

# Reframing the TOE Framework for Industry 5.0: From Systematic Mapping to Diagnostic Framework Development

Arfan Shahzad<sup>1\*</sup>, Irsa Umer Draz<sup>2</sup>, Muhammad Saqib Nawaz<sup>3</sup>

<sup>1 2 3</sup> Malik Firoz Khan Noon Business School, University of Sargodha, Pakistan

\*Corresponding author's Email: arfan.shahzad@uos.edu.pk

## Article History

Received: 07 July 2025    Revised: 19 Sept 2025    Accepted: 22 Sept 2025    Published: 30 Sept 2025

## Abstract

Industry 5.0 (IR5.0) represents a shift beyond the efficiency-driven logics of Industry 4.0, emphasizing human-centricity, resilience, and sustainability. To support this transition, this study repositions the Technology–Organization–Environment (TOE) framework by systematically mapping recent adoption research (2021–2025) from Scopus and Web of Science. From 21 eligible studies, we extracted TOE factors and reclassified them into diagnostic centricities forming the basis for an enhanced TOE–IR5.0 framework. Results show a persistent tilt toward technological/organizational readiness, while sustainability and ethical enablers remain under-specified. High-frequency drivers (infrastructure, cybersecurity, leadership, competence) indicate partial but incomplete IR5.0 alignment. We propose an enhanced TOE–IR5.0 framework that embeds human-centricity, resilience, and sustainability across technological, organizational, and environmental domains while clarifying where current scholarship still reflects IR4.0 logics. Most importantly, the framework introduces a diagnostic methodology—operationalizing IR5.0 values as transformative lenses applied to the TOE domains. This diagnostic orientation provides researchers, managers, and policymakers with a tool to systematically evaluate and realign technology-adoption strategies toward inclusive, resilient, and sustainable industrial transformation.

**Keywords:** IR5.0, IR4.0, human-centricity, innovation, sustainability, resilience, technology adoption, technology–organization–environment (TOE), tech-centric.

## 1. Introduction

The Fourth Industrial Revolution (Industry 4.0) marked a profound digital transformation in manufacturing through the integration of cyber-physical systems, the Internet of Things (IoT), artificial intelligence (AI), and big data analytics. These technologies enabled automation, real-time monitoring, and interconnected production processes, resulting in significant efficiency and responsiveness gains (Xu et al., 2018; Ghobakhloo, 2018). As

advances continue to be made, Industry 4.0 remains subject to critiques from the social and environmental spectrum, particularly regarding the automation-induced displacement of jobs, unequal access to technology, and the ecological impact of mass automation. These issues have therefore triggered the need to look for a more balanced and sustainable paradigm—one that redefines industrial evolution to include human-centricity, resilience, and sustainability: Industry 5.0.

IR5.0 is here to tackle the issues that were left unaddressed. Instead of merely concentrating on automation and optimization, IR5.0 promotes human cooperation with machines, systematic disruption resilience, and proactive sustainability (Breque et al., 2021; Nahavandi, 2019). It is not expected that workers to be viewed as replacements for machines, but as partners with the necessary tools to amplify creativity, moral reasoning, and problem-solving. The European Commission (2021) describes IR5.0 as a framework to achieve competitiveness that also supports social progress, digital equity, and the principles of a circular economy.

**Table 1: Industry 4.0 & Industry 5.0 Comparison**

<b>Aspect</b>	<b>Industry 4.0</b>	<b>IR5.0</b>
Core Focus	Automation and optimization	Human-centric collaboration with machines
Technology Role	Replaces or automates human tasks	Enhances human capabilities
Key Technologies	IoT, AI, Cyber-Physical Systems	AI + human integration, ethical design, sustainability
Production Model	Mass customization	Hyper-personalized, resilient, and ethical production
Strategic Goal	Operational efficiency	Social, environmental, and economic harmony

As shown in Table 1, Industry 4.0 and IR5.0 are not simply sequential stages but represent distinct paradigms. While Industry 4.0 is rooted in efficiency, automation, and technical sophistication, IR5.0 redefines industrial priorities around human-centric collaboration, resilience, and sustainability.

This paradigm shift has significant implications for both scholarship and practice, calling for frameworks that can capture not only technological readiness but also human, ethical, and environmental dimensions of industrial transformation. Studying IR5.0 adoption through the Technology–Organization–Environment (TOE) lens provides timely insights into how firms can balance efficiency with inclusivity, resilience, and sustainability.

Despite its wide use, applications of the TOE framework remain anchored in efficiency and technical readiness, reflecting an Industry 4.0 orientation. This leaves critical IR5.0 values—human-centricity, resilience, and sustainability—largely unaccounted for. The

lack of systematic classification of TOE factors against these pillars represents a significant theoretical and practical gap.

To address this gap, the present study systematically maps TOE-based adoption research from 2021–2025 and reclassifies factors into diagnostic centricities aligned with IR5.0. This reclassification forms the basis for an enhanced TOE–IR5.0 framework. The study contributes to both theory and practice: it extends the TOE framework toward IR5.0 values while offering Researchers, managers, and policymakers a diagnostic tool to design inclusive, resilient, and sustainable industrial transformations.

## 2. Literature Review

The Technology–Organization–Environment (TOE) framework was first developed by Tornatzky and Fleischer (1990) and analyzes the adoption of innovations in the scope of three areas such as Technology, Organization, and the Environment. The framework postulates that the adoption of an innovation involves an organizational technological capability, an organizational scope, and an outer contextual variable. It has grown to be one of the leading frameworks in understanding technology adoption in organizational settings.

The framework has been used in understanding technology adoption in digital transformation, e-business, and even in the broader context of Industry 4.0. It has been praised for its ability to encompass and explain the influences of technological factors, the organizational factors, and the contextual factors that shape adoption decisions (Oliveira & Martins, 2011; Baker, 2012; Gangwar et al., 2014). However, most of the literature seems to be focused on efficiency-driven approaches that are characteristic of Industry 4.0, and not the broader human-centered and sustainability-driven IR5.0 (Javaid et al., 2021; Ghobakhloo, 2018; Soori et al., 2023).

Recent studies show that the TOE framework is still vital to adoption/usage studies in Industry 4.0 and even in sustainable supply chains, though these applications, again, emphasize performance and technology readiness rather than the principles of IR5.0 (Amin et al., 2024).

Satyro et al. (2024) broadened the traditional TOE model by expanding it to the TOES framework. This added sustainability as the fourth pillar in Industry 4.0 implementation projects. Their research states that the drivers of sustainability (eco-efficiency and regulatory compliance) are consistently and systematically underemphasized, especially in adoption models that predominantly prioritize the technical and organizational dimensions. This observation resonates with studies concerning the EU's industrial vision, which argue for the framing of sustainability and resilience as fundamental components in the technology adoption constructs (European Commission, 2021; Breque et al., 2021). This perspective is supported by new developments concerning the IR5.0 Community of Practice by the European Commission and more recent policy changes that stress the

importance of incorporating human-centricity, resilience, and sustainability into adoption frameworks (European Commission, 2024).

In this context, Rijwani et al. (2025) authored an extensive overview of the new technologies and trends we are seeing with the emerging IR5.0. Their coverage of new themes included human–AI collaboration, resilience, and flexible industrial ecosystems, arguing that we must consider IR5.0 a more transformative industrial paradigm rather than just a linear advancement of Industry 4.0. This is consistent with the emerging conceptual frameworks that promote the ethical, human-centric, and sustainable perspectives in the factory of the future (Elia et al., 2020; Longo et al., 2020; Xu et al., 2021).

Building on these conceptual foundations, newer studies have examined practical tensions in achieving human-centricity and proposed strategic frameworks for IR5.0 manufacturing, reinforcing the shift toward operationalizing IR5.0 priorities (Pacheco et al., 2024; van Erp et al., 2024). The reviewed studies collectively demonstrate the need to reposition the TOE framework in light of IR5.0’s expanded priorities of human-centricity, resilience, and sustainability. This emerging research gap establishes the foundation for the present review, which builds upon these observations to define clear objectives and methodological direction.

### *2.1 Objective of the Review*

The present study systematically reviews TOE-based adoption research published since 2021 and reclassifies identified factors into diagnostic centricities aligned with IR5.0. By integrating bibliometric mapping with factor analysis, the review develops an enhanced TOE–IR5.0 framework that clarifies where current scholarship aligns with IR5.0 priorities and where critical gaps remain. In doing so, it offers a diagnostic tool for researchers and policymakers to advance inclusive, resilient, and sustainable industrial transformation.

Specifically, this review intends to:

1. Extract and classify TOE factors influencing technology use.
2. Categorize factors into diagnostic centricity groups (e.g., tech-centric, human-centric, resilience-centric) to assess alignment with IR4.0 and IR5.0 orientations.
3. Identify factors that reflect IR5.0 values, such as ethics, well-being, resilience, and sustainability.
4. Lay the groundwork for developing a TOE-based interpretive model for IR5.0 readiness.

### *2.2 Addressing Research Gaps*

Building on the limitations identified in the preceding section, this review integrates bibliometric and scoping methods to operationalize the identified gaps. The enhanced TOE–IR5.0 framework offers a structured response by categorizing adoption factors into centricities that align with IR5.0’s human-centric, resilient, and sustainable principles.

### **3. Methodology: Combined Bibliometric and Scoping Review**

To strengthen methodological rigor and align with established bibliometric practices, this study follows analytical procedures similar to Contreras and Abid (2022), who conducted a bibliometric mapping analysis of social sustainability research using the Web of Science database and VOSviewer software. Their mixed quantitative–qualitative approach guided the present study’s integration of bibliometric mapping with factor classification to explore the TOE–IR5.0 research landscape.

#### *3.1 Scope and Data Sources*

Bibliometric data were collected from the Scopus and Web of Science Core Collection databases covering the period 2021–2025. The search strings combined “TOE framework,” “Technology–Organization–Environment,” “Industry 4.0,” and “Industry 5.0.” After screening for relevance and removing duplicates, 21 articles were retained for analysis.

The research followed four consecutive stages: (1) data retrieval; (2) screening and duplicate removal; (3) bibliometric mapping using VOSviewer, charts, and tables using Excel; and (4) qualitative reclassification of TOE factors under IR5.0 centricities.

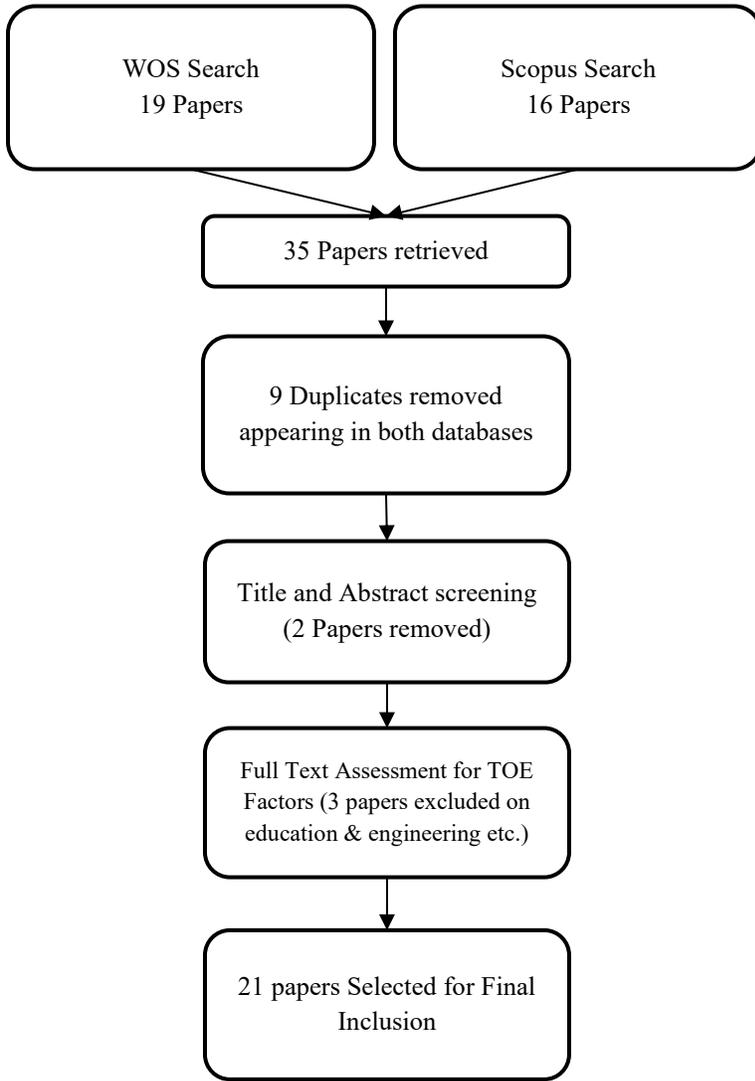
This condensed four-stage version adapts the five-stage research process described by Contreras and Abid (2022) to the smaller dataset.

#### *3.2 Search Strategy and Eligibility*

Searches combined TOE terms with Industry 4.0/5.0 keywords (e.g., “technology–organization–environment” AND “IR5.0/Industry 4.0/adoption/use/readiness”). Eligible studies: (i) explicit use of TOE (or clear TOE-mapped factors), (ii) organization/industry context, (iii) English, (iv) journal articles (conceptual or empirical). Exclusions: domains outside organizational technology adoption (e.g., engineering education only), papers lacking extractable TOE factors, and non-scholarly sources.

#### *3.3 Screening and Study Selection*

The database search yielded 35 records (Scopus 16, WoS 19). Duplicates were removed, titles/abstracts screened, and full texts assessed for eligibility. After exclusions, 21 studies met all criteria and were included. The literature selection followed a structured, multi-step process.



**Figure 1: Paper Selection Process**

### 3.4 Data Extraction and Coding

From each study we extracted: bibliographic details, data source (Scopus/WoS), times cited, study method, all TOE factors and sector/industry with 'SME' classified as a distinct organizational context where it was the study's primary focus. Journal quartile/ranks were inserted based on up to date JCR ranking available. Factors were coded into diagnostic centricities to assess IR5.0 alignment: tech-centric, human-centric, resilience-centric, sustainability-centric, and strategic/enabling/external. Hybrid factors were coded to the dominant interpretation used in each study.

To ensure analytical robustness, only peer-reviewed journal articles indexed in Scopus or Web of Science and published in Q1–Q2 ranked venues were prioritized when identifying the most influential studies. Citation frequency and journal quartile were used as secondary quality indicators during factor extraction.

### 3.5 Bibliometric Mapping Procedure

To visualize thematic structures, keyword co-occurrence mapping was conducted in VOSviewer (version 1.6.19; Van Eck & Waltman, 2010), following established bibliometric procedures outlined by Contreras and Abid (2022). Because the present corpus comprised only 21 studies, the analysis focused on keyword frequency and co-word mapping, rather than large-scale co-citation or bibliographic-coupling analyses. Keywords meeting a minimum occurrence threshold of  $\geq 2$  were included to generate co-occurrence networks that informed the qualitative factor classification.

### 3.6 Synthesis and Thresholds

We report (i) descriptive corpus characteristics (publication trend, citations, journal quartiles, sectors, methods, co-occurrence clusters) and (ii) factor analytics (counts by centrality, high-frequency factor groups). “High-frequency” factor groups are flagged at  $n \geq 5$  occurrences.

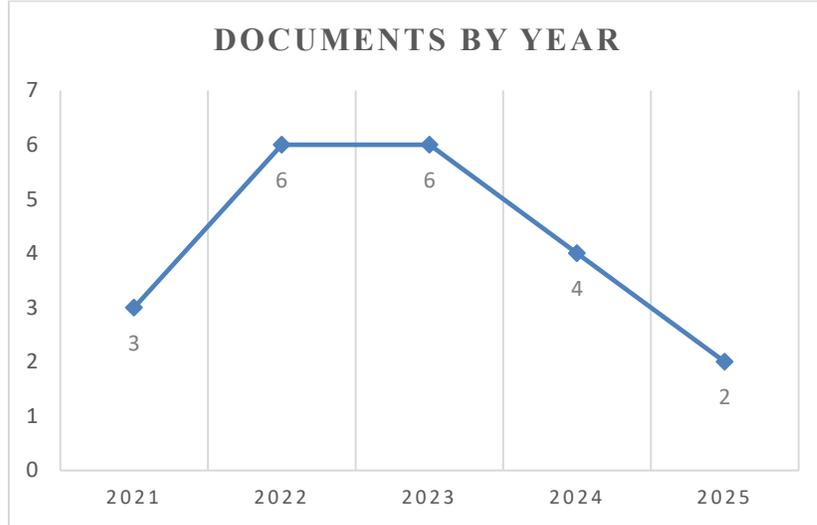
## 4. Results

### 4.1 Corpus Bibliometrics

The literature included in this review is restricted to studies published from 2021 onward. This temporal boundary is intentional and aligns with the emergence and formalization of IR5.0 as a distinct research paradigm. While Industry 4.0 has been extensively studied since its introduction in the early 2010s, IR5.0 only began receiving scholarly and institutional attention in the last few years. The European Commission’s white paper (Breque et al., 2021) and other seminal contributions (e.g., Nahavandi, 2019; Elia et al., 2020) catalyzed the academic framing of IR5.0 around human-centricity, resilience, and sustainability. Therefore, to ensure relevance and alignment with contemporary discourse, only studies published from 2021 onwards were included. This cutoff helps capture the

latest advancements in TOE-based research that reflect IR5.0's expanded values and strategic focus.

The final corpus consists of 21 studies published between 2021 and 2025. Journals are predominantly Q1–Q2 venues, reflecting the growing scholarly maturity of this field. To highlight the most influential works, Table 2 lists the most frequently cited publications from our corpus (with a threshold of  $\geq 15$  citations), while Figure 2 shows their annual publication trend.



**Figure 2: Annual Publication Frequency of TOE-based Studies**

**Table 2: Most Frequently Cited publications**

Article Title	Source	Journal Rank	Times Cited
Understanding AI adoption in manufacturing and production firms using an integrated TAM-TOE model	Both	Q1	327
How digitalization transforms the traditional circular economy to a smart circular economy for achieving SDGs and net zero	WOS	Q1	66
Prioritizing barriers for the adoption of Industry 4.0 technologies	WOS	Q1	66
Exploring paths underlying Industry 4.0 implementation in manufacturing SMEs: a fuzzy-set qualitative comparative analysis	Both	Q1	26
Development of a digital maturity model for Industry 4.0 based on the technology-organization-environment framework	WOS	Q1	21
Determinants of emerging technologies adoption in the South African financial sector	Scopus	Q4	19
Remote integration of advanced manufacturing technologies into production systems: integration processes, key challenges and mitigation actions	Scopus	Q1	16
Statistical Assessment of Business Intelligence System Adoption Model for Sustainable Textile and Apparel Industry	WOS	Q2	15

The reviewed studies span multiple industrial contexts, with manufacturing, logistics, and supply chain sectors dominating the corpus (Table 2). This distribution reflects the early concentration of digital-transformation efforts in production-intensive and SME-driven environments, where technology adoption challenges are most visible.

**Table 3: Industrial Sectors Covered by Selected Studies**

Sector	Count
Manufacturing	8
SMEs	6
Logistics & Supply Chain	3
Textile & apparel	2
Others	2
Total	21

#### *4.2 Methodological Insights*

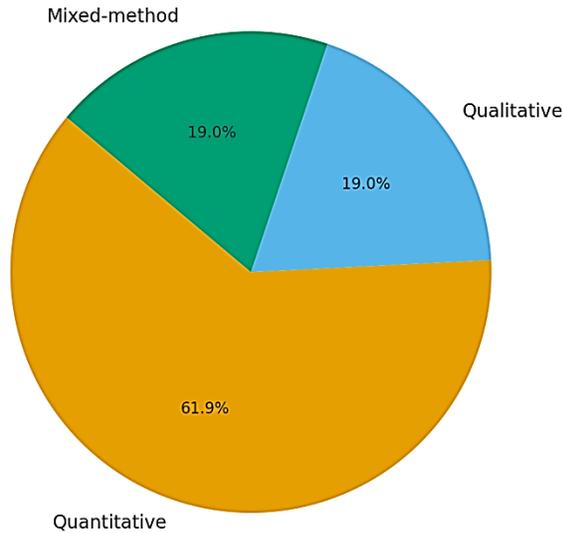
The methodological landscape of TOE-based studies on Industry 4.0 and 5.0 adoption reveals a diverse yet uneven profile. Quantitative approaches clearly dominate, with many studies employing advanced statistical and decision-making techniques such as PLS-SEM (Partial Least Squares Structural Equation Modeling) and fuzzy logic-based methods (e.g., Fuzzy-AHP, Fuzzy-ANP, DEMATEL). These tools are frequently applied to rank, weight, and model interdependencies among TOE factors, thereby producing robust statistical models, particularly in large-scale survey research.

In contrast, qualitative contributions remain limited but provide valuable contextual insights through case studies and interview-driven thematic analysis. Such approaches are especially useful in exploratory settings or in underrepresented regions such as SMEs in the Global South.

A smaller yet important stream of mixed-method research combines systematic literature reviews with expert interviews or hybrid designs (e.g., Fuzzy-AHP + DEMATEL). These studies attempt to bridge theoretical gaps while also addressing practical decision-making priorities. Importantly, this integrative orientation resonates with IR5.0, where socio-technical complexity, human-machine collaboration, and sustainability concerns demand both structured modeling and contextual validation.

Taken together, this methodological landscape highlights an over-reliance on quantitative rigor, leaving a gap in capturing organizational culture, workforce well-being, and ethical dimensions. Addressing these gaps through richer qualitative or mixed designs will be essential for realizing the human-centric and sustainable transformation envisioned in IR5.0 (Elia et al., 2020; Aheleroff et al., 2022).

## Methodological Distribution of TOE-IR5.0 Studies (2021-2025)



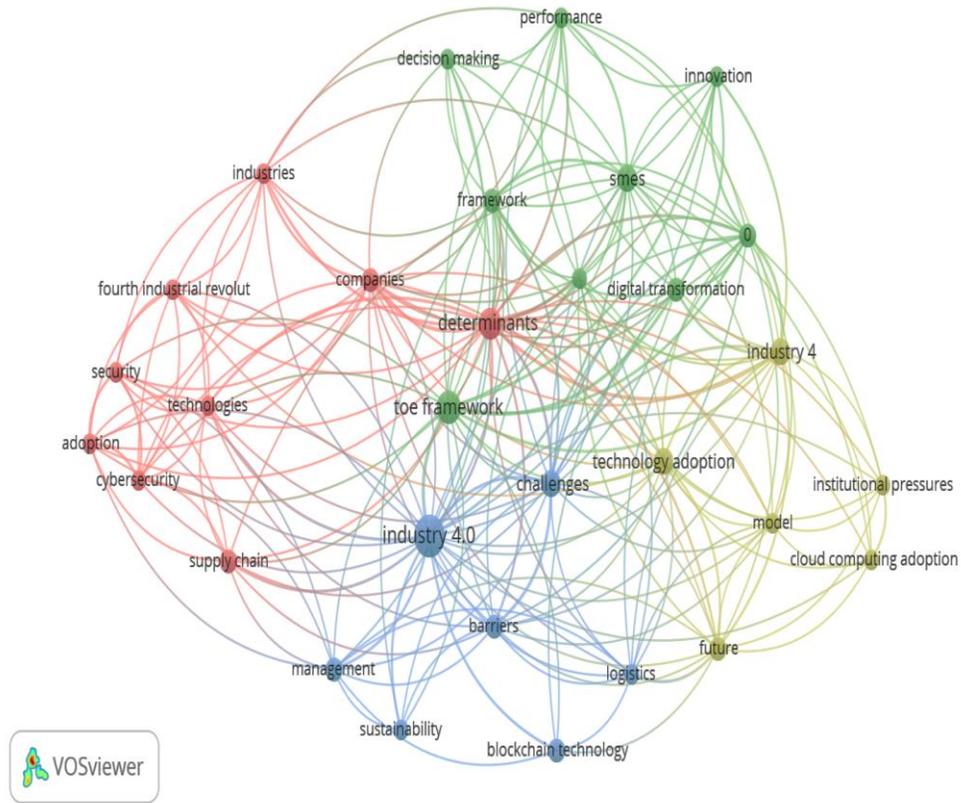
**Figure 3: Methodological Distribution of TOE-IR5.0 Studies (2021-2025)**

#### 4.3 Keyword Co-occurrence Network (VOSviewer)

An analysis of the full 21-paper corpus reveals a wide range of citation impact (min = 1, max = 327, mean  $\approx$  31), which is characteristic of an emerging field consolidating around a few influential works (as shown in Table 2) alongside newer contributions.

Figure-3 illustrates the keyword co-occurrence network of the selected studies, generated using VOSviewer. In this map, node size reflects the frequency of keyword usage, the distance between nodes indicates co-occurrence strength, and distinct colors represent clusters of related themes (Van Eck & Waltman, 2010). Four dominant clusters can be observed, each highlighting a specific research orientation.

Taken together, the keyword mapping shows that technological and organizational readiness still dominate the literature, reflecting an Industry 4.0 orientation. However, the growing presence of sustainability, resilience, and human-centric terms indicates a gradual conceptual shift toward IR5.0's broader priorities of collaboration, well-being, and ecological alignment (Breque et al., 2021; Aheleroff et al., 2022). This bibliometric evidence strengthens the case for reclassifying TOE factors into tech-centric, human-centric, resilience-centric, and sustainability-centric categories, forming the basis of the enhanced TOE-IR5.0 framework proposed in this study.



**Figure 4: Co-occurrence Network of Keywords**

The co-occurrence clusters underscore that the language of adoption scholarship remains dominated by digitalization and readiness themes, with limited emergence of IR5.0-aligned terms such as “human-centricity,” “resilience,” or “sustainability.” This suggests that IR5.0 discourse is still in its early integration phase within TOE-based studies.

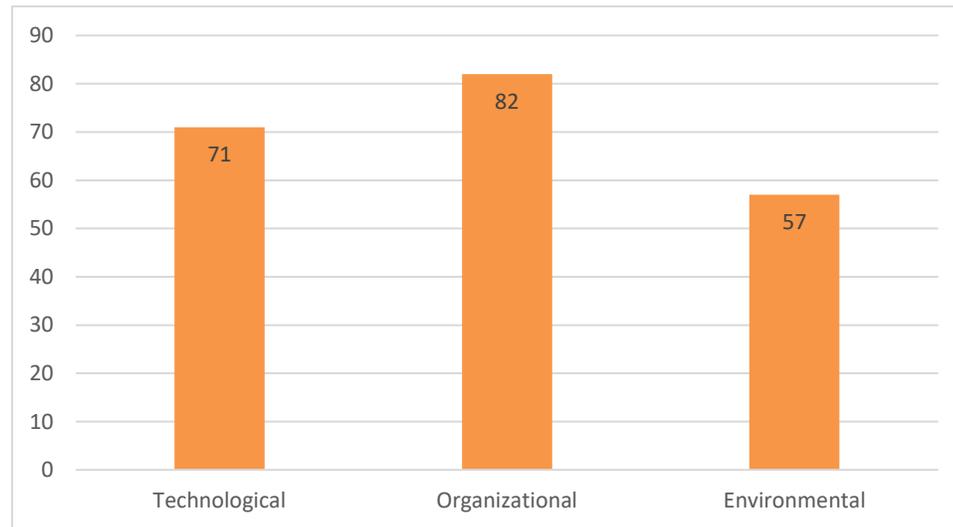
We now turn from thematic clusters to specific adoption drivers by extracting and reclassifying TOE factors.

*4.4 Distribution and Reclassification of TOE Factors*

The Technology–Organization–Environment (TOE) factors extracted from the reviewed studies reveal that most research continues to emphasize technological and organizational concerns. Organizational factors are frequently linked with technology-related capabilities

such as cybersecurity management, IT strategy, and digital competence. This pattern shows that TOE applications largely retain an Industry 4.0 orientation, where digital readiness and efficiency remain dominant.

Figure 5 illustrates the overall frequency of factors across the original Technology, Organization, and Environment categories, showing the dominant focus on technical and organizational concerns within recent TOE-based research.



**Figure 5: Frequency of Factors in TOE Categories**

To better capture the evolving focus of technology adoption studies in the context of IR5.0, the extracted factors were reclassified into diagnostic centricities aligned with its three foundational pillars—human-centricity, resilience, and sustainability (i.e., the core values of IR5.0). Two cross-cutting categories—Strategic & Enabling Factors and External Factors—were also retained to reflect overarching organizational and environmental influences.

- Tech-Centric: Infrastructure, automation, and technical maturity (IR 4.0–style readiness).
- Human-Centric: Leadership, ethics, digital skills, and workforce well-being.
- Resilience-Centric: Cybersecurity, adaptability, and risk management.
- Sustainability-Centric: Eco-efficiency, circularity, and alignment with SDGs.
- Strategic & Enabling Factors: Organizational alignment, transformation strategy, and long-term planning.

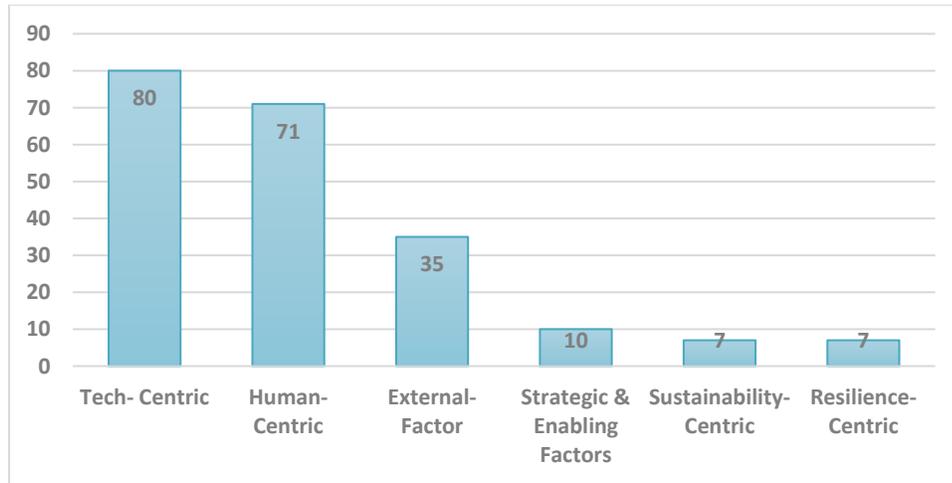
- External Factors: Market conditions, industry dynamics, and regulatory frameworks.

This classification provides a diagnostic view of how existing TOE-based literature aligns with—or diverges from—IR5.0 priorities. While certain elements such as cybersecurity and organizational readiness straddle multiple domains, each factor was coded according to its dominant treatment within the reviewed studies.

**Table 4: Frequency of Diagnostic Centricity Categories Based on TOE Factors**

TOE Category	Frequency
Tech- Centric	80
Human- Centric	71
External- Factor	35
Strategic & Enabling Factors	10
Sustainability- Centric	7
Resilience- Centric	7
Total	210

Figure 6 visualizes this distribution, illustrating the heavy concentration of technological and organizational factors relative to the limited attention given to sustainability and resilience.



**Figure 6: Distribution of TOE Factors by Diagnostic Centricity**

A closer look at the high-frequency factor groups (Table 4) further highlights the persistence of performance-driven and infrastructure-oriented themes such as technological infrastructure, top-management support, and organizational readiness.

**Table 5: High-Frequency TOE Factor Groups (n ≥ 5)**

Factor Group	Factors	Freq.	Rank	TOE
Technology Infrastructure	Tool Availability, technology roadmap and proof of concept, technology maturity, Technology Infrastructure, Technology, Technologies For Smart Products & Services, Structure, Modular technology, Lack of Communication and IT Infrastructures, Infrastructure, Increasing access of digital tools, Digital Twin Characteristics, Digital self-service technology, Compatibility/IT Infrastructure, closed software, blockchain technology, Availability, Maturity & Effectiveness of Technology, automatic calibration, AMT (advanced manufacturing techniques) requirements, Advanced Manufacturing Technologies	20	Q1(12), Q2(7), Q4(1)	T, O, E
Competency & Capability	User's Traits, Technology Competence, Technological Infrastructure and competence, Technical Skills, Technical competencies, Organizational Competency, Organizational Compatibility, Compatibility of Tech, Compatibility, Organizational Capabilities, I4.0 Integration Capabilities, Embracing digital capabilities and collaborative solutions)	15	Q1(7), Q2(4), Q4(2), N/A(2)	T, O
Government policy & support	support programs, regulatory support, regulatory environment, Regulatory & compliance Factors, Legal and regulatory aspects, Governmental Regulations, Government Support,	12	Q1(4), Q2(4), Q4(1), N/A(2)	E

Reframing the TOE Framework for Industry 5.0

	Government regulations, Government Policy and Regulations, Government policy & support			
Culture & Knowledge	Lack of knowledge management systems and data knowledge, Knowledge, skill & attitude, Knowledge, External Knowledge Search, external knowledge, combining different knowledge domains, Organizational Culture, Experimental culture, Culture Resistance to Change, Knowledge Management, Entrepreneurial Culture)	10	Q1(8), Q2(1), Q4(1)	T, O, E
Competitive Pressure	Market Pressure, customer demands, Competitive/Industry Pressure, Competitive Pressure	9	Q1(1), Q2(3), Q4(2), N/A(1)	E
Top Management Support	Top Management Support, Management Support & Leadership, Management Support, Leadership Commitment & Support, Governance	9	Q1(4), Q2(2), Q4(1), N/A(1)	O
Organizational Readiness	technology readiness & Capabilities, technology readiness, Technological Readiness, Organizational Readiness	8	Q1(2), Q2(1), Q4(1), N/A(2)	T, O
Competitive OR relative Advantage	Relative Advantage, Competitive Advantage	7	Q1(2), Q2(1), N/A(1)	T, E
Complexity	Organizational Complexity, increased complexity, Complexity in Technology, complexity	7	Q1(3), Q4(1), N/A(2)	T, O
Data related Concerns	Sustainable Data Quality & Integrity, Digital Data collection & Analysis, different data structures, Data Technologies, common information model., Business intelligence and data science, Availability & quality of data	7	Q1(5), Q2(2)	T, O

Strategic Alignment & Flexibility	Strategy (Investment, risk & performance management), strategy, Strategic Flexibility, Strategic alignment, starting with feasible plans, Reimagining the workplace, Business Transformation	7	Q1(5), Q2(1), Q4(1)	T, O
Industry	Market Trends, Market Perspective, Industry Specific Forces, industry	6	Q1(2), Q2(1), Q4(1), N/A(1)	E
Internal Barriers	Lack of Standardization Efforts, Lack of Seamless integration and Interoperability Capabilities, Lack of Qualified Workforce, Lack of off-the-shelf solutions, Lack of Digital Strategy, Lack of clear comprehension about IoT benefits	6	Q1(6)	T, O, E
Perceived benefit / Ease of use	Perceived Usefulness, Perceived Ease of Use, Perceived benefit of Technology, perceived benefit, Ease of use	6	Q1(3), N/A(2)	T
Security & Privacy	User Insecurity, Security & Privacy, security, need to consider Security, Safety and Privacy Issues, data security	6	Q1(3), Q4(2), N/A(1)	T, E
Communication & collaboration	unified communication interface, Stakeholder collaboration & information sharing, secure and authenticated communication, Interpersonal Communication, Communication Mechanism	5	Q1(3), Q2(1), Q4(1)	O, E
Leadership Type	Transformational Leadership, Strategy & Leadership, Opinion leadership, HR, Leadership, Talent Acquisition and Retaining, Training, Adhocracy	5	Q1(1), Q2(1), Q4(2), N/A(1)	O
Organization Size	Organization Size	5	Q1(1), Q2(1), Q4(1), N/A(1)	O

These findings reveal where scholarly attention is concentrated—and where it is lacking. Human well-being, ethical design, and sustainability are seldom operationalized, underscoring the gap between Industry 4.0’s efficiency focus and IR5.0’s human-centric vision.

Many of the frequently cited factors also exhibit cross-cutting characteristics that blur traditional TOE boundaries. For instance, data security combines technical safeguards with organizational governance, while competency integrates workforce development with policy and institutional support. Such hybrid attributes emphasize the socio-technical complexity of industrial transformation and validate the need for a diagnostic-centricity approach that embeds human-centricity, resilience, and sustainability across all dimensions of technology adoption.

Overall, this analysis shows that TOE-based adoption research remains weighted toward technological and organizational readiness. Embedding the broader human-centric and sustainable values of IR5.0 across these domains is therefore critical for the next generation of adoption frameworks.

#### *4.5 Enhanced TOE–IR5.0 Framework and Factor Mapping*

We first present the baseline TOE structure re-read through IR5.0 (Figure 6). We then operationalize this lens with our data in two stages: (i) Table 6 maps the high-frequency factor groups to the TOE domains and IR5.0 pillars; (ii) Table 7 consolidates these results into a diagnostic matrix that adds centrality (human- vs tech-oriented) and dominant application context (IR4.0 vs IR5.0). Finally, Figure 7 visualizes the integrated diagnostic framework (the three IR5.0 beams across TOE).

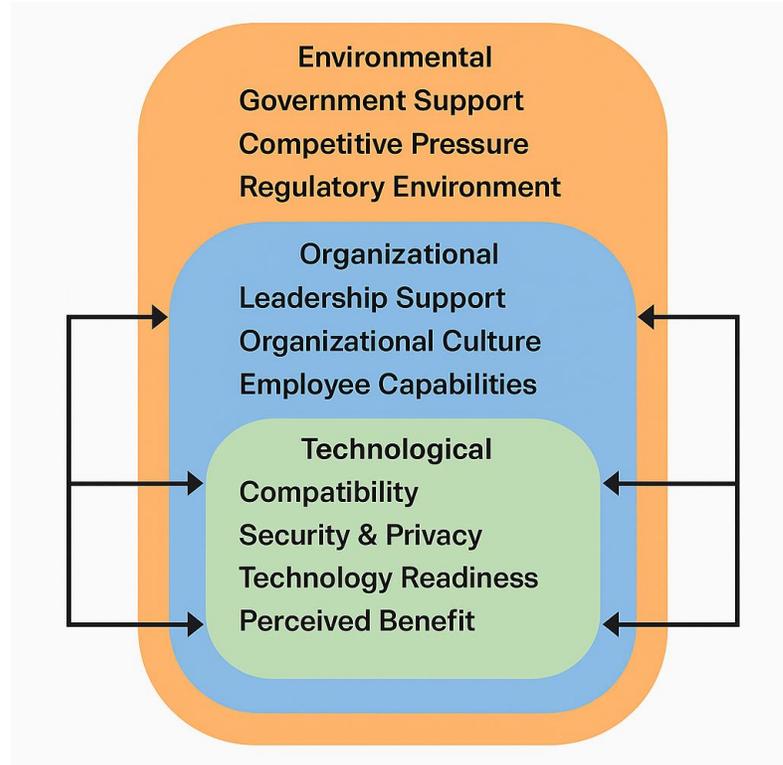
Table 6 summarizes this mapping, showing, for example, that leadership, communication, and workforce competencies align strongly with human-centricity; cybersecurity, data integrity, and continuity planning align with resilience; and policy/regulatory support and eco-efficiency link with sustainability.

The Technology–Organization–Environment (TOE) framework (Tornatzky & Fleischer, 1990) remains a widely accepted theoretical model for analyzing technology-adoption determinants. In this enhanced visualization, the TOE model is structured into three nested layers—Technological, Organizational, and Environmental—to represent the multi-dimensional nature of technology diffusion in the context of both Industry 4.0 and IR5.0 (Baker, 2012; Oliveira & Martins, 2011).

- Environmental layer: External drivers such as government regulations, market dynamics, sustainability mandates, and competitive pressures define the landscape within which firms operate and innovate.
- Organizational layer: Internal capabilities including leadership support, workforce competencies, financial readiness, and cultural adaptability determine how firms respond to environmental challenges.

- Technological layer: System compatibility, data security, scalability, and infrastructure readiness directly influence technology deployment.

Arrows in the framework illustrate interdependence: environmental pressures shape organizational strategies; organizational preparedness influences technology integration; and regulatory or market demands may directly affect technological choices (e.g., cybersecurity or data-architecture standards). This layered model affirms that technology adoption is not merely a technical decision but a systemic response shaped by organizational and environmental contexts—a premise central to TOE (Baker, 2012). For IR5.0, these interdependencies take on added significance by emphasizing traceability, systemic alignment, and human–technology synergy—core principles of the post-Industry 4.0 era (Breque et al., 2021; Nahavandi, 2019).



**Figure 7: Baseline TOE in the Context of IR5.0**

*Mapping High-Frequency Factor Groups to IR5.0 Dimensions*

To operationalize the expanded TOE framework, high-frequency factor groups (occurring  $\geq 5$  times across reviewed studies) were aligned with corresponding TOE domains and IR5.0 dimensions. These dimensions—human-centricity, resilience, and sustainability—reflect both the analytical findings of this review and the strategic imperatives emerging from IR5.0 scholarship.

**Table 6: Map High-Frequency TOE Factor Groups to TOE Domains and their IR5.0 Pillar**

TOE Dimension	Factor Group	Key Focus Areas	IR5.0 Alignment
Technological	Technology Infrastructure	Tool availability, modular systems, digital platforms	Resilience
	Security & Privacy	Cybersecurity, data integrity, privacy protocols	Resilience
	Data-Related Concerns	Quality, integration, analytics	Tech & Resilience
	Perceived Benefit / Ease of Use	User-centric design, usability	Human-centric
Organizational	Top Management Support	Leadership buy-in, decision-making power	Human-centric
	Organizational Readiness	Digital maturity, internal preparedness	Resilience
	Competency & Capability	Technical skills, organizational compatibility	Human-centric
	Communication & Collaboration	Internal-external knowledge flows, trust	Human-centric
	Culture & Knowledge	Knowledge systems, resistance to change, learning culture	Human-centric
Environmental	Complexity	System/process overload, integration challenges	Tech & Organizational strain
	Government Policy & Support	Regulations, incentives, standards	Sustainability + Resilience
	Competitive Pressure	Market dynamics, customer expectations	Resilience
	Industry Context	Sector-specific technological norms	Sustainability (sectoral Eco norms, regulatory pull)

The mapping confirms that organizational factors—such as leadership, competencies, and communication—most strongly align with human-centric imperatives, reflecting IR5.0’s shift toward empowerment and participatory innovation (Aheleroff et al., 2022; Nahavandi, 2019). Technological dimensions—including cybersecurity, data integrity, and infrastructure—remain crucial for both IR 4.0 and IR5.0 but now emphasize resilience and continuity rather than efficiency alone. Environmental drivers—particularly government policy and regulatory frameworks—display dual centricity, linking institutional structures with sustainability and ethical governance.

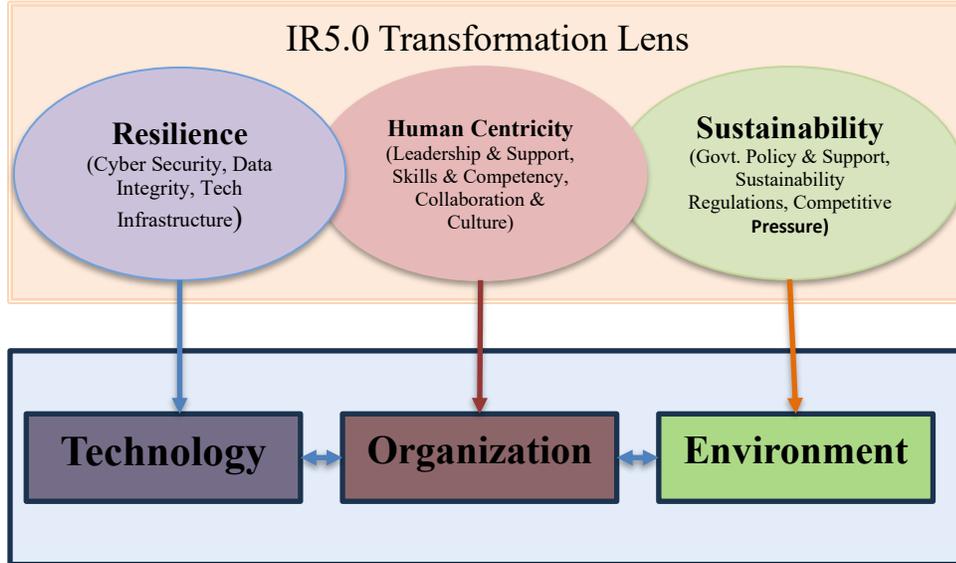
4.5.1 Consolidated Mapping of TOE Factors to IR5.0 Pillars

To integrate these insights, a consolidated mapping was developed to align high-frequency TOE factors with the foundational pillars of IR5.0 while classifying each factor’s centricity (human- or tech-oriented) and its dominant application context (IR 4.0 or IR5.0).

**Table 7: Consolidated Diagnostic Matrix**

TOE Domain	Factor Group	IR5.0 Pillar	Centricity	Primary Orientation
Technological	Technology Infrastructure	Resilience	Tech-Centric	IR4.0 & IR5.0
Technological	Security & Privacy	Resilience	Tech-Centric	IR5.0
Technological	Data-Related Concerns	Resilience	Tech-Centric	IR4.0
Technological	Perceived Benefit/Ease	Human-Centric	Human-Centric	IR4.0
Organizational	Top Management Support	Human-Centric	Human-Centric	IR5.0
Organizational	Competency & Capability	Human-Centric	Human-Centric	IR4.0 & IR5.0
Organizational	Organizational Readiness	Resilience	Tech-Centric	IR4.0
Organizational	Culture & Knowledge	Human-Centric	Human-Centric	IR5.0
Organizational	Communication & Collaboration	Human-Centric	Human-Centric	IR5.0
Environmental	Government Policy & Support	Sustainability & Resilience	Tech-Centric & Human-Centric	IR5.0
Environmental	Competitive Pressure	Resilience	Tech-Centric	IR4.0
Environmental	Industry Context	Sustainability	Tech-Centric	IR4.0

This consolidated table demonstrates that while human-centric drivers are gaining visibility, sustainability and resilience remain comparatively under-represented and are often treated as compliance-oriented rather than core adoption imperatives. The pattern underscores a persistent conceptual lag between IR5.0’s integrative ideals and the current empirical focus of TOE-based studies.



**Figure 8.: The TOE–IR5.0 Diagnostic Framework: Transformative Lenses for Technology Adoption**

The framework operationalizes IR5.0 values as transformative lenses applied to the TOE domains, incorporating the high-frequency factors identified through this review. It serves as a diagnostic tool to assess where technology-adoption initiatives align with IR5.0 principles versus remains anchored in IR4.0 efficiency logic.

This framework directly embodies the empirical findings of our review. The mapping of high-frequency factors is not arbitrary but grounded in the core results of our systematic analysis, where each domain of the TOE framework was reinterpreted through the corresponding IR5.0 lens.

- Technological Domain → Resilience Lens: This layer must be assessed against the critical factors our analysis identified—cybersecurity, data integrity, and technology infrastructure. These elements address the disruptive and continuity risks repeatedly noted in the literature, moving the discussion beyond mere efficiency toward system robustness and adaptive capacity.
- Organizational Domain → Human-Centricity Lens: The organizational core of IR5.0 is fundamentally reconfigured around people. Our findings show that

success depends on top management support, workforce competency and capability, and a collaborative culture—human factors that remain secondary in much of the current adoption research. Embedding these within the TOE structure restores balance between digital readiness and social readiness.

- Environmental Domain → Sustainability Lens: The external context must now prioritize government policy and support, sustainability regulations, and competitive pressure—factors our review found most underrepresented. Reframing them as strategic enablers elevates sustainability from a compliance issue to a central performance imperative.

The two-way arrows in the framework visualize these critical interdependencies: environmental regulations shape technological investment; organizational competencies enable technology integration; and market pressures continuously reshape organizational strategy. This systemic, circular logic reflects the complex socio-technical nature of IR5.0, where resilience, human-centricity, and sustainability operate as mutually reinforcing forces rather than discrete pillars.

Together, Table 6, Table 7, and Figure 8 show where contemporary TOE studies concentrate (tech/organization) and what remains under-specified (sustainability, ethical human-centricity, and resilience depth). The diagnostic matrix converts literature signals into an assessment tool for firms and policymakers. We next position this contribution against TOES (Satyro et al., 2024) and broader IR5.0 trajectories (Rijwani et al., 2025) to clarify the study's theoretical novelty.

## 5. Discussion

### 5.1 Theoretical and Diagnostic Contribution

Our analysis reveals that although the TOE framework is extensively applied in Industry 4.0 and 5.0 studies, its usage remains predominantly aligned with efficiency-oriented and technological priorities. The IR5.0 pillars of human-centricity, resilience, and sustainability are comparatively underrepresented, indicating that current TOE applications still reflect a transitional rather than transformative orientation.

Relative to Satyro et al. (2024), who extend TOE additively to TOES by introducing sustainability as a fourth pillar and Rijwani et al. (2025), who map high-level IR5.0 trajectories (human–AI collaboration, resilience), our framework integrates these insights into a unified diagnostic structure. Unlike these additive or descriptive models, the enhanced TOE–IR5.0 framework embeds sustainability as a cross-cutting dimension that interacts with human-centricity and resilience.

Most significantly, the enhanced TOE–IR5.0 framework contributes what previous approaches lack—a diagnostic methodology for assessing IR5.0 alignment. While Satyro et al. (2024) extend TOE additively by adding sustainability as a fourth pillar, and Rijwani et al. (2025) map high-level IR5.0 trajectories, our lens-based approach operationalizes

these ideas into an evaluative tool. It enables researchers and practitioners to systematically diagnose where current adoption practices remain anchored in IR4.0's efficiency logic versus where they have been transformed by IR5.0's human-centric, resilient, and sustainable values. This represents a shift from descriptive categorization to diagnostic transformation.

Key Missing Elements in the Traditional TOE Model:

- Human-AI collaboration and employee empowerment (Organizational)
- Ethics, trust, and sustainability metrics in technology design (Technological & Environmental)
- Ecosystem engagement and digital equity across stakeholders (Organizational & Environmental)

### *5.2 Practical and Diagnostic Application*

The enhanced TOE-IR5.0 framework provides both conceptual guidance and practical diagnostic value for diverse stakeholder groups. It translates IR5.0's human-centric, resilient, and sustainable ideals into actionable evaluation criteria that can be applied across technological, organizational, and environmental domains.

**Managers and decision-makers:** Balance technical investments in infrastructure with equal attention to leadership, workforce skills, and communication systems. Adoption should be approached as a socio-technical transformation, not merely a digital upgrade.

**Policymakers and regulators:** Move beyond compliance-driven sustainability. Incentives should prioritize circular economy integration, resilience planning, and human-AI upskilling to help firms operationalize IR5.0 values.

**Technology vendors and consultants:** Design solutions that emphasize usability, explainability, and resilience safeguards (e.g., cybersecurity, redundancy, data integrity), ensuring alignment with both organizational needs and societal expectations.

Beyond these general implications, the framework also offers a diagnostic methodology that allows researchers and practitioners to assess readiness and guide transformation efforts:

- 1) **Factor Assessment:** Evaluate ongoing or proposed technology-adoption initiatives against the high-frequency factors in each domain (see Figure 8). For example: "Does our AI-implementation plan address all Resilience-Lens factors—cybersecurity, data integrity, and infrastructure robustness?"
- 2) **Alignment Gap Analysis:** Identify where current strategies overemphasize tech-centric readiness while neglecting sustainability-centric or human-centric enablers.
- 3) **Intervention Planning:** Use the framework to design targeted interventions. For instance, if Competitive Pressure (Environmental) is the dominant driver, ensure

parallel attention to Skills and Competency (Organizational/Human-Centric) to avoid workforce disruption.

This diagnostic logic directly supports the study's research objectives by offering a structured method to assess IR5.0 readiness, locate misalignments, and prioritize transformation actions. Collectively, these applications convert the framework from a conceptual model into a practical diagnostic instrument for achieving inclusive, resilient, and sustainable industrial transformation.

### *5.3 Empirical Evidence and IR5.0 Dimensions in Literature*

The synthesis of reviewed studies reveals that elements of IR5.0—particularly human-centricity and resilience—are beginning to appear within TOE-based research, though often in fragmented or implicit forms. These emerging themes demonstrate that while scholars recognize the socio-technical transformation of industry, the integration of IR5.0 values remains partial and uneven.

**Human-Centricity.** Several studies emphasize leadership commitment, digital skills, and workforce empowerment as key enablers of successful digital transformation (Elia et al., 2020; Aheleroff et al., 2022). These contributions highlight the participatory and creative dimensions of Industry 5.0, where technology augments rather than replaces human capability. However, most frameworks still treat human factors as secondary to technical readiness, underscoring the need for a more explicit human-centric orientation in adoption models.

**Resilience.** A growing number of works integrate resilience-related constructs such as cybersecurity, adaptive infrastructure, and continuity planning (Javaid et al., 2021; Ghobakhloo et al., 2021). These studies extend the traditional TOE lens by addressing risk management and system robustness—core to IR5.0's vision of disruption-ready enterprises. Nevertheless, resilience remains narrowly operationalized as data protection or business continuity rather than systemic adaptability.

**Sustainability.** Sustainability considerations appear least represented in TOE-based adoption studies, typically confined to compliance or energy-efficiency metrics (European Commission, 2021; Breque et al., 2021). Broader ecological or social sustainability goals—such as circular-economy integration, ethical AI design, and lifecycle accountability—are rarely embedded as strategic adoption criteria. Broader IR5.0 literature, however, calls for exactly this integration, advocating for ethical, explainable, and sustainable technologies (Nahavandi, 2019; Longo et al., 2020; Van Erp et al., 2024).

Collectively, these findings confirm that the TOE framework is in a transitional phase: its technological and organizational orientations dominate, but early traces of IR5.0's three pillars are visible. Embedding human-centricity, resilience, and sustainability more explicitly within future TOE applications will be essential for achieving the systemic and people-focused transformation envisioned in Industry 5.0.

#### *5.4 Limitations and Future Research Implications*

This review has several limitations that should be acknowledged. First, the proposed TOE–IR5.0 framework is based on factors mapped from the reviewed studies. While this provides a systematic baseline, it does not yet include other potentially relevant constructs such as ethics, digital well-being, inclusive innovation, or socio-environmental resilience. Future studies should expand the framework by incorporating these emerging dimensions and validating them empirically.

Second, the bibliometric analysis is constrained by the novelty of IR5.0 research. Attempts to generate co-authorship and co-citation networks did not yield meaningful clusters because the publication base remains small and dispersed—a common challenge in emerging domains (Van Eck & Waltman, 2010). Consequently, this review relied on keyword co-occurrence, citation counts, and sectoral distributions to capture the intellectual contours of the field.

Third, the temporal and database scope also shapes the findings. The review focused on studies published from 2021 onward to align with the formal articulation of IR5.0 (Breque et al., 2021; Nahavandi, 2019). While appropriate for capturing recent developments, this decision may have excluded earlier research implicitly addressing human-centric or sustainability concerns. Similarly, reliance on Scopus and Web of Science, though comprehensive, may have omitted relevant gray literature or sector-specific cases (Donthu et al., 2021).

Fourth, the classification of TOE factors into centricities involves interpretive judgment. Some factors—such as cybersecurity or organizational readiness—span multiple domains and could reasonably be coded in more than one category. Although coding was grounded in the reviewed studies, such subjectivity is an inherent limitation of qualitative synthesis.

Finally, the corpus is dominated by manufacturing-focused studies, which restricts the generalizability of insights to other sectors such as healthcare, education, and public governance. Future research should broaden the dataset, diversify sectoral coverage, and apply mixed-method or longitudinal approaches to test and refine the TOE–IR5.0 framework. Integrating complementary theoretical perspectives—such as institutional theory, socio-technical systems, and dynamic capabilities—could further strengthen its explanatory power. Future bibliometric extensions could include co-citation and thematic evolution analyses as the IR5.0 corpus expands.

#### **6. Conclusion**

This review consolidates fragmented TOE-based adoption factors into an integrative framework aligned with the principles of IR5.0. By embedding human-centricity, resilience, and sustainability across technological, organizational, and environmental domains, the proposed model provides a diagnostic tool for both scholars and practitioners.

For researchers, it identifies where future empirical work should focus—particularly in operationalizing human-centric, ethical, and sustainability-driven adoption drivers. For

managers and policymakers, it offers guidance on steering digital transformation toward inclusive and resilient growth.

In doing so, this study moves TOE-based research beyond efficiency-oriented logics and contributes to the systemic, people-centered transformation envisioned by IR5.0. Widespread adoption of this reframed TOE diagnostic can thus accelerate the transition toward genuinely human-centered, resilient, and sustainable industrial systems.

### Research Funding

The authors would like to acknowledge that this article is the outcome of research that was fully funded by the HEC-NRPU research project (Project No. 87646) titled “Industry 5.0 Use and Innovation for Sustainable Business Growth in the Manufacturing Sector of Pakistan”.

### REFERENCES

- Aheleroff, S, Huang H, Xu X and Zhong RY (2022) Toward sustainability and resilience with Industry 4.0 and Industry 5.0. *Frontiers in Manufacturing Technology*, 2, 951643. <https://doi.org/10.3389/fmtec.2022.951643>
- Amin, A., Bhuiyan, M. R. I., Hossain, R., Molla, C., Poli, T. A., & Milon, M. N. U. (2024). The adoption of Industry 4.0 technologies by using the technology organizational environment framework: The mediating role to manufacturing performance in a developing country. *Business Strategy & Development*, 7(2), e363. <https://doi.org/10.1002/bsd2.363>
- Baker, J. (2012). The technology-organization-environment framework. In Y. K. Dwivedi, M. R. Wade, & S. L. Schneberger (Eds.), *Information systems theory* (pp. 231-245). Springer. [https://doi.org/10.1007/978-1-4419-6108-2\\_12](https://doi.org/10.1007/978-1-4419-6108-2_12)
- Contreras, F., & Abid, G. (2022). Social sustainability studies in the 21st century: A bibliometric mapping analysis using VOSviewer software. *Pakistan Journal of Commerce and Social Sciences*, 16(1), 167-203. <https://doi.org/10.64534/Commer.2022.120>
- Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., & Lim, W. M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. *Journal of Business Research*, 133, 285-296. <https://doi.org/10.1016/j.jbusres.2021.04.070>
- European Commission, Directorate-General for Research and Innovation, Breque, M., De Nul, L., & Petridis, A. (2021). IR5.0: Towards a sustainable, human-centric and resilient European industry. Publications Office of the European Union.
- European Commission, Directorate-General for Research and Innovation, Renda, A., Schwaag Serger, S., Tataj, D., Morlet, A., et al. (2021). IR5.0, a transformative vision for

Europe - Governing systemic transformations towards a sustainable industry. Publications Office of the European Union.

European Commission. (2024). IR5.0 Community of Practice (CoP 5.0) Final Report. Publications Office of the European Union. [https://research-and-innovation.ec.europa.eu/document/download/8aea695d-2b97-4366-812f-971b7ebbfda8\\_en](https://research-and-innovation.ec.europa.eu/document/download/8aea695d-2b97-4366-812f-971b7ebbfda8_en)

Elia, G., Margherita, A., & Passiante, G. (2020). Digital entrepreneurship ecosystem: How digital technologies and collective intelligence are reshaping the entrepreneurial process. *Technological Forecasting and Social Change*, 150, 119791. <https://doi.org/10.1016/j.techfore.2019.119791>

Gangwar, H., Date, H., & Ramaswamy, R. (2014). Understanding determinants of cloud computing adoption using an integrated TOE-DOI model. *Journal of Enterprise Information Management*, 27(4), 418-443. <https://doi.org/10.1108/JEIM-08-2013-0065>

Ghobakhloo, M. (2018). The future of manufacturing industry: a strategic roadmap toward Industry 4.0. *Journal of Manufacturing Technology Management*, 29(6), 910-936. <https://doi.org/10.1108/JMTM-02-2018-0057>

Ghobakhloo, M., Iranmanesh, M., Grybauskas, A., Vilkas, M., & Petraitė, M. (2021). Industry 4.0, innovation, and sustainable development: A systematic review and a roadmap to sustainable innovation. *Business Strategy and the Environment*, 30(8), 4237-4257. <https://doi.org/10.1002/bse.2867>

Javaid, M., Haleem, A., Singh, R. P., Suman, R., & Rab, S. (2021). Industry 4.0 adoption: an analysis of barriers. *Journal of Manufacturing Technology Management*, 32(6), 1127-1147. <https://doi.org/10.1016/j.bcra.2021.100027>

Lee, J., Bagheri, B., & Kao, H. A. (2015). A cyber-physical systems architecture for Industry 4.0-based manufacturing systems. *Manufacturing Letters*, 3, 18-23. <https://doi.org/10.1016/j.mfglet.2014.12.001>

Longo, F., Padovano, A., & Umbrello, S. (2020). Value-oriented and ethical technology engineering in IR5.0: A human-centric perspective for the design of the factory of the future. *Applied Sciences*, 10(12), 4182. <https://doi.org/10.3390/app10124182>

Low, C., Chen, Y., & Wu, M. (2011). Understanding the determinants of cloud computing adoption. *Industrial Management & Data Systems*, 111(7), 1006-1023. <https://doi.org/10.1108/02635571111161262>

Nahavandi, S. (2019). IR5.0-A human-centric solution. *Sustainability*, 11(16), 4371. <https://doi.org/10.3390/su11164371>

Oliveira, T., & Martins, M. F. (2011). Literature review of information technology adoption models at firm level. *The Electronic Journal Information Systems Evaluation*, 14(1), 110-121.

- Pacheco, D. A. D. J., & Iwaszczenko, B. (2024). Unravelling human-centric tensions towards IR5.0: Literature review, resolution strategies and research agenda. *Digital Business*, 4(2), 100090. <https://doi.org/10.1016/j.digbus.2024.100090>
- Rijwani, T., Kumari, S., Srinivas, R., Abhishek, K., Iyer, G., Vara, H., ... & Gupta, M. (2025). IR5.0: A review of emerging trends and transformative technologies in the next industrial revolution. *International Journal on Interactive Design and Manufacturing*, 19(2), 667-679. <https://doi.org/10.1007/s12008-024-01943-7>
- Satyro, W. C., Contador, J. C., Gomes, J. A., Monken, S. F. D. P., Barbosa, A. P., Bizarrias, F. S., ... & Prado, R. G. (2024). Technology-organization-external-sustainability (TOES) framework for technology adoption: critical analysis of models for industry 4.0 implementation projects. *Sustainability*, 16(24), 11064. <https://doi.org/10.3390/su162411064>
- Soori, A., Bigdeli, A. Z., & Uden, L. (2023). Integrating Industry 4.0 technologies into manufacturing: A roadmap and readiness model. *Journal of Manufacturing Systems*, 66, 385-400. <https://doi.org/10.1016/j.jmsy.2022.10.012>
- Tornatzky, L. G., & Fleischer, M. (1990). *The Processes of Technological Innovation*. Lexington Books.
- Van Eck, N., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics*, 84(2), 523-538. <https://doi.org/10.1007/s11192-009-0146-3>
- Van Erp, T., Carvalho, N. G. P., Gerolamo, M. C., Gonçalves, R., Rytter, N. G. M., & Gladysz, B. (2024). IR5.0: A new strategy framework for sustainability management and beyond. *Journal of Cleaner Production*, 461, 142271. <https://doi.org/10.1016/j.jclepro.2024.142271>
- Xu, L. D., Xu, E. L., & Li, L. (2018). Industry 4.0: state of the art and future trends. *International Journal of Production Research*, 56(8), 2941-2962. <https://doi.org/10.1080/00207543.2018.1444806>
- Xu, X., Lu, Y., Vogel-Heuser, B., & Wang, L. (2021). Industry 4.0 and IR5.0-Inception, conception and perception. *Journal of Manufacturing Systems*, 61, 530-535. <https://doi.org/10.1016/j.jmsy.2021.10.006>

**Appendix A**

<b>Factor Group</b>	<b>Factors</b>	<b><i>f</i></b>	<b>Rank count</b>	<b>TOE</b>
Technology Infrastructure	Tool Availability, technology roadmap and proof of concept, technology maturity, Technology Infrastructure, Technology, Technologies For Smart Products & Services, Structure, Modular technology, Lack of Communication and IT Infrastructures, Infrastructure, Increasing access of digital tools, Digital Twin Characteristics, Digital self-service technology, Compatibility/IT Infrastructure, closed software, blockchain technology, Availability, Maturity & Effectiveness of Technology, automatic calibration, AMT (advanced manufacturing techniques) requirements, Advanced Manufacturing Technologies	20	Q1(12), Q2(7), Q4(1)	T, O, E
Competency & Capability	User's Traits, Technology Competence, Technological Infrastructure and competence, Technical Skills, Technical competencies, Organizational Competency, Organizational Compatibility, Compatibility of Tech, Compatibility, Organizational Capabilities, I4.0 Integration Capabilities, Embracing digital capabilities and collaborative solutions)	15	Q1(7), Q2(4), Q4(2), N/A (2)	T, O

Government policy & support	support programs, regulatory support, regulatory environment, Regulatory & compliance Factors, Legal and regulatory aspects, Governmental Regulations, Government Support, Government regulations, Government Policy and Regulations, Government policy & support	12	Q1(4), Q2(4), Q4(1), N/A (2)	E
Culture & Knowledge	Lack of knowledge management systems and data knowledge, Knowledge, skill & attitude, Knowledge, External Knowledge Search, external knowledge, combining different knowledge domains, Organizational Culture, Experimental culture, Culture Resistance to Change, Knowledge Management, Entrepreneurial Culture)	10	Q1(8), Q2(1), Q4(1)	T, O, E
Competitive Pressure	Market Pressure, customer demands, Competitive/Industry Pressure, Competitive Pressure	9	Q1(1), Q2(3), Q4(2), N/A (1)	E
Top Management Support	Top Management Support, Management Support & Leadership, Management Support, Leadership Commitment & Support, Governance	9	Q1(4), Q2(2), Q4(1), N/A (1)	O
Organizational Readiness	technology readiness & Capabilities, technology readiness, Technological Readiness, Organizational Readiness	8	Q1(2), Q2(1), Q4(1), N/A (2)	T, O
Competitive OR relative Advantage	Relative Advantage, Competitive Advantage	7	Q1(2), Q2(1), N/A (1)	T, E

Reframing the TOE Framework for Industry 5.0

Complexity	Organizational Complexity, increased complexity, Complexity in Technology, complexity	7	Q1(3), Q4(1), N/A (2)	T, O
Data related Concerns	Sustainable Data Quality & Integrity, Digital Data collection & Analysis, different data structures, Data Technologies, common information model., Business intelligence and data science, Availability & quality of data	7	Q1(5), Q2(2)	T, O
Strategic Alignment & Flexibility	Strategy (Investment, risk & performance management), strategy, Strategic Flexibility, Strategic alignment, starting with feasible plans, Reimagining the workplace, Business Transformation	7	Q1(5), Q2(1), Q4(1)	T, O
Industry	Market Trends, Market Perspective, Industry Specific Forces, industry	6	Q1(2), Q2(1), Q4(1), N/A (1)	E
Internal Barriers	Lack of Standardization Efforts, Lack of Seamless integration and Interoperability Capabilities, Lack of Qualified Workforce, Lack of off-the-shelf solutions, Lack of Digital Strategy, Lack of clear comprehension about IoT benefits	6	Q1(6)	T, O, E
Perceived benefit / Ease of use	Perceived Usefulness, Perceived Ease of Use, Perceived benefit of Technology, perceived benefit, Ease of use	6	Q1(3), N/A (2)	T
Security & Privacy	User Insecurity, Security & Privacy, security, need to consider Security, Safety and Privacy Issues, data security	6	Q1(3), Q4(2), N/A (1)	T, E
Communication & collaboration	unified communication interface, Stakeholder collaboration & information sharing, secure and authenticated communication,	5	Q1(3), Q2(1), Q4(1)	O, E

	Interpersonal Communication, Communication Mechanism			
Leadership Type	Transformational Leadership, Strategy & Leadership, Opinion leadership, HR, Leadership, Talent Acquisition and Retaining, Training, Adhocracy	5	Q1(1), Q2(1), Q4(2), N/A (1)	O
Organization Size	Organization Size	5	Q1(1), Q2(1), Q4(1), N/A (1)	O
External Barriers	Supply chain challenges (Complexity & Uncertainty, loss & waste, safety and security), Lack of Regulatory Framework, Lack of Legal and Contractual Assurances, External Barriers (high implementation cost, lack of collaboration, relevant data issues)	4	Q1(4)	O, E
External Support	Wider Technology Support, Support for CE actors, Partner Support, External Support	4	Q1(3), Q2(1)	T, O, E
Innovation	Technology Innovation Decision Making, Personal Innovativeness, Knowledge of innovation, enabling technology innovated R & D	4	Q1(1), Q2(1), Q4(2)	T, O, E
Motivations	Willingness & motivation to use Technology, SDGs and net zero as a motivation, Satisfaction with existing system, Internal Motivations (improve efficiency, enhance visibility & Transparency)	4	Q1(2), Q2(2)	T, O
Adaptation	Software adaptation, Need for Adaptive Retrofitting Implementation, Need for	3	Q1(3)	T, O

Reframing the TOE Framework for Industry 5.0

	Adaptive Modifications at Organizational and Process Levels			
Awareness & Training	Tech Awareness & Training, organizational training, Awareness	3	Q1(1), Q2(1), Q4(1)	O
Costs	Low-cost Proofs of concepts, Labor cost, Cost of Implementation	3	Q1(2), Q2(1)	T, O, E
New/old way of working	Old Way of working, New Way of working & Standardization, new types of requirements	3	Q1(3)	O, E
Resources & Budget	Resources, IT Resource Availability, Allocating Sufficient Resources & Budget for Tech	3	Q2(3)	T, O
Sustainability	Sustainability, Sustainable textile trades, Investigation of SDG and net zero benefits of textile production, Production and consumption of natural fibers	4	Q1(3), Q2(1)	E
Investment	Return on Investment, Need for high level of investment	2	Q1(1), Q2(1)	O
Organizational Agility	Organizational Agility, Longevity	2	Q1(2)	O
Risk & Risk Orientation	Risk Orientation, External Risk & threat	2	Q2(1), Q4(1)	O, E
Role Definition	Well Defined Roles, lack of role description	2	Q1(1), Q2(1)	O
System Integration concerns	System integration & information flow, Synchronization & system integration issues	2	Q1(2)	T
Dedicated Cyber security Teams	Dedicated Cyber security Teams	1	Q2(1)	O
Environmental Dynamism	Environmental Dynamism	1	Q1(1)	E

Financial Expectations	Financial Expectations	1	Q1(1)	O
Geographical proximity	Geographical proximity	1	Q1(1)	O
Human Capital	Human Capital	1	Q1(1)	O
Incentives	Incentives	1	Q1(1)	E
Increase sorting quality and efficiency	Increase sorting quality and efficiency	1	Q1(1)	E
Inter-organizational Aspects	Inter-organizational Aspects	1	Q1(1)	E
Market competitive recycled fibers	Market competitive recycled fibers	1	Q1(1)	E
Organization change	Organization change	1	Q4(1)	E
Partnerships	Partnerships	1	Q1(1)	O
Processes	Processes	1	Q1(1)	O
Redefined requirement specifications	Redefined requirement specifications	1	Q1(1)	E
Strategic closed loop chains	Strategic closed loop chains	1	Q1(1)	E
Trial ability	Trial ability	1	Q4(1)	T