Industry 4.0 and support the sector's complete transformation.

7 Theoretical and practical implications

The theoretical and practical implications are discussed as follows:

7.1 Theoretical implications

Introducing TOE concepts at every level of readiness positively impacts changes in other pertinent concepts, readiness dimensions, and overall readiness when incorporating new variables. Our research objective is to integrate Industry 4.0 readiness in the context of digital transformation and organization capability and adaptability, which can yield long-term results and support the transformation process. TOE framework is an integrated technological, organizational, and environmental approach. However, only these three aspects may not meet some readiness requirements, so one additional aspect was added. Adding additional aspects to the existing framework will support the readiness and implementation of Industry 4.0, which is one of the essential objectives of the research. So, the new TOE-P (Technological, Organizational, environmental, process) framework can be widely used across the organization and industry verticals for readiness checks prior to proceeding with the implementation process, which saves time and resources and can play a pivotal role in the fourth industrial revolution.

7.2 Practical implications

The TOE-P Framework is a conceptual framework to support readiness and support in technological transformation. Its impact lies in its ability to address various challenges during technological transformation and provide a roadmap. Also, this framework will support various industrial settings, including manufacturing, healthcare, retail, logistics, and service sectors. So, management can leverage the study as follows:

- **Technological aspect:** Conduct a thorough technology readiness assessment, develop the use cases, work on scalability across the industry vertical and across the enterprises, align the technological deployment, and ensure a stringent review mechanism
- **Organizational aspect:** Conduct through skill gap analysis, design robust training and development program, manage the change management, ensure transparent communication with sharing the clear vision and mission statement of the company
- **Environmental Aspect:** Stakeholders can develop the industry's strategic framework and business ecosystem. Engage with experts from industries and academia to understand the technological trends. Select the suitable technology with an expert and use ecosystem support to create the use cases. Scale the adoption across industries by leveraging the ecosystem.
- **Process Aspect:** Leaders can perform detailed process capability analysis. Based on gap analysis, the team can generate the requirements management plan. Define clear scope, time, and cost management metrics to drive the implementation. Top management can form 'SteerCo reviews' for smooth implementation and ensure all the support in the implementation lifecycle.
- **Policy Recommendations:** The Government of India's SAMARTH Udyog Bharat 4.0 initiative supports Industry 4.0 adoption through technical and financial assistance. The auto sector has leveraged this policy to boost car exports. Similarly, the sugar sector can benefit from Industry 4.0 adoption, aligning with the Ethanol Blended Petrol (EBP) policy, which targets a 20% ethanol blend. This transformation will enhance productivity and product focus in the sugar industry.

Small and medium enterprises (SMEs) face challenges like working capital, skilled labor, and access to Industry 4.0 technologies. The TOE-P framework is comprehensive and supports sugar SMEs. All four dimensions of this framework intersect and complement each other. The "process" dimension boosts technological scalability and supports adaptability. The intersection of these four dimensions helps to develop a new ecosystem that supports environmental aspects. This ecosystem helps SMEs in the sugar sector to benefit from various government policies, such as the SAMARTH Udyog Bharat 4.0 initiative. It also enables resource management strategies, shared services, and new I4.0 models like Software as a Service, which can ease operations and reduce immediate capital investment.

Various policy initiatives like SAMARTH Udyog Bharat 4.0, Make in India 2.0, production-linked incentive (PLI) scheme and Digital India are pivotal in driving I4.0 in the Indian manufacturing sector. Furthermore, these programs promote I4.0 in manufacturing and provide financial incentives. The SAMARTH Udyog Bharat 4.0 is essential in modernizing the Indian manufacturing sectors. By supporting the adoption of I4.0 technologies, the policy aims to improve productivity, quality, competitiveness, and efficiency. However, the initiative also supports the development of eco-systems like manufacturers, vendors, and customers. It provides training, awareness, and consulting services to manufacturing sectors to adopt I4.0.

Furthermore, this production-linked incentive (PLI) scheme offers financial incentives to companies to boost local manufacturing and reduce the country's import dependency. TOE-P framework supports the I4.0 adoption in the sugar sector. However, after successful adoption, the same concept is scalable in various other industries like electronics, Solar PV modules, pharmaceuticals, specialty steel, telecom & networking products, food products, textile products, and advanced chemistry cell (ACC) batteries. Furthermore, the government acknowledges the transformative opportunity I4.0 can present for the country to boost its global manufacturing competitiveness, create high-value employment, and enhance economic integration with international supply chains.

8 Conclusion and scope for future research

There is a requirement for a strategic framework for implementing I4.0 in sugar industries. This research provides a comprehensive framework for the I4.0 implementation and readiness for the Indian sugar industries. Integration of operations and information technology supports process flexibility and cyber security. The raw materials come from farmers, and industries face challenges like lower crop yields, loan burdens, and the risk of insolvency, necessitating support from NGOs, academia, and industries. The rural location of sugar industries has barriers like lack of power and connectivity, co-cogeneration, renewable energy, and lack of rural infrastructure. Studies suggest that process readiness is a critical dimension of I4.0 readiness. It also provides information on how process and production capability can play a vital role in the ecosystem and support sustainability, supply, and economic benefits to the sugar sector. The absence of a firm policy and governance framework does not provide enough confidence to banks and financial institutions

to provide funds to support the transformation. Well-drafted sustainability-driven incentive schemes and governance frameworks can drive the adoption of Industry 4.0 and sustainability. Addressing socio-economic and policy challenges can support the sugar sector for sustainable growth.

The suggested evaluation approach seeks to improve readiness assessments' breadth, depth, and efficacy for companies and sectors embracing I4.0. Organizations may more accurately evaluate their readiness and successfully negotiate the challenges of this revolutionary transition by considering the intricate interactions between the many factors involved in implementing Industry 4.0. This research highlights key gaps in the Indian sugar sector to address challenges before Industry 4.0 implementation, guiding developing nations in adopting suitable technological frameworks. The research enhances the readiness assessments for the sugar sector for I4.0. By considering the intricate interrelations among factors impacting the sugar Industry, the proposed approach also offers a more reliable and actionable readiness evaluation for other sectors. It also provides the process readiness framework, which is critical for sugar industries. This framework also supports the technologically advanced framework for sugarcane cultivation. The research developed a theoretical framework to evaluate Industry 4.0 readiness in the sugar sector. It enhances the technology-organization-environment (TOE) paradigm by adding a "process" dimension for a more comprehensive assessment.

8.1 Future research directions

The study focused on developing the sugar sector's economy. Future research can drive the same study for infrastructure, oil, and gas sectors. India is a part of the existing studies, but geographical expansion is possible in other countries like Bangladesh, Sri Lanka, and Tanzania. There is another possibility of future research on testing of TOE-P model. The empirical study in other sectors and across geographical locations can also be another future research areas. Based on the study, the following are the future research questions:

I. How can the sugar sector's investment be further developed using the TOE-P model?
II. What are the opportunities and challenges for applying the TOE-P model in other sectors, such as infrastructure, oil, and gas?
III. How does the application of the TOE-P model vary across different geographical regions, such as Bangladesh, Sri Lanka, and Tanzania, compared to India?
IV. What specific technological advancements can drive economic growth in the sugar sector?
V. How can organizational readiness and capabilities in the sugar sector contribute to its economic development?
VI. What environmental factors most significantly influence the economic performance of the sugar industry
VII. What modifications are needed in the TOE-P model to adapt it for use in different industries and regions?
VIII. How does the TOE-P model's empirical application differ between emerging and developed economies?

8.2 Opportunities for interdisciplinary research

This study also provides opportunities for interdisciplinary research in areas like agriculture and technology, economics and sustainability, business and sociology, geography and policy, global trade and policy, and supply chain and technology. Some of the research questions are as follows:

I. How can IoT, digital twin, and AI technologies optimize sugarcane farming practices to improve yield and reduce resource wastage?
II. What is the economic impact of transitioning sugar mills to green energy solutions like biofuels and solar power?
III. How does sustainability affect the competitiveness of the sugar industry in global markets?
IV. How do labor practices and working conditions in the Indian sugar industry affect productivity and long-term workforce sustainability?
V. What role do gender dynamics play in labor allocation and decision-making in sugarcane farming households?
VI. Which geographical regions in emerging economies best suit sugarcane cultivation based on climatic, soil, and water resource factors?
VII. How can policy frameworks support sustainable sugarcane farming in regions facing water scarcity or climate change impacts?

VIII. How can digital twin & blockchain technology enhance transparency, traceability, and trust in the sugar industry's supply chain?
IX. What are the economic and ethical implications of implementing blockchain in the sugar supply chain?
X. What factors influence sugar trade flows between India and African countries like Tanzania and Ethiopia?
XI. How do trade policies and tariffs affect the competitiveness of Indian sugar exports in global markets?
XII. What innovative technologies can help to convert sugar industry waste into high-value by-products?
XIII. What are the economic implications of climate change on sugarcane yield and production costs in India?
XIV. What adaptive strategies can sugarcane farmers implement to mitigate the impact of water scarcity and erratic rainfall patterns?

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Data availability The datasets generated and/or analysed during the current study are available from the authors on reasonable request.

Declarations

Ethics approval and consent to participate This study was approved by the Ethics Committee of the Indian Institute of Management -Sambalpur, India. The research was conducted in accordance with the institution's ethical guidelines.

Consent for publication Not applicable.

Informed consent Informed consent was obtained from all participants involved in the study. No participants were below the age of 18 years. Consent to participate and to publish was documented for each participant.

Clinical trial number Not applicable.

Competing interests The authors declare no competing interests.

Appendix 1

The following questions were asked, which are as follows:

1. How well-versed is your company in the principles of the fourth industrial revolution?
2. Has your company taken any steps toward implementing the Industry 4.0 standard?
3. Does your company have a well-defined strategy and vision for the Industry 4.0 revolution?
4. Is there active participation from senior-level executives and leadership in the activities that drive Industry 4.0?
5. How would you describe the current state of the digital infrastructure at your organization, and what are the criteria?
6. Have you made any investments in the technologies of Industry 4.0?
7. How will you train your workers for Industry 4.0's new working conditions?
8. How are you measuring the success of your Industry 4.0 projects using KPIs?
9. Are there any noteworthy advancements or accomplishments that you can discuss?
10. What are your long-term goals for implementing and developing Industry 4.0?

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