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Mapping the Industry 5.0-Oriented Enablers for Driving Organisational Operational Performance Excellence

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Abstract: Although Industry 4.0 promotes organisational efficiency, it has ignored or misunderstood many prevailing concerns to drive operational performance in industrial operations. While the desired operational performance value of Industry 5.0 (I5.0) is well recognised, how the same can be delivered through the lens of its enablers has not been explored. The present study fills this knowledge gap by first identifying I5.0-oriented enablers that drive operational performance, then grouping them into legitimate categories, and then prioritising them, so organisations can focus on the critical enablers for operational performance. The enablers were first identified from the literature and then grouped into legitimate categories using content analysis of the literature. The enablers were then prioritised using grey relational analysis (GRA) and further validated using the best-worst method (BWM). The study also provides the technological, organisational, and environmental (TOE) framework of the identified enablers that facilitate the path to drive organisational sustainability. The study finds that management-related (MR) and finance and knowledge-related (FKR) barriers are key enablers that must be prioritised to realise operational excellence from the perspective of I5.0. The findings of the present study drive implications for practitioners by fostering a deeper understanding of enablers for driving operational performance in routine tasks. Furthermore, the TOE framework facilitates decision-makers by enhancing workforce readiness and fostering stakeholders' collaboration for achieving sustainable resilience and human-centric operations.

Keywords: Industry 5.0, Enablers, Operational Performance, Grey Relational Analysis, Best-Worst Method, Human-Centric System.

1. Introduction

The increased global competition has forced industrial organisations to adopt advanced digital technologies (Industry 4.0) to remain flag-bearers in the competitive world (Ali & Johl, 2024). But these changes are not confined to organisations but also affect the environment and society. Although Industry 4.0 (I4.0) inadvertently reduces some micro-environmental sustainability metrics, such as production efficiency and carbon credits, it cannot move past the profit-centric mechanism (Ghobakhloo *et al.,* 2022). Critiques of I4.0 advocate that it is focused on a capitalist economic model that further leads to strengthening socio-environmental concerns related to environmental and regional aspects (Kaswan *et al.,* 2025). Furthermore, the recent crisis related to the socio-environment and economy, like regional inequality and environmental degradation, was exacerbated by unrest caused by the USA-Iran and Ukraine-Russia war, which required a deep transformation that allows human beings to live in peace and prosperity on Mother Earth. Further, in a recent briefing of the European Commission, it has been stated that I4.0 cannot be considered as a single solution to make the sustainable industrial transformation that also alleviates the socio-economic challenges (Kaswan *et al.,* 2026). It is also argued that I4.0 lacks the circularity model that creates value within the supply chain (SC), which promotes social harmony and protects Mother Earth from environmental footprints (Kumar *et al.,* 2024). I4.0 is only a decade old, and the hasty introduction of I5.0 leads to different controversies. As I4.0 is technology-oriented, I5.0 is also technology-oriented and supports social initiatives driven by government and social groups to drive industrial transformation toward human and environmental values

(Ghobakhloo *et al.,* 2023). Further, I4.0 is still unfolding and must drive full-throttle potential. I4.0 is primarily for industrial pioneers and small businesses, and classic SC are still struggling to achieve the desired level of implementation (Singh *et al.,* 2026). So, the current understanding of large-scale execution of I4.0 is still in its infancy. These circumstances worsen when explaining how the novel phenomenon of I5.0 can transform social, environmental and economic values within the SC. In other words, it is obvious that I5.0 transforms the sustainability values in organisations, but the current understanding of how this can be done under I5.0 is still lagging in the academic literature.

I5.0 is a new industrial model that connects digital technologies with humans at the centre, focusing on making the industry more resilient and vibrant (Maddikunta *et al.,* 2022). It is a new industrial paradigm that leads to improvement in all aspects of sustainability through an interconnected system of digital technologies coupled with human intelligence (Sharma *et al.,* 2025). Being a new industrial revolution, it is imperative to understand the key features that facilitate the easy execution of this sustainable technological model (Mohan et al., 2025). These key features that make an organisation ready to adopt a new approach are called enablers. There are studies in the literature that deal with barriers to I5.0 for improved organisational efficacy, but there are limited studies that provide a comprehensive mapping of enabling features related to I5.0 execution (Sharma *et al.,* 2022; Mukherjee *et al.,* 2023; Rajesh, 2023). Furthermore, as I5.0 is a new industrial paradigm, successful execution of the same demands prioritising the key enablers that must be focused on with utmost priority (Figure 1).

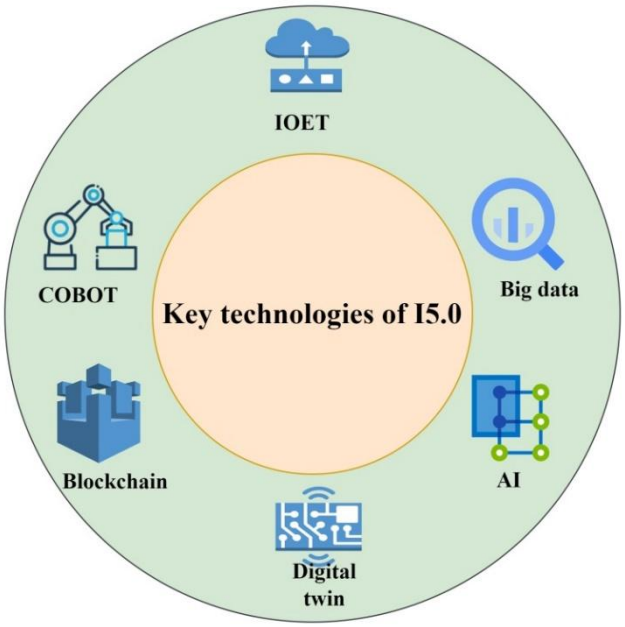


Figure 1. Industry 5.0 key technologies.

This also demands prioritising the enablers of I5.0 using decision-making approaches. For these gaps in the academic literature, the present study tends to answer the following questions:

RQ1: What are the I5.0-oriented enablers that ensure the successful execution of I5.0 within the industry?

RQ2: What are the key enablers that the organisation must focus on at the initial stage of the execution of I5.0?

To answer the stated research questions, the study first identifies the enablers from the literature and then group the same into logical groups and then priorize the same using grey relational analysis (GRA). GRA can handle datasets with numerous variables and assess their interdependencies (Rathi *et al.,* 2021). It provides decision support by highlighting the factors that have a significant influence on outcomes (Yadav *et al.,* 2024). It helps decision makers to identify critical factors that contribute most to the desired outcomes or performance. Further, the study also validates the results of the study using the best-worst method (BWM). To make the findings more comprehensive and relevant to the policy makers and practitioners, the study also provides the technological, organisational, and environmental (TOE) framework of the identified enablers that facilitate the path to drive organisational sustainability.

The present manuscript has been divided into five sections. The first section illustrates the introduction of the article, coupled with the stated research questions. The second section examines the literature and background of the study. The third section presents the methodology adopted in the study. The fourth section depicts the results, discussion, and implications derived from the study. The final section of the article presents conclusions, limitations, and future aspects of the study.

2. Literature Review

I5.0 is the advancement of I4.0 that has been designed to use human creativity, coupled with intelligent and smart machines (Longo *et al.,* 2026). It leads to improved organisational performance by integrating diverse digital technologies (Huang *et al.,* 2022). It also makes the system more productive and engaging by assigning repetitive tasks to robots and tasks that require intelligence to the human workforce, thus working in a blended manner that leads to a comprehensive industry ecosystem (Tallat *et al.,* 2023). Table 1 depicts the key differences between I4.0 and I5.0.

Table 1. Distinction between I4.0 and Industry 5.0 (I5.0)

Parameters	I4.0	I5.0
Prime focus	Smart factories and transformation through digital set of technologies	Human integration into digital technologies to make the business function more sustainable and resilient
Production approach	Continuous mass production coupled with little focus on customisation	Personalised mass production with a customer-driven approach
Sustainability	Secondary function as productivity is run by a profit-driven mechanism	Sustainability is the primary function with a major focus on social and environmental aspects
Decision mode	Data and machine learning based	Decisions are made in collaboration between humans and AI
Key performance metrics	Productivity and profitability	Innovation and human well-being in terms of social sustainability
Level of automation	Highly automated systems	Intelligent automation with human intelligence for timely and crucial decisions

The literature has studies related to the investigation of different barriers and key features of digital technologies and I4.0; there are studies related to the development of different theoretical models of I5.0. But the literature has very limited studies on I5.0; further, there is also a lack of theoretical foundation for different aspects of I5.0. To date, no study has explored aspects of key enablers of I5.0. The identified gaps in the study and the proclivity to make organisations more socially and environmentally sustainability provides the impetus and direction for this research. Figure 2 depicts the evolution time frame of the different industrial revolutions. Table 2 depicts I5.0-oriented enablers behind the execution of I5.0.

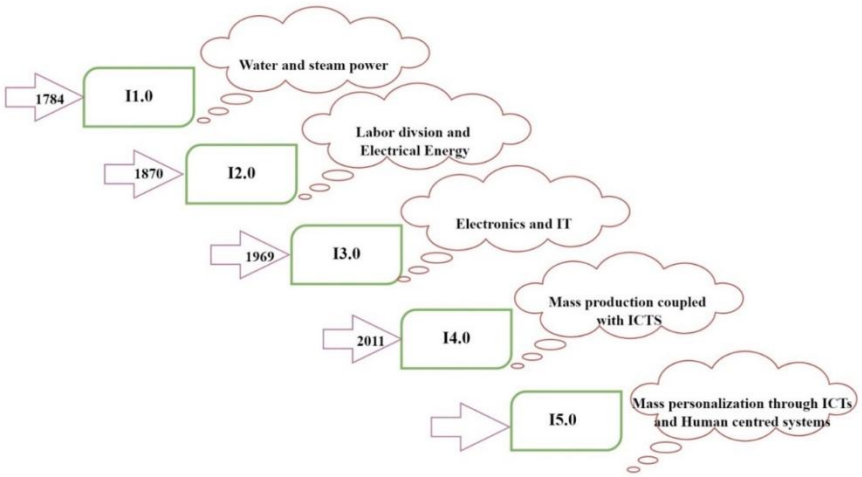


Figure 2. Different industrial revolutions.

Table 2. I5.0-oriented enablers

Enablers	Technology/ Conceptual Origin	I5.0 Status	Role and relevance in I5.0	Categories	Description	References
Eco-innovation	I5.0	Directly I5.0-oriented	Facilitates the shift toward sustainable production through the development of ecologically responsible products, processes and technologies integrating economic, environmental and social objectives.	GFC	Eco-innovation under the I5.0 paradigm refers to approaches that drive environmental and social innovation and advance sustainable development goals. Environmental innovation means implementing new solutions that make the business, process, or product more environmentally friendly. Social innovation means improving society's well-being by introducing novel social solutions.	(Ghobakhloo *et al.*, 2022; Aslam *et al.*, 2020)
Competency toward digital transformation	I4.0	I4.0-origin; enhanced in I5.0	Digital competences are vital in I4.0. I5.0 extends them in terms of ongoing reskilling, human empowerment and effective collaboration between employees and modern digital technology.	FKR	I5.0 is also a technological phenomenon that requires technological innovation to be an integral part of the hyper-connected value network. Thus, organisations must have enough competencies to execute and integrate technological constituents of I5.0.	(Ribeiro *et al.*, 2025)
Adaptation of Exoskeleton and Ergonomics in Systems	I5.0	Directly I5.0-oriented	Strongly demonstrates the human-centric philosophy using assistive technologies and ergonomic system design to enhance worker wellbeing, physical capabilities, safety and human–technology interaction.	TE	Ergonomics is a combined study of engineering and human-robot-environment systems and aims to enhance productivity and reduce the discomfort of workers and operators. The major role of Ergonomics in I5.0 will be to analyse, understand and design human work. In exoskeletons, there is a detailed study of equipment and devices wearable for humans and operated by actuators and motors to reduce fatigue and maximise the efficiency of humans while working in Industries.	(Dal Prete *et al.*, 2025)
Proper utilisation of Blockchain computing	I4.0	I4.0-origin; enhanced in I5.0	Blockchain is established in I 4.0. Its I5.0 role is related to trusted, transparent and secure information sharing,	TE	Blockchain is a superior database management technology that supports information sharing transparently, where the data is stored in blocks and is linked	(Fraga-Lamas *et al.*, 2024)

			accountable data management and resilient inter-organisational ecosystems		together in a chain. When supported by decentralised computing, it enhances the security of the data and reduces the monitoring cost of I5.0.	
Adaptation of Human-Robot collaborative technologies and higher levels of automation	I4.0/ emerging I5.0	Enhanced I5.0 role	Collaborative robots and automation are not new; they existed before I5.0. However, the focus of automation is shifting from productivity-driven automation to human-machine complementarity, augmentation of human capabilities, flexibility, and worker well-being.	TE	Human-Robot collaboration (HRC) is the most advanced version of Human-Robot Interaction (HRI). Collaborative robots (Cobots) and related technologies are recent advancements in this field where the robots work in collaboration with humans to achieve a higher degree of automation, efficiency and productivity.	(Islam *et al.*, 2025; Lima *et al.*, 2025)
Zero defect Manufacturing through traceability and product quality management	I4.0	Enhanced I5.0 role	Digital traceability and zero-defect techniques are already well-established practices; under I5.0 they may support robust, sustainable and human-informed quality management while lowering defects, waste and resource consumption.	TE	The concept of zero-defect manufacturing involves the strict implementation of 4 strategies: detection, repair, prediction and prevention. If both product- and process-based ZDM are successfully implemented, it may lead to real-time detection and prediction of defects and will lead to zero defects in manufacturing.	(Rahardjo *et al.*, 2024; Psarommatis *et al.*, 2024)
Adaptation of Uniform standards throughout and use of Innovative technologies in products and processes	I5.0	Enhanced under I5.0	Standards and interoperability underpin technological integration and, in I5.0, also assist the safe, responsible, sustainable and human-centric deployment of emerging technologies across goods and processes.	TE	Adapting the universally acceptable standards is necessary for the successful implementation of I5.0. Guidelines and standards given by the International Society of Automation (ISA) are essential to achieve excellence in automation and production. Using Innovative approaches such as Green Lean Six Sigma will lead to the optimum utilisation of all available infrastructure.	(Sheikh *et al.*, 2025; Ghobakhloo *et al.*, 2026)
Commitment of management	Management / organisational	I5.0-oriented	Management commitment acts as a facilitating factor for organisational change across hierarchical levels and	MR	Commitment at the managerial level is very important for the proper implementation of enabling technologies. Managers need to investigate various factors such as the	(Cillo *et al.*, 2022;Olsson *et al.*, 2025)

personnel at all levels		organisational enabler	enables businesses to integrate technology transformation with human-centricity, sustainability and resilience.		required competencies of the workforce, the level of training required, as all these factors have significance in the successful adoption of this new paradigm.	
Clear vision in terms of organisational objectives and pathways to achieve them	Organisational strategy	I5.0 strategic enabler	Strategic vision is not exclusive to I5.0, but it is vital for integrating human-centric, sustainable and resilient objectives in technology adoption and organisational transformation.	MR	The pathway for successful implementation must be crystal clear, whether in terms of infrastructure, advanced training or enabling technologies. Success during implementation largely depends on the planning stage, and therefore every minute detail must be analysed multiple times.	(Pan *et al.*, 2026)
Proactive government support	Institutional / policy	I5.0 ecosystem enabler	Government policies, incentives, laws and institutional support can help promote responsible I5.0 adoption, especially on sustainability, workforce transformation, innovation and resilience.	MR	I4.0 has been criticised due to the unregulated pace and direction of I4.0 in various industries or regions of the world. This leads to unbalanced regional development and an inequitable pace of digitisation in different parts of the world. I5.0 demands a new form of proactive government support that promotes research and development, industrial ecosystem or market dynamics that support the core values of I5.0, like open innovation, low carbon credit, and inclusive value chain.	(Ghobakhloo *et al.*, 2022)
Availability of resources and capabilities	I4.0/Organisational	Cross-paradigm enabler with I5.0 relevance	Transformation needs financial, technological, human and organisational resources; in I5.0, they need to be used for digitisation, human development, sustainability and resilience.	FKR	I5.0 demands continuous innovation, and it has long payback periods. So, it demands continuous investment in terms of finance and the associated resources, so organisations must have enough resources and the capabilities to nurture the associated benefit of the I5.0.	(Ghobakhloo *et al.*, 2022)
Integration of digital technologies	I5.0	Directly I5.0 oriented	One of the key conceptual transitions to human–technology symbiosis, where modern technologies assist,	TE	Proper utilisation of Collaborative robots is inevitable, and integration of human capabilities with digital technologies can enhance the success rate of I5.0	(Horvat *et al.*, 2025)

with human capabilities			not just replace, human talents and decision-making.			
Collaboration among shareholders	I4.0/ I5.0	I5.0 - oriented	I5.0 envisions a more extensive engagement of employees, management, technology vendors, supply chain partners and other stakeholders to accomplish resilient, sustainable and human-centric transformation.	MR	I5.0 under the stakeholders' collaboration entails the process that allows corporations, communities, and labour unions to transparently communicate their needs, expectations, and conflicts of interest for colobratley shape the core theme of sustainable development under the I5.0 paradigm	(Ghobakhloo *et al.*, 2022)
Sustainability performance measurement metrics	Sustainability / I5.0	Directly I5.0-oriented	It helps businesses assess the environmental, social and operational impacts of change and ensure technology adoption delivers measurable sustainability objectives.	GFC	I5.0 has a wide variety of micro and macro sustainability objectives, which force new sustainability performance measurement metrics to evolve in response to the traditional financial metrics.	(Ghobakhloo *et al.*, 2022)
Know-how and training aspects	I4.0/ I5.0	I4.0-origin, enhanced under I5.0	Training has always been a key component of technology adoption, but I5.0 places more emphasis on continual learning, reskilling and upskilling so people can operate effectively with intelligent technologies.	FKR	Regular, continuous, and advanced training among the workforce is inevitable, as most of the experienced workers are unaware of the latest enabling technologies and processes. Imparting the required skill set is an important aspect during the adaptation of I5.0. Virtual and Augmented reality techniques should be used to impart the skills required in workers.	(Kumar *et al.*, 2024)
Organisation's readiness to adopt new technologies	I4.0/ organisational readiness	Cross-paradigm / enhanced under I5.0	Organisational readiness is a well-established concept in the study of technology adoption. Under I5.0, it refers to the technological, human, organisational and cultural preparedness for human-centric, sustainable and resilient transformation.	GFC	Every organisation has a different culture, and the organisation's readiness to adopt new technologies will play a crucial role in the successful implementation of I5.0.	(Tallat *et al.*, 2023)

To clarify the conceptual positioning and novelty of the selected enablers, six dimensions have been included in Table 2: enablers, technology/conceptual origin, I5.0 status, role and relevance in I5.0, categories, and description. The proposed classification aims to differentiate between enablers that are directly connected to the paradigm of I5.0 and existing I4.0 technologies or practices that assume a more extended or transformed function within I5.0. The classification therefore does not consider all the enablers that have been recognised as technologically specific to I5.0. The "Technology/Conceptual Origin" column indicates the origin of an enabler in I4.0, I5.0, sustainability, organisational theory, or any other existing management and technology areas. The "I5.0 status" column then explains whether the enabler is directly I5.0-oriented or whether it is an established I4.0 enabler that is reinforced under the I5.0 paradigm. "Role and relevance in I5.0" column show how each enabler contributes to the human-centric, sustainable and resilient goals of I5.0.

The column "Categories" classifies the enablers into logical groups of go-forward culture (GFC), finance and knowledge-related (FKR), technology-related enablers (TE), and management-related (MR); the column "Description" outlines the conceptual meaning and implementation relevance of each enabler. This distinction is crucial as several of the highlighted aspects, such as blockchain, automation, digital competencies, standards, training and zero-defect manufacturing, have set foundations in I4.0 and are particularly important. Their presence in the current model does not mean that they are the latest innovations in I5.0. Instead, in I5.0, where technologies are being used to complement human capabilities, increase worker wellness, support sustainability and promote organisational and SC resilience, the purpose, integration logic and strategic contribution of these technologies alter. Conversely, enablers such as eco-innovation, ergonomic/exoskeleton-based systems, digital technologies-human capabilities integration, and sustainability performance evaluation reveal a more direct conceptual connection with the fundamental values that define I5.0.

3. Research Methodology

The research methodology (Figure 3) adopted in this study consists of three distinct phases as follows:

Phase 1: In the first phase, a comprehensive review of I5.0 has been done to find out the pertinent enablers of I5.0. Databases of SCOPUS and Web of Science have been used to unearth enablers using different keywords: 'Enablers', 'Industry 5.0', 'Industry 4.0-human centric system ', 'Digital technologies and human interaction system'. From the review, sixteen enablers have been found. The structured literature synthesis revealed that the identified enablers shared some similar conceptual traits and functional linkages. Thus, a literature-driven qualitative content analysis was applied to organise the enablers into logically coherent groupings rather than a statistically driven classification technique. First, the identified enablers were analysed in terms of their conceptual meaning, underlying characteristics, implementation needs, and contribution to I5.0 transformation. First-order codes were then allocated to reflect the main notion depicted by each enabler. Then, focused coding was done to ascertain commonalities and correlations between the codes. Then, similar conceptual features of Enablers were combined into higher-order dimensions. The thorough coding and comparison procedure led to the establishment of four conceptually independent but complementary groups. They are (i) TE, (ii) MR, (iii) FKR enablers and (iv) GFC enablers. Following this, the resulting classification was evaluated by means of expert-informed content analysis to determine the conceptual validity and consistency of the allocation of individual enablers to the four groups. Thus, the four groupings are conceptual dimensions derived from literature, not statistically retrieved components.

Phase 2: Not all identified enablers have the same impact on realising inclusive execution of the I5.0, so it is imperative to prioritise the enablers. For this multi-criterion decision-making approach, GRA has been used in this study. GRA is basically an essential part of the Grey system theory originated by Professor Julong Deng' in Wuhan, China (Lawal *et al.,* 2026). It is used where the information is either undetermined or incomplete (Yan *et al.,* 2026). It can be used to find the best condition or combination of input parameters for getting optimum response values (Khan *et al.,* 2026). Furthermore, multiple-response optimisation problems can be easily solved using GRA in combination with other techniques, such as Analysis of Variance (ANOVA) and the Taguchi method. Another advantage of GRA is that there is no sample size limitation. Apart from that, the calculations and statistics involved are not very complex.

A purposive sampling method was used in the study since the aim was to get informed judgements from respondents who have actual knowledge and expertise with I5.0 and its implementation. Since GRA and BWM were

used in the study to rank I5.0 enablers, the quality and relevance of the respondents' domain knowledge were regarded as more essential than statistical representativeness. This expert-oriented sampling logic is in line with the use of decision-making methods, where well-informed comparative judgements are given by knowledgeable respondents. A total of 173 potential respondents were invited, and 115 responded with complete, usable data (response rate 66.47%). The respondents were industry professionals and academicians with appropriate experience in manufacturing, operations, sustainability, digital transformation, I4.0/5.0 and associated managerial and technology domains. Potential respondents were approached through LinkedIn, professional networks, email communication and personal/professional contacts of the authors. This broad coverage allowed for the inclusion of perspectives from varied industrial and institutional contexts rather than a single country sample. Participants were eligible if they had professional or academic experience relevant to I5.0, manufacturing, operations management, sustainability, digital transformation, I4.0/I5.0 technologies, or other related industrial management areas and were sufficiently familiar with the concepts evaluated in the questionnaire. Incomplete responses and responses that did not meet the standards of the study were eliminated from the final dataset. We also acknowledged the limitations of purposive sampling and non-response.

Since the respondents were chosen for their relevance and accessibility, not through probability sampling, the findings should not be considered statistically representative of the global I5.0 population. In a similar vein, although the response rate was 66.47%, non-response bias cannot be entirely ruled out as the non-participants may have been different from the responding participants in terms of experience, organisational setting or attitudes to I5.0. Hence, the results are regarded as indicative of the aggregate judgements of the expert/industry respondent group involved, and not as generalisable population estimates. The questionnaire was voluntary, and no sensitive personal information was collected; it was a minimal-risk professional/academic survey. The applicable institutional research-ethics requirements did not require formal institutional ethics approval for this type of anonymous, non-interventional questionnaire; the study was treated as exempt from formal ethical review. Participants were briefed on the purpose of the research, the voluntary nature of participation, confidentiality/anonymity and the use of the data for research purposes. All participants provided informed consent prior to participation in the questionnaire. Table 3 depicts the demographic details of the respondents.

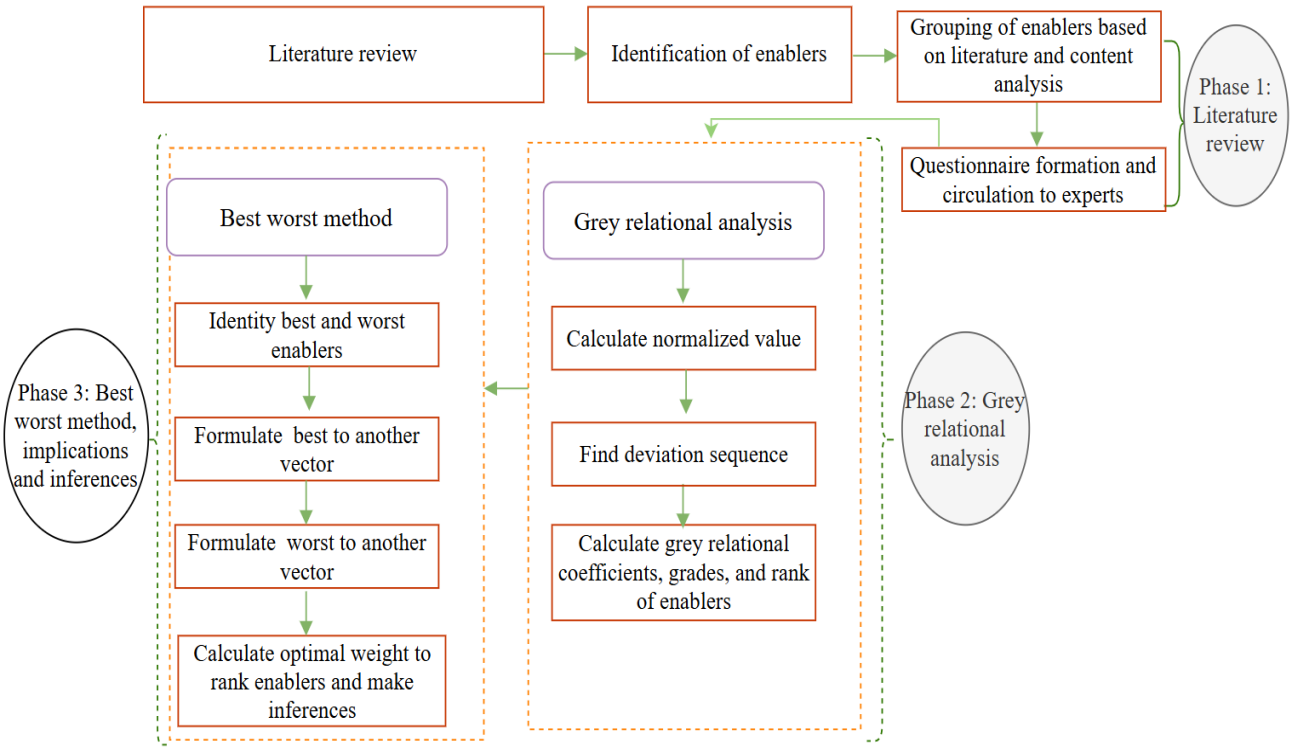


Figure 3. Research Methodology.

Table 3. Demographic details of respondents

Continent	Countries	No of respondents	Main category	Sub-category	Frequency	Percentage
Asia	India	13	Designation	Senior Manager	41	35.65%
	China	8		Manager	28	24.35%
	Japan	4		Senior Engineer	26	22.61%
	South Korea	4		Professor	20	17.39%
Europe	UK	11	Sector/industry	Information technology	22	19.13%
	Germany	9		Education	16	13.91%
	Spain	4		Manufacturing	35	30.43%
	Netherlands	5		Automotive	24	20.87%
	Italy	4		Healthcare	18	15.65%
	France	7	Experience	10 to 15	19	16.52%
	Russia	2		16 to 20	51	44.35%
North America	USA	9		>20	45	39.13%
	Canada	3	Organisation size (in terms of employees)	Small (up to 100)	9	7.83%
South America	Brazil	6		Medium (100 to 250)	18	15.65%
	Argentina	4		Large (>250)	88	76.52%
	Colombia	2	Familiarity with the technological set (I4.0/ I5.0)	Basic level	17	14.78%
	Chile	2		Moderate level	44	38.26%
Africa	South Africa	7		Advanced level	54	46.96%
	Egypt	5	Type of organisation	Multinational	18	15.65%
Oceania	Australia	4		Public	22	19.13%
	New Zealand	2		Private	75	65.22%

The collected responses from the respondents were analysed using GRA. Different steps associated with GRA are as follows:

Step 1: Data processing or normalisation is the initial step of GRA. Process parameters and response variables are also defined before normalisation. Summing up all the response variables gathered against every alternative (process parameter). In the present case, y_j^k shows the addition of responses of barriers 'j' for the person 'k'. Equation 1 is used to get normalised values. y_j^k signifies the normalised value of j(barriers) for person k.

$$y_j^{k*} = \frac{y_j^k - \min y_j^k}{\max y_j^k - \min y_j^k} \quad (1)$$

Step 2: The derivation sequence (Δ_{jk}) is then calculated in the second step by using equation 2.

$$\Delta_{jk} = \max y_j^{k*} - y_j^{k*} \quad (2)$$

Step 3: Grey Relation coefficients (ξ_{jk}) calculation is then done in the next step by use of equation 3. The maximum value of the deviation sequence is represented by Δ_{max}, and the minimum value of the deviation sequence is represented by Δ_{min} [74], [75]. The value of ξ here is taken as 0.5

$$\xi_{jk} = \frac{\Delta_{min} + \xi.\Delta_{max}}{\Delta_{jk} + \xi.\Delta_{min}} \quad (3)$$

Step 4: In the final step, the calculation of Grey Relation Grade (γ_{jk}) is done by using equation 4. In equation 4, n represents the number of respondent groups for the case under consideration[76].

$$\gamma_{jk} = \frac{1}{n}\sum_{j=1}^{n}\xi_{jk} \quad (4)$$

Phase 3: In phase 3, to validate the results of the study, the best worst method (BWM) has been used. The same set of respondents as used for GRA has been used in BWM to rank the enablers of the I5.0. Once the study results are validated, a systematic discussion of the aspects of I5.0 is conducted, and useful recommendations from researchers, practitioners, policymakers, and industrial managers are provided. Finally, the study's inferences have been presented to demonstrate its after-effects.

4. Results and Discussion

The sixteen I5.0 enablers found from the literature were classified through a structured qualitative content-analysis approach (Table 4). The goal of the content analysis was to find conceptual connections between the enablers and to formulate a theoretically appropriate categorisation and not to statistically extract latent components.

Table 4. Content-analysis process for categorisation of I5.0-oriented enablers

Enabler	Literature-derived meaning/evidence focus	First-order code	Second-order concept	Final category	Categorisation rationale
Eco-innovation	Development and utilisation of novel products/processes to reduce impact on environment and encourage sustainable production	Green innovation	Sustainability-oriented innovation	GFC	Represents an organisational perspective for environmental innovation, sustainability and future-oriented transformation.
Competency toward digital transformation	Workforce capacity to understand, implement and effectively deploy evolving digital technologies.	Digital competency	Digital capability development	FKR	Emphasis is placed on the knowledge, skills and capability development needed for I5.0 transformation.
Adaptation of exoskeleton and ergonomics in systems	Use of assistive and ergonomic technologies to enhance worker safety, physical capabilities and human-technology interaction.	Worker augmentation	Human–technology integration	TE	The enabler is based on the use of innovative technical and ergonomic systems to enhance human capabilities.
Proper utilisation of blockchain computing	Blockchain provides secure information sharing, traceability, transparency and trusted transactions	Blockchain capability	Digital trust and traceability	TE	Blockchain is a new digital technology that enables safe, transparent and resilient industrial information systems.
Adaptation of human–robot collaborative technologies and higher levels of automation	Integration of humans with collaborative robots and automated systems to promote flexibility, productivity and human-machine interaction.	Human–robot collaboration	Advanced human–machine systems	TE	The predominant technique is technical integration of robotics, automation and human capabilities.
Zero-defect manufacturing through traceability	Use of digital traceability and quality-management systems to reduce	Digital quality management	Intelligent quality capability	TE	Highly dependent on technical systems for traceability, monitoring, quality

and product quality management	defects and increase the quality of production.				control and defect prevention.
Adaptation of uniform standards throughout and use of innovative technologies in products and processes	Standardisation, interoperability and integration of modern technologies with products and processes.	Standardisation and interoperability	Technology integration	TE	Standards enable interoperability and coordinate implementation of new technology across industrial systems.
Commitment of management personnel at all levels	Leadership commitment and managerial support for technical and organisational change	Management commitment	Leadership support	MR	The managerial commitment to initiate, coordinate and sustain the I5.0 transition.
Clear vision in terms of organisational objectives and pathways to achieve them	Organisational purpose and pathways of transformation with strategic clarity.	Strategic vision	Strategic alignment	MR	Provides management direction and alignment between I5.0 objectives and organisational strategy.
Proactive government support	Government policy, incentives, regulation and institutional support for technological and sustainability transitions	Government support	Institutional facilitation	MR	It shows the external institutional and governance systems, which are needed to support I5.0 adoption.
Availability of resources and capabilities	Availability of financial, technological, Human and organisational resources needed for transformation.	Resource availability	Organisational capability	FKR	Transformation requires enough resources and capabilities, such as financial and human resources.
Integration of digital technologies with human capabilities	Advanced technologies working in conjunction with human understanding and decision making as opposed to technology working on its own.	Human–technology integration	Human-centric digital capability	TE	Although the focus is very much on humans, the immediate mechanism is the integration of digital technology with human skills.
Collaboration among stakeholders	Collaboration and Knowledge Sharing Between Internal and External Stakeholders in the I5.0 Transformation	Stakeholder collaboration	Collaborative coordination	MR	Requires coordination, relationship management, and collaborative governance across stakeholders.
Sustainability performance measurement metrics	Measurement and Monitoring of Environmental, Social and Operational sustainability performance	Sustainability measurement	Sustainability performance management	GFC	Encourages companies to incorporate sustainability goals and performance tracking into long-term development

Know-how and training aspects	Capabilities development for emerging technologies, work force training, knowledge acquisition, reskilling	Training and know-how	Workforce capability development	FKR	Directly related to knowledge, skills, training and human-capital development necessary for I5.0
Organisation's readiness to adopt new technologies	Organisational Readiness, Adaptability and Willingness to Adopt New Technologies.	Technology readiness	Organisational adaptability	GFC	Demonstrates an open, flexible and ready organization for future-oriented technological change.

The analysis was done in four successive steps. A literature-based identification and extraction was first conducted. A thorough literature review was performed, and statements explaining factors facilitating I5.0 adoption were retrieved. Each identified factor was reported with the specific source, contextual meaning and supporting data from the respective study. Secondly, first-order coding was used to find out the main idea that each enabler represented. For instance, blockchain was coded with reference to digital trust, traceability and secure information exchange; management commitment was coded with reference to leadership and organisational support; training and know-how were coded with reference to workforce competence and knowledge development. At this level, the coding was close to the terminology and meaning as published in the literature. Third, focused coding was done, and categories were developed by comparing the first-order codes and searching for conceptual parallels and links among the codes. The TE category was created from codes on advanced digital technologies, automation, human–technology integration, and technological infrastructure. Enablers related to management included codes relating to leadership, strategic direction, governance and stakeholder coordination. FKR enablers included codes relating to resources, competencies, training, know-how and capability development. Finally, codes that showed organisational readiness, innovation orientation, sustainability awareness, flexibility and future-oriented change were classified under GFC enablers. Fourth, an expert-informed content analysis was employed to review and revise the preliminary categorisation. The descriptions of the sixteen enablers, the suggested categories, and the conceptual reason for their placement were reviewed by domain experts. Where an enabler included features related to more than one category, it was categorised according to its main conceptual role within the implementation of I5.0. Expert comment was incorporated, and the classification was modified further by discussion and consensus. The procedure improved the conceptual consistency and face validity of the four-category structure.

The framework thus represents a literature-based and expert-informed conceptual classification of I5.0 enablers. The four areas, namely technological, management-related, financial and knowledge, and forward-culture, are complementary dimensions of I5.0 implementation and should be seen as philosophically derived dimensions, not statistically extracted components.

The grouped enablers of I5.0 were then analysed using GRA and then validated using the BWM. First, the responses gathered from the experts were used to prioritise the enablers of the I5.0. The summed responses for each category of the enablers have been presented in Table 5.

Table 5. Summed responses from the experts

Enablers Category	Senior Manager	Manager	Senior Engineer	Professor
TE	90	62	71	65
MR	140	90	95	82
FKR	132	82	88	71
GFC	72	60	36	34

Once the responses have been collected from the respondents. Normalisation is performed using equation 1 to obtain the normalised value for ranking the enablers of I5.0. Table 6 illustrates the normalised value of GRA.

The normalised values are then converted into the deviation sequence using equation 2. Table 7 shows the deviation sequence of each categorised enabler.

Table 6. Normalised Values

Enablers Category	Senior Manager	Manager	Senior Engineer	Professor
TE	0.264706	0.066667	0.59322	0.645833
MR	1	1	1	1
FKR	0.882353	0.733333	0.881356	0.770833
GFC	0	0	0	0

Table 7. Deviation Sequence

Enablers Category	Senior Manager	Manager	Senior Engineer	Professor
TE	0.735294	0.933333	0.40678	0.354167
MR	0	0	0	0
FKR	0.117647	0.266667	0.118644	0.229167
GFC	1	1	1	1

Table 8 depicts the grey relational coefficients of each category of enablers for a specific set of respondents. (ξ_{jk}). The grey relational coefficients are calculated using equation 3.

Table 8. Grey Relation Coefficients

Enablers Category	Senior Manager	Manager	Senior Engineer	Professor
TE	0.404762	0.348837	0.551402	0.585366
MR	1	1	1	1
FKR	0.809524	0.652174	0.808219	0.685714
GFC	0.333333	0.333333	0.333333	0.333333

Once grey relational coefficients have been estimated, grey relational grades (GRGs) are calculated, and from the GRGs, the ranks of the enablers are calculated. Table 8 depicts GRGs and ranks of I5.0 enablers. It has been found that management-related enablers are the most significant enablers for the execution of I5.0. FKR enablers ranked second in the prioritisation table 9.

Table 9. Grey Relation Grade and Ranks of I5.0 Enablers

Enablers Category	Senior Manager	Manager	Senior Engineer	Professor	Grey Relation Grade	Rank
TE	0.404762	0.348837	0.551402	0.585366	0.4726	3
MR	1	1	1	1	1	1
FKR	0.809524	0.652174	0.808219	0.685714	0.7389	2
GFC	0.333333	0.333333	0.333333	0.333333	0.3333	4

To establish methodological rigour beyond the reporting of final criterion weights, BWM was implemented through a structured sequence of best/worst selection, preference elicitation, optimisation, consistency assessment, and aggregation of respondent judgments. A total of 115 valid respondents participated in the assessment of four criteria. Each respondent first independently identified the most important enabler (best) and the least important enabler (worst). As shown in Table 10, MR was most frequently selected as the best criterion, whereas GFC was most frequently identified as the worst enabler.

Thus, the best and worst criteria were determined from respondent judgments rather than being decided by the researchers. Following the best and worst selection, respondents evaluated the relative importance of the best

criterion (Table 11) over each of the four criteria using the standard nine-point BWM preference scale. The scale ranged from 1, representing equal importance, to 9, representing extreme importance, with intermediate values of 2, 4, 6 and 8 permitted to capture intermediate preference intensities. The judgments founded the best-to-others (B–O) comparison vector as A = (1.000, 3.421, 4.982, 6.431).

Table 10. Best and worst enablers

Criterion	Best, n	Best, %	Worst, n	Worst, %
MR	43	37.39	12	10.43
FKR	31	26.96	18	15.65
TE	27	23.48	22	19.13
GFC	14	12.17	63	54.78

Table 11. Frequency distribution of the best-to-other enablers

Comparison	1	2	3	4	5	6	7	8	9
MR → MR	115	0	0	0	0	0	0	0	0
MR → FKR	8	15	31	27	19	9	5	1	0
MR → TE	5	9	18	22	29	18	10	3	1
MR → GFC	1	3	8	14	19	22	27	15	6

Subsequently, respondents evaluated the relative preference of each enabler over the selected worst enabler (Table 12), generating the others-to-worst (O–W) vector. Because four enablers were evaluated, each respondent provided five independent comparisons, corresponding to (2n-3=5), excluding the two self-comparisons and the redundant best-to-worst comparison. The others-to-worst enabler is found as B= (6.431, 3.761, 2.847, 1.000).

Table 12. Frequency distribution of the others-to-worst enabler

Comparison	1	2	3	4	5	6	7	8	9
MR → GFC	1	3	8	14	19	22	27	15	6
FKR → GFC	5	12	25	32	23	11	6	1	0
TE → GFC	7	19	35	29	17	7	2	0	0
GFC → GFC	115	0	0	0	0	0	0	0	0

The individual judgments were then aggregated to obtain a collective assessment of the 115 respondents. Geometric-mean aggregation was adopted because BWM judgments represent relative preference intensities and therefore have a ratio-based interpretation. It is important to distinguish these aggregated values from the individual judgments: all respondent-level judgments were recorded using the integer 1–9 BWM scale, whereas the decimal values resulted only from the subsequent aggregation process.

The aggregated comparison vectors were introduced into the BWM optimisation model. For the four categories of enablers, the optimisation model was formulated as:

$$\min \xi$$

subject to:

$$\left|\frac{w_B}{w_j} - a_{Bj}\right| \leq \xi,\ j = 1, \ldots, 4$$

and

$$\left|\frac{w_j}{w_W} - a_{jW}\right| \leq \xi,\ j = 1, \ldots, 4$$

subject to:

$$\sum_{j=1}^{4} w_j = 1 w_j \geq 0$$

where $w_j$represents the weight of the enabler j, $w_B$is the weight of the best enabler, $w_W$is the weight of the worst enabler. The optimisation minimised the maximum absolute deviation between the stated preference ratios and the corresponding ratios implied by the estimated criterion weights. Table 13 depicts the BWM weights found using the optimisation model.

Table 13. Ranks of I5.0 oriented enablers using BWM

Criterion	Final weight	Rank
MR	0.447	1
FKR	0.276	2
TE	0.193	3
GFC	0.084	4

The resulting criterion weights were 0.447, 0.276, 0.193 and 0.084 for MR, FKR, TE and GFC, respectively. Consequently, the criteria were ranked MR > FKR > TE > GFC. In addition to the final weights and ranking, the internal consistency of the BWM judgments was evaluated at the respondent level. For each respondent, the consistency ratio was calculated. The consistency of the BWM judgments was evaluated using the BWM consistency ratio (CR).

The consistency ratio was calculated as:

$$CR = \frac{\xi^*}{CI(a_{BW})}$$

where:

- ξ^*= optimal value of the maximum deviation obtained from the BWM model;
- $CI(a_{BW})$= consistency index corresponding to the best-to-worst comparison.

The mean CR was 0.046, and the median CR was 0.039. Furthermore, 106 of the 115 respondents (92.17%) achieved a CR of 0.10 or below, while only nine respondents (7.83%) recorded CR values above 0.10. The maximum observed CR was 0.142. These findings indicate a generally high level of consistency among the expert judgments. So, it can be deduced from the analysis of the BWM that the ranks of I5.0 enablers are in agreement with the results found through GRA.

In the modern age of high competition and demands for high-quality customised products to sustain in the business domain, industrial organisations must embed breakthrough practices. I5.0 is a refinement of I4.0 that leads to better human-machine interaction, putting humans at the centre and a design process that leads to eco-friendly production and improved social sustainability aspects of the organisation. I5.0 is a new paradigm for the industry. In the literature, there are only conceptual studies on the framework of I5.0, but no real-time execution framework of the same has been fully explored to its full potential. To have a full-scale and effective implementation of a novel aspect or approach, it is imperative to explore different key enablers of the approach. This study identifies and critically examines different enablers of I5.0. "Management-related enablers" are the most significant enablers for the implementation of I5.0. This class of enablers encompass enablers like 'Commitment of management personnel at all levels' and 'Clear vision in terms of organisational objectives and pathways to achieve them'. As in any organisation, the prime power to make decisions lies with the management, and I5.0 needs organisational and infrastructure change to execute it, so a high level of commitment is sought from all levels of the management. The findings of the study have been supported by Karnik *et al.* (2022), who asserted that management commitment is a key enabler for the successful execution of a novel approach. Further, it is also imperative for organisations to align goals and methods to achieve I5.0 benefits with the organisational objectives. The results of the same have been

supported by the findings of Čater *et al.* (2021). The researchers found that embedding new approaches and methods into organisational objectives makes the organisation's members more responsible for carrying forward the successful execution of the novel approach. "Financial and knowledge-related" are also found to be significant enablers for implementing I5.0. This category of enablers includes: 'Integration of digital technologies with human capabilities', 'Know-how and training aspects'. To ensure the social aspects of sustainability, it is imperative to keep the human at the centre and integrate different digital aspects. Further, as I5.0 has new aspects, it needs comprehensive training of employees in different technological, organisational, and operational aspects. The findings of the study are in agreement with the study of Tallat *et al.* 2023, who asserted that understanding tools/techniques and different organisational key aspects is imperative to have full-scale successful execution of the digital-oriented approaches. "Technology-related" enablers are also the key enablers to ensure the success of I5.0. This class of enablers includes: 'Integration of digital technologies with human capabilities',' Adaptation of Human-Robot collaborative technologies and higher levels of automation ', and 'Proper utilisation of Blockchain computing ', etc. The adoption of I5.0 is primarily focused on the digital set of technologies. The integrated set of technologies, where technologies interact with each other and provide real-time data and responses, is required to have a seamless I5.0 system in the organisation.

To strengthen the findings of the study, the present study also proposes a technological, organisational, and environmental framework (Figure 4) that leads to a sustainable and resilient industry through the lens of I5.0 execution. The technological context emphasises the collaboration of humans and robots, blockchain technology, and quality management aspects to reduce human efforts, increase system transparency and improve defects and waste in the system. The integration of key technologies of I5.0 with humans leads to a reduction in human efforts, improved workplace safety, and better coordination between humans and machines, which consequently leads to improved organisational and social sustainability of the organisation.

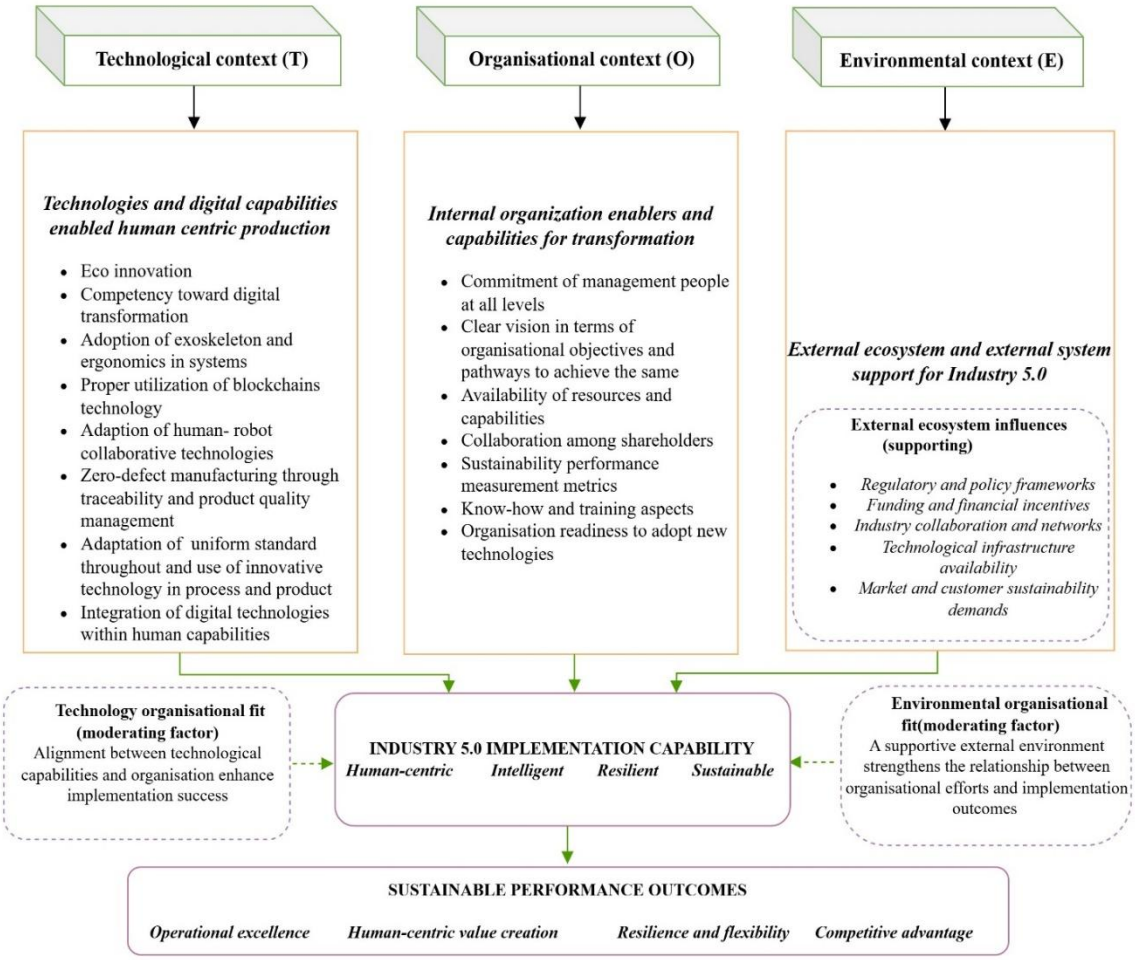


Figure 4. TOE framework of I5.0 enablers.

The organisational context depicts the importance of the internal capabilities, viz, management support, availability of organisational resources to support the technologies of I5.0, and aspects related to training and development. The organisation's set of enablers prepares the foundation that leads to the integration of key principles of I5.0 within the operations of the organisation. The environmental context pinpoints the external ecosystem support that propels the adoption of I5.0. The environmental context prompts industrial collaboration networks, funding for the purchase of technologies, and incentives for the use of I5.0 technologies. This will, in turn, lead to industrial symbiosis and a smart factory run by human intelligence, which consequently makes the industrial ecosystem more resilient and vibrant. Further, the model proposes that technological organisation fit and environmental organisation fit work as moderators for TOE enablers and I5.0 execution. So, from the TOE framework, in a nutshell, it can be deduced that I5.0 enables the industry to be more human-centric, intelligent and resilient, which leads to improved environmental and social sustainability. TOE model proposed in this study leads to improved operational performance, human-centric value creation and makes the organisation more competitive in the global business platform.

4.1 Implications

The present study offers different implications for researchers, practitioners and policy makers. I5.0 is a sustainable future model of the industry that has surpassed the classic productivity and consumption-driven economic model. I5.0 has the potential to overcome many socio-economic constraints like unequal regional development, labour market disruption, and environmental degradation. I5.0's exclusive and optimistic objectives demand a different set of enablers that facilitate I5.0 transformation to meet sustainable development goals. For this, our study provides sixteen unique I5.0 enablers that are indispensable to I5.0 transformation. The present study depicts that these enablers must be prioritised so that the organisation, at the initiation of the I5.0 transformation, must focus on these enablers to ensure full-throttle success of the I5.0 program. For instance, in the prioritisation table, management-related enablers got the top priority; management-related enablers such as strong commitment from managerial-level personnel and continuous ties among industry stakeholders are very important for encouraging innovative technologies, sharing knowledge, and creating a favourable environment for I5.0 to succeed. This study provides different know-how of I5.0 to potential researchers, which will enable them to strengthen their knowledge base, understanding the functionality and interaction among the I5.0 enablers. I5.0 overcomes the lost 'inclusive sustainability' dimension of I4.0 by striking a balance between stakeholders and industry. By integrating stakeholders with industry, I5.0 drives a functional economy that requires society and industry to strike a balance between socio-environmental needs and economic prosperity. The study facilitates industrial managers in integrating all the stakeholders into the core of the I5.0 transformation. I5.0 demands whole synergy among suppliers, manufacturers, technology providers, and customers, so that the core objective of sustainability must be entrusted at each level of the SC. From the perspective of policymakers, the study provides impetus to policymakers to provide funds for the purchase of the new technologies to the frontrunner industries related to I5.0 implementation. Further, the government must also relax taxes on the industries that are promoting the I5.0 transformation. Moreover, within the industry, industrial organisations must promote incentivisation related to the adoption and attainment of key performance indicators related to I5.0.

5. Conclusions, Limitations, and Future Perspectives

I5.0 is a new industrial paradigm, moving from technology-based automation to a human-centric, resilient and sustainable manufacturing ecosystem. Organisations need to identify and manage the critical enablers that enable them to implement I5.0 to achieve this transformation. To meet this need, the following study systematically identified 16 I5.0 enablers from the available literature and grouped them into four main categories: TE, GFC, FKR, and MR, and ranked them to find their relative importance. The results show that the MR enablers are the most influential, followed by FKR enablers. This reinforces the importance of leadership at the top in creating strategic vision, showcasing leadership commitment, ensuring resource availability, and establishing an organisational culture that promotes innovation, human-centricity and sustainable change. Also, the successful implementation of I5.0 requires a significant financial commitment to digital technologies, as well as to the reskilling of workers and the building of organisational capabilities. Therefore, sufficient financial resources and knowledge management systems are essential to speed up the adoption of I5.0 and ensure sustainable implementation of the industry. Theoretically,

this study builds on the existing I5.0 literature by adding a structured classification and prioritisation of the different enablers of the implementation, further developing the knowledge about the organisational enablers that influence I5.0 readiness. The study departs from the previous studies, which largely concentrated on technological developments, and shows that managerial commitment and organisational capacity are just as important, if not more, in successful implementation. The suggested prioritisation framework also provides a starting point for future empirical studies on the interactions between these enablers in various industrial sectors and countries. On the managerial side, the results give a tangible guide to the industrial practitioner, policymaker and decision-maker as to where to start thinking strategically when implementing I5.0. Organisations should invest in advanced technologies while also building up leadership commitment, employee capabilities, knowledge-sharing mechanisms, and financial readiness to ensure a greater return on investment from I5.0. This holistic approach can have a major impact on organisational resilience, operational excellence, employee health, and sustainability. Although this study has contributed, it has a few limitations. The prioritisation framework is based on expert judgments and a predefined set of enablers identified from the literature. Future studies could confirm these results with larger empirical data across various industries and countries; examine causal relationships between the enablers by applying more advanced multi-criteria decision-making or structural modelling methods; and explore sector-specific implementation strategies. This research will contribute to reinforcing the theoretical underpinnings and practical use of the implementation frameworks of I5.0 in various organisational contexts.

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Yes

Conflict of Interest

The authors have no conflicts of interest to declare. There is also no financial interest to report. The author certifies that the submission is original work and is not under review at any other publication.

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