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Industry 5.0 and its Implementation in Manufacturing SMEs

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Abstract

With the advancement of Industry 4.0 and its predecessors came the consequential reduction in human involvement in various industries, environmental decline. By the onset of COVID, many companies showed the lack of economic resilience of many companies. Industry 5.0 aims to rectify these arising errors working on a three-pronged agenda of human, environmental and economic sustainability, our report focuses on manufacturing SME sectors across the world as they seem to be left out due to lack of resources, this research aims to generate a framework of industry 5.0 implementation, an approximate 30 different publications have been studied for this research.

Keywords
Industry 5.0, Industry 4.0, Sustainability, SMEs, Digital Transformation.

1. Introduction
Industry 4.0 (I4.0) refers to the ongoing fourth industrial revolution promoting digitalization, connectivity, and information sharing with some key enabling technologies, including internet of things (IoT), simulation, and digital twin (Malaibari et.al 2024 and Ji and Abdoli 2023). Industry 4.0 is a developing and ever-growing concept (Abdoli 2023). Industry 5.0 (I5.0), introduced by the European commission, has a focus on three aspects: sustainability, human, and resilience, to improve human and technological interactions (Grosse et al. 2023, Vongchaisaree and Abdoli 2025). This research focuses on small/medium enterprises, known as SMEs, mainly due to their key role impact all around the world, with 90% of all organizations worldwide are considered SMEs, employing 50% of the world's workforce (de Mendonça Santos and Sant'Anna 2024). However, limited research has been done regarding the path towards implementation of I5.0 on SMEs (Grosse 2023, Leng 2023, Lu 2022, Cagliano 2019). This paper aims to analyze the existing research, challenges and barriers, and suggests future directions for achieving the full potential of industry 5.0 in SMEs.

2. Methodology
We have defined the following research questions to critically review the literature surrounding the practical integration of Industry 4.0 technologies within SMEs to achieve Industry 5.0 objectives. Considering that the industry 4.0 technologies have a transformative nature and the unique challenges faced by SMEs, it is essential to systematically investigate both the barriers to adoption and the broader impact of such technologies on sustainability, resilience, and human-centric outcomes.

- Research Question: What are the barriers for feasible application of industry 4.0 technologies in SMEs to achieve sustainability goals?

The aim of RQ1 is to enlist feasible technologies which can be implemented in SMEs. Feasibility will be determined via a systematic literature review in the space of industry 4.0, sustainability, and industry 5.0, and SME. Feasibility would be based on economic, existing infrastructure, ability to tackle preconceived notions and availability of technology based on different regions. However, we may not be able to define feasibility as an absolute concept. The research plans to identify existing literature which focuses on key aspects of industry 4.0 technology, followed by comparing it to our list of feasibility criteria, if they pass the criteria, we assume that technology is feasible for implementation for SMEs.

By answering the research question, we aim to gather insights that help to establish a framework for successful application of industry 4.0 technologies in SMES while achieving sustainability goals, including environmental sustainability, human sustainability and economic sustainability. Economic sustainability has been widely researched yet remains an important point of focus as it enables an SME to improve environment and human sustainability.

We conducted a structured literature review on databases including Scopus and Web of Science, using keyword combinations including "Industry 4.0", "Industry 5.0", "SMEs", "Sustainability", "Human-centric", "Industry 4.0 feasibility", "Industry 5.0 feasibility", "SME 5.0", and "Resilience". Only peer-reviewed publications were considered. We initially screened titles and abstracts to ensure relevance, selecting studies that addressed the adoption of Industry 4.0 technologies in SMEs and their potential alignment with Industry 5.0 principles. The selected papers were then analyzed and categorized based on key enabling technologies, identified barriers, and their contribution to Industry 5.0 goals. This process allowed us to identify research gaps and informed the formulation of our research questions and proposed roadmap.

The literature review is conducted in such a way that gives the reader the current scenario, from understanding the importance of SMEs to the concepts of sustainability, understanding different sustainability parameters, ways to establish sustainability through various frameworks, the positives and negatives of each. We investigated the rectifier of the existing drawbacks, the concept of industry 5.0 the framework, possible outcomes and current research gaps. The process of review and how it leads to the derived insights is shown in Figure 1 which is explained further in the next sections.

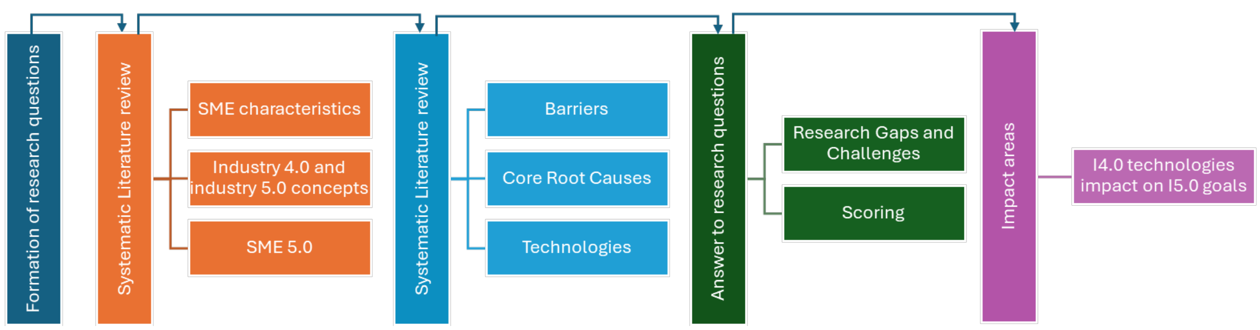

Figure 1. Research approach

3. Review Results

3.1 SMEs Characteristics

The organization of economic cooperation development defined SME's as 'non subsidiary independent enterprises where the salient features are number of employees and extent of financial assets' (de Sousa Jabbour et al. 2023). A study stated that almost 99% of firms identified themselves as SME in Asia, therefore influencing the social and economic aspects with being responsible for providing employment for more than half of the workforce across. Likewise, Europe is seeing 70% of employment in the manufacturing sector being done by SMEs (Garetti and Taisch, 2012).

Prasanna, et.al (2019) suggested assessing an SME performance with three parameters (1) survival, growth, profit (2) philosophy and value (3) public image. The effect of better SME performance is visualized through the overall growth in industrial revenue, creation of employment, an increase in export growth and productivity improvements. The study highlights the importance of organizational culture, training and education being the driving force of an SME's performance. One of the highlighted issues existing in SMEs is their low survival rates. The cause of this in most cases is the low adoption of innovative strategies in production compounded with lack of capital, inadequate technical knowledge, and skill shortage (Prasanna, et.al. 2019). A significant barrier to sustainable development in SMEs stems from the lack of willingness to change. A study conducted on the Fish processing industry in Thailand in [10] concluded that there is only partial adoption of industry 4.0 technologies in SME's and most of the industry still uses traditional practices and there is a resistant to change to use advanced technologies.

3.2 Industry 4.0, Sustainability Goals and Transition to 5.0

In this section we review the content related to three aspects of sustainability based on triple bottom line model: environmental for planet, economic for prosperity, and social for people.

Environmental sustainability in manufacturing refers to incorporating methods which promote a more environmentally friendly product (Abdoli 2023). A study defined Sustainability 4.0 as a collective societal responsibility and addressing a need to tackle problems in social ethical and environmental spheres (Javaid et.al. 2022). The movement is characterized by incorporating digital technologies into all aspects of the organizations with the use of industry 4.0 technologies such as cloud computing, internet of things (IoT), additive manufacturing, big data analysis, cyber physical systems or CPS and artificial intelligence. The expected outcome of the implementation of these technologies is an instant feedback loop via data and visualization, increased safety and efficiency in operations and indication of problem areas to aid in improving sustainability (Javaid et.al. 2022). Sustainability 4.0 aims to use the data generated from the application of industry 4.0 technologies to track energy expenditure during manufacturing processes and with the advanced data analytics methods such as machine learning (ML) models, inefficiencies in the process can be identified, rectified and improved leading to significant reduction in consumption. That paper discusses that since additive manufacturing consumes a lower volume of raw materials compared to conventional manufacturing, it supports efficient processes. It was argued that with process efficiency improvement, the businesses are left with free cashflow which helps them grow their business and with a well thought product life cycle they can achieve greater lengths of sustainable products. However, the mentioned work misses out on the key cause and effect relationships of application of new technology.

The concept of Pi mind clones was brought up by Golovianko et al. (2023). which talks about finding a hybrid solution of industry 4.0 and industry 5.0, where efficiency meets human touch, where to replicate the human touch they suggest that humans can be kept in the loop via their digital representatives known as cognitive clones or pi mind clones, these clones are expected to maintain the biases and features of each person, while maintain efficiency by making the machine work which they consider a win-win.

The negative impacts of application of industry 4.0 technologies were discussed by Oláh et.al. (2020), stated that the focus of industry 4.0 and its application has been left solely on producing to generate higher profits which has caused harm to natural resources (Abdoli et al., 2020, unequal distribution of wealth and led to unsustainable levels of consumption patterns environmentally, socially and economically. The authors argued that in most cases industry 4.0 technologies were implemented without considering sustainable consumptions of raw materials, allowing time for regeneration, and without measuring the capacity of the environment to absorb the waste that is generated, leading to failure to achieve sustainable production. The paper highlights important negative impacts of shift from technologies such as redundant machinery generating waste the culture of overconsumption due to improved efficiency for businesses. However, the paper suggests that application of industry 4.0 technologies leads to improved human sustainability by providing better working conditions, reduced time in the factory and a safer working environment. The study mentions the need to focus on switching to clean sources of energy to make the environmental sustainability via industry4.0. Although the paper misses out on the cost of such an implementation for companies may be high, especially for SMEs.

Nahavandi (2019) argued that industry 4.0 technologies such as AI and ML have positive impact on achieving various sustainability goals, but the potential to improve sustainability is larger than currently out in practice.

Some studies focused on issues of waste generation to upgrade equipment. Stock and Seliger (2016) mentions the practicality and effectiveness of retrofitting as integrating modern technologies such as sensors, cameras and recording devices with existing machinery such that by using their generate data improving the manufacturing process. This data can be analyzed by machine learning models. Since capital goods tend to have a long life in the manufacturing sphere, usually up to 20 years, the use of sensors and actuators to upgrade, rather than replace existing machinery is a viable option for SMEs as it does not require big investments. Stock and Seliger (2016) also argued that economic sustainability has encouraged industry 4.0 implementation, which some studies adopting to industry 4.0 technologies have helped them to be more cost efficient (Puniani and Abdoli 2025), with production costs being reduced by 10-30%, logistics costs being reduced by 10-30% and the cost to manage quality by 10-20%.

Nahavandi (2019) discusses that when the application of industry 4.0 sees its full potential, its drawbacks will seem to surface, with pushbacks from labor unions, intervention from politicians, which might lead to neutralization of the benefits industry 4.0. The research argues that industry 5.0 will further utilize human intelligence and creativity with machines' ability to be efficient and create a more advanced industrial process which will combine intelligent systems and workflows, so industry 5.0 will be a 'synergy between humans and autonomous machines. A collaborative effort between humans and robots rather than a replacement effort helps ease worker anxiety, where they would be aware that their robotic coworkers would be able to understand them and possess the quality to collaborate with them (Abdoli and Djukic 2025).

Tóth et.al. (2023) introduces 15arc method and aims on integrating wearables for digitalization of user interaction and using devices which enable VR/AR. This framework, shown in Figure 2, addresses digital stakeholder collaboration culture to improve coordination between upper management and frontline workers, services for remote working and on demand learning which will improve the work life balance of workers (Tóth et.al. 2023). The 15arc method gives an exhaustive list of all that can be done to achieve industry 5.0, however a comprehensive implementation plan isn't provided. Although the reference mentions the need to train staff and an onboarding process, it does not describe a training plan. Furthermore, the financial implications aren't discussed given the fact that many SMEs may not be capable of applying such a heavy resource method of industry 5.0.

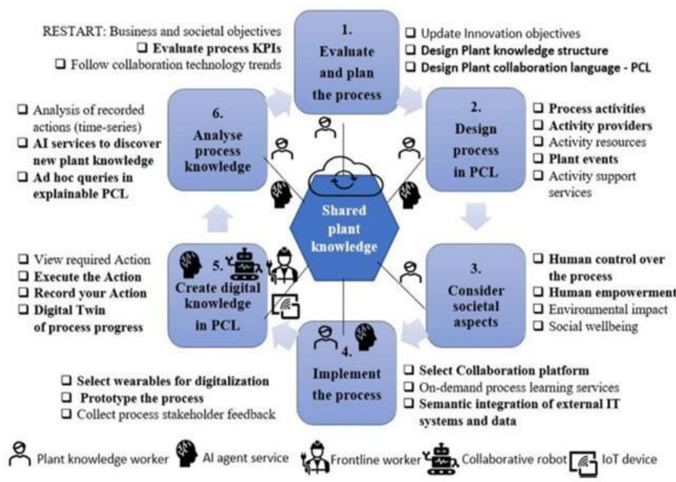

Figure 2. 15 arc Framework

Nazarejova et.al. (2024) describes that human sustainability can be achieved in multiple ways, including improving workplace safety and comfortability. The study suggests using sensors to survey worker wellbeing and establish ergonomic workspaces. Sensors can inform workflow designers to understand incorrect skeletal movements, over exertion or lifting heavy loads, to reduce short and long-term injuries. Working environment conditions such as temperature, air and sunlight can be monitored using IoT to understand the quality of workspace and make amends. Collected data from sensors can be analyzed by ML to prevent repetitive mistakes, reducing work repetition aiding for reduction of worker fatigue and improving productivity. Sensors can play the important role of being the safety component in preventing collisions between humans and robots and aid machines to adapt to a collaborative environment, studying worker patterns and anticipating their movements to make for effective collaboration. This gives perspective for managers to understand processes better and make necessary changes. However, that work does not discuss with more automation, the number of workers needed would be less and they would be redundant.

A cluster analysis in (Ivanov 2023) discusses the ways in which human centricity can be achieved and concludes that technologies such as artificial intelligence, human machine collaboration and cyber physical systems will play a major role in achieving human centricity with an emphasis on the need to establish collaboration, communication, identification, coordination, automation and data processing technologies.

Based on the discussed literature, this paper makes the first observation which that is advanced data analytics such as ML will play a major role in achieving human centricity in application of various industry4.0. Overall, technology remains at the forefront of achieving sustainability goals in context of industry 5.0.

3.3 Sustainable Digital transformation

Digital transformation refers to the adoption of new technologies to upgrade existing processes and improve competitiveness (Martínez-Peláez et.al. 2024) with some key features including customer centricity, digital maturity, robust IT infrastructure, vibrant organizational culture, and orientation to strategy. Martínez-Peláez et.al. (2024) concludes that existing research of digital transformation focused primarily on bigger corporations, leaving a research gap or framework for SMEs to achieve digital transformation. The study has focused on incorporating the following aspects in their sustainable digital transformation framework for SMEs:

- Economic dimension: the digital transformation framework must ensure economic dimension is met since it directly impacts the long-term survival of SMEs.
- Human dimension: the framework must investigate all round the wellbeing of people and prioritize continuous development within the organization and its ecosystem with a focus on adopting upskilling, individual growth and providing job satisfaction.
- Social dimension: the framework must have a broader community impact beyond the organization by promoting ethical practices, diversity and positively impacting social wellbeing
- Environmental dimension: the framework must aim to minimize ecological impression and push for the application of ecofriendly practices and technologies that support environmental sustainability goals such as science-based targets.
- Technological dimension: active innovation is expected from the framework where digital transformation contributes to the emergence of new technologies.

It is discussed that the cost of digital transformation for SMEs is higher compared to larger organizations. However such a transformation would make SMEs more resilient, which is a pillar of industry 5.0. To tackle the organizational inertia with respect to adoption of digital transformation and their hesitance to change, researchers suggest methods such as ‘overall planning’ and ‘local first’, which means that digital transformation must happen in staggard stages rather than all out rollout. The researchers suggest starting with sales and procurement which could help display visible benefits and increase their confidence in the process. The researchers acknowledge that certain possible holdbacks for digital transformation for SMEs include perceived short-term failure, skepticism within organizations employees, and the irregular investments in the digital transformation sector could inhibit progress. The framework suggested by Martínez-Peláez et.al. (2024) for sustainable digital transformation is shown in Figure 3.

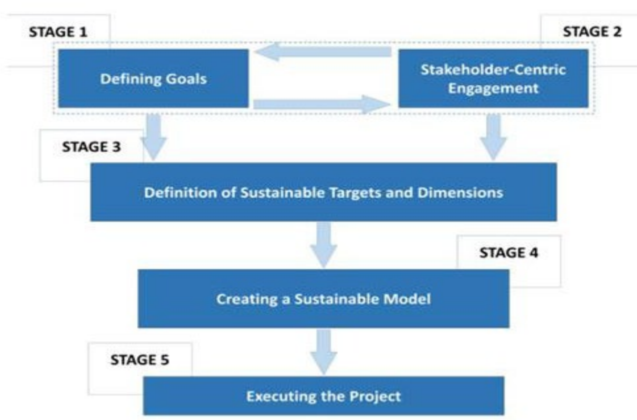

Figure 3. Framework for sustainable digital transformation from (Martínez-Peláez et.al. 2024)

The first step is to define the goal by the managements aligned with organizational culture and vision. Secondly stakeholders must be given a central stage, and the transformation must be purposeful to be successful. The third stage is defining sustainable targets and dimensions. The key point is to set achievable and local goals first as well as develop a long-term vision to make sure the transformation goes through smoothly. The fourth stage is making sure all previously mentioned dimensions are either directly or indirectly being benefitted from the model, and lastly is execution of the project. However, such framework is based on management-to-management level of decision making. If management can't make the right decisions, then the implementation would be unsuccessful or incomplete. Secondly the framework seems to ignore the feedback loop which would make the process continuously improve, ad part of successful digital transformation. A second shortcoming could be the generalist view taken in using advanced technologies, hence more specific research can go into studying the viable technologies that can be used to achieve sustainable digital transformation for SMEs in specific sectors.

The gaps discussed highlight a need for a long-term detail plan for implementation of digital transformation in SMEs.

3.4. Human Centric CPS

A key component of industry 5.0 application is the use of cyber physical systems or CPS. According to Kumar et.al., (2024). The implementation of a CPS seeks to promote workplace safety, better the services provided to customers, enhances the abilities of humans to interact and control the physical environment and would be essential to improve human and robot collaboration ecosystem. The researchers identify various challenges that have been created due to rapid digitalization of manufacturing ecosystems such as cyber security threats, safety in manufacturing systems, socio-technical challenges, improved work life balance, health management, lifelong learning, sustainability, human centricity, resilience demographic change etc. The listed issues need to be addressed by developing a human centric cyber physical system. The study proposed a QFD based approach which converts stakeholder or customer requirements into engineering characteristics by following the essential steps to establish a QFD matrix as shown in Figure 4. The proposed QFD matrix was successful in translating social requirements into engineering characteristics, which enables manufacturers to prioritize their resources in developing subsystems which will boost customer satisfaction and improve the quality of a human centric CPS. Customer satisfaction helps a firm achieve economic sustainability and makes the firm resilient, as two key components of industry 5.0. The research acknowledges certain drawbacks that exist in practicing such a system, one of them being the possibility of not being able to include all possible engineering and design criteria needed for establishing a human centric cyber physical production system. However, the research focuses on implementing economic sustainability, although it does acknowledge the need for human and environmental sustainability the methods mentioned do not seem to be of much importance. Secondly the research excludes the important section of 'what next' where we must study the implementation of CPPS and check what impact it would have on current workforce, what would be the necessary steps needed to align the workforce to such a system and what jobs would be impacted by the decided implementation and what steps are to be followed for the workforce, therefore the cause and effect relationship of such an implementation still remains as a research gap.

Quality function deployment matrix		Functional/design requirements of modular CPPS (How?)																		
		Physical world	Data acquisition system		Cyber world								Smart management system							
		Sensors, devices, & actuators	Communication protocol	Data storage & management	Analysis	Human models	Application Programming Interface	Cybersecurity	Human digital twin	Analytics	Hybrid human body modelling	Computing platform	Graphical user interface	Enterprise resource planning	Augmented reality	Autonomy/control	Voice-enabled assistants	Sequence planning	Assessment	Knowledge based system
CPPS requirements (What?)	Simplicity		●										▲							
	Affordability																			
	Data Security																			
	Didactics		Relationship matrix Strong - ▲(9), Moderate - ● (3)Weak- ■ (1)																	
	Transparency																			
	Waste management																			
	Resiliency																			
	Health management																			
	Human characteristics																			

Figure 4. QFD matrix made to formulate a human centric CPS, from (Kumar et.al., 2024)

An alternative for human centric CPS comes in the form of the 5C architecture according to researchers of (Lou et.al., 2024). The 5C architecture consists of 5 layers: connection, conversion, cyber, cognition and configuration. The process works by connecting lower layers of connection and conversion to machines, where they actively collect data and send it to intermediate layer of cyber and cognition where this data goes through advanced computing methodologies and aid in producing manufacturing execution systems and enterprise resource planning and the highest layer of configuration coordinates with other systems building a fortified system of systems. The framework of 5C can be applied to integrate human aspects of human in the loop and human on the loop or commonly known as HitL and HotL, to generate a human CPS. The paper discussed the 'data to information' or D2I which is an effective way to improve human working conditions by making workers wear wearable devices with sensors to monitor discomfort causing work and identifying solutions to existing workplace issues. However, the paper does not account for human cooperation for wearable devices, as many workers may be reluctant to wear devices due to being uncomfortable.

Another component suggested in (Turner and Oyekan 2023) to achieve sustainability goals of industry 5.0 is the use of life cycle assessment methods, as a study of the entire lifecycle of a product to analyze resources required for and the emission that occurs during products life from "cradle to grave". Concept of life cycle assessment can be a key factor in establishing circular economy, which is a change from the use and dispose model to reuse, repurpose, and recycle mentality wherever possible. Therefore, a complete lifecycle study enables the industry to anticipate the viability of circular economy components and planning the product lifecycle in such a way that it is viable.

3.5. SME 5.0 or Hybrid SMEs

The concept of SME 5.0 (Mohammadian et.al 2022) aims to make industry 4.0 transition to industry 5.0 aligned with SME characteristics. This works aims to check the readiness of SMEs to adapt to SME 5.0 methodologies and frameworks. The possible components of a framework for SME 5.0 application begins with IoT education and training the stakeholders and in adoption of SME5.0. The researchers then investigated the viability of cloud computing to support learning in SMEs, the technological revolution the organizations who had higher computing power saw more growth and profits, cloud computing would help organizations to store data and interact and collaborate with different departments better. The study also indicates that resource pooling can be established via the use of cloud computing.

Mohammadian et.al. (2022) introduced the concept of hybrid SMEs, where equal importance is given to business and corporate social responsibility. Role of government strategies is pivotal, with government schemes and subsidies to promote the adoption of technologies help small businesses reach their hybrid organization structure faster.

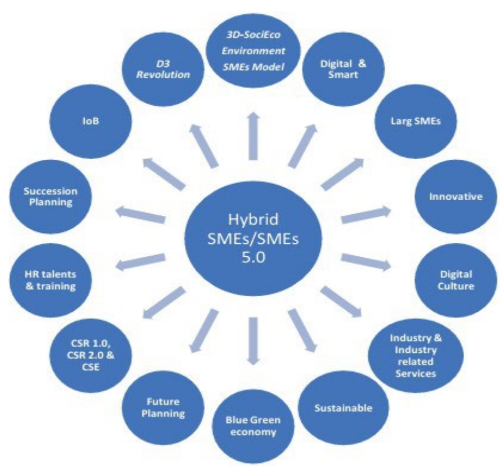

Figure 5. 14-point structure for hybrid SME, from (Mohammadian et.al. 2022)

Mohammadian et.al. (2022) comes up with a list of various components for hybrid SME as shown in Figure 5. However, this work relies on micro financing and government grants for implementation and removal of barrier of financial investment, which might be impossible for countries where governments have other priorities such as social wellbeing, where industries are yet to see the full potential of the second or third industrial revolution. The application seems to incorporate the software components of industry 4.0 technology only. Although the idea of continuous learning through IoT tools is considered, another drawback would be the lack of worker migration techniques.

4. Answer to Research Question

The tables presented in this section are the outcome of a structured and critical literature review, as detailed in Sections 2 and 3. The review included over 30 peer-reviewed studies that were thematically analyzed and categorized using criteria aligned with the objectives of Industry 5.0: human-centricity, environmental sustainability, and resilience. The barriers and enabling technologies identified here are not simply listed but are the result of comparative synthesis across studies. Each element in the tables was chosen based on its frequency in literature, cross-study relevance, and contribution to the implementation of Industry 4.0 technologies in SMEs. This synthesis constitutes a major contribution to the field, offering a consolidated evidence base that maps key challenges and actionable enablers for SMEs transitioning towards Industry 5.0. To our knowledge, such a rating-based, literature-grounded classification and re-clustering of barriers and technological enablers has not been previously presented with this level of integration and practical relevance.

To answer the research question, we identified key barriers from the literature and rated them on a scale from 1 to 5, where 1 indicates minimal difficulty and impact, and 5 represents significant difficulty and wide-ranging impact. The ratings were based on the frequency and emphasis of each barrier across the reviewed studies. Our approach was that barriers that appeared frequently or were identified as root causes of other challenges were assigned higher scores, as addressing these would likely mitigate multiple related issues. Table 1 demonstrates the evaluation of Industry 4.0 technologies based on their contribution to Industry 5.0 goals as human-centricity, sustainability, resilience.

Table 1. Evaluation of Industry 4.0 technologies based on their contribution to Industry 5.0 goals

Barrier	Score	Explanation
Lack of economic resources	5	SME's have lesser Free Cash Flow compared to larger firms to implement new technologies
Impact on workforce	5	I5.0's goal is human centric hence the impact on workforce must be on top priority
Need for tangible short-term benefits	2.5	SMEs due to their poor Free Cash Flow need to see tangible benefits in short run to apply new methodologies and justify investments
Lack of training or implementation frameworks	4	Current methods have not included SMEs and their challenges when it comes to I4.0 &5.0 implementation
Negative outlook towards change	3	Management in SMEs usually might resist to change as they fear losing out existing revenues and market share which is a big challenge in implementing I4.0 and 5.0
Lack of enabling infrastructure	5	Facilities such as high speed and stable internet connection, constant electricity supply, data centers, are needed for the implementation of I5.0 & 4.0.
Threat to data security	4	Cyber threats to businesses are a reason for the reluctance to switch over to digital tech by many companies.
Skilled labor shortage	2	In the short run the lack of skill labor impact implementation, but this can be mitigated with proper training therefore not a long-term threat.
Low degree of standardization	2	A general implementation framework for I4.0 &5.0 implementation does not exist. Firms are confused about what standard their machinery are set; data collection and analysis techniques need to be achieved to I4.0&5.0
Lack of understanding of system architecture	1	lack of training and standardization leads to poor understanding of systems which would be needed to establish I4.0
Disregarding the importance of I4.0	3	Failing to highlight the importance of I4.0 due to poor standardization and awareness is discouraging businesses to move to I4.0
Lack of vision	3	Stems from lack of short-term gains, management view, no standardization, and disregard for I4.0
Challenges in value chain integration	4	Products/services involve a series of stakeholders. Having them on board with digital transformation is necessary, which each might have their own barriers to adopt to I4&I5.
Lack of digital skills	2	Basic digital skills can be a challenge in many regions
Disruption to existing jobs	5	Digital transformation may lead to loss of jobs; the goal is to reduce the number of jobs loss to a minimum via training and upskilling.

Lack of digital strategy along with resource scarcity	3	Lack of positive outlook towards digitization stemming from underlying issues such as cyber security
Data management related challenges	4	Lack of data management infrastructure such as data centers and lack of understanding and sorting of data means that implementing I4.0 would not work.
Possible job polarization	5	With the need to upskill, many older employees may not be able to catch on with the needed requirements and feel putting their jobs at risk
Wearable technologies might be uncomfortable	3	Although a great way to source real time data, making workers wear sensors and smart glasses could lead to ergonomic discomfort to them and possible work hazard if not designed and tested properly
Concerns with cyber security/safety of workers wearing wearable tech	2	These techs post threat to worker privacy and firm privacy as believed majorly in many polls conducted
Increased offshoring of work	3	A problem in first world countries causing domestic job market disruption, companies opting to offshore their work to take advantage of cheaper job market.
Data related issues	3	Collection, storage and analysis of data requires the use of energy, which is expensive economically and environmentally. Use of conventional energy resources pushes firms away from achieving I5.0 commitment to sustainability and due to the high cost might be impossible for smaller firms
Lack of homogeneity of remote devices	2	Many different devices are used to manage the same process, but lack of common User Interface may complicate their management.
Heightened use of electricity	1	If clean energy isn't used, it pushes back the sustainability goals of I5.0
Low technology standardization	1	The firms currently push clients to buy all technology from a single firm to ease up their UI experience which makes it costly
Lack of universal AI models	2	AI models are usually task specific making them expensive and 1themed, if universal models are generated which target multiple problems it'll be better
Humans lack trust in technology	3	The mindset of humans makes them not trust decisions taken by AI or ML models

We can reclassify these problems on the core barriers to implementation

1- Lack of training and implementation methods – this leads to a) Skilled labor shortage, b) Lack of trust on decisions taken by technology, c) Disruption to existing jobs, d) Lack of digital skills, e) Lack of understanding of system architecture.
2- Lack of economic resources- this leads to a) Data collection storage and analysis concerns, b) Lack of enabling infrastructure, c) Need for short term tangible benefits of implementation
3- Negative management outlook towards change and innovation- this leads to a) disregarding importance of industry 4.0 implementation, b) prevalence of short-sighted vision c) Lack of digital strategy along with resource scarcity
4- Low degree of standardization- this leads to a) Lack of universal AI models, b) Low technology standardization, c) Lack of homogeneity of remote devices.

The above 4 barriers and their related challenges add up to almost 67% of the total, therefore these 4 major issues are to be addressed as priority.

Based on the literature reviews, we rank the impact of industry 4.0 technologies on achieving human centricity, sustainability and resilience, as industry 5.0 goals. In this ranking, 1 means the least and 5 being the highest impact. Table 2. demonstrates comparative evaluation of Industry 4.0 technologies based on their contribution to Industry 5.0 goals.

Table 2. Comparative Evaluation of Industry 4.0 Technologies Based on Their Contribution to Industry 5.0 Goals

I4.0 technology/ method	Scoring	Explanation
Retrofitting and smart sensors	5	Retrofitting is the practice of installing data collection tools such as sensors on older generation machines to make them modernized and in line with new generation machines, thus helping achieve modernization in a sustainable and resilient way.
Cloud computing	3	Cloud computing practices would essentially play a big role in the human aspect of transition to I5.0. E-learning can play a major role in aiding labor upskilling and transitioning to human machine collaborated work.
AI	4	Use of AI directly impacts human centricity by reducing the workload of humans as AI can take care of repetitive tasks allowing humans to be creative.
Big data	5	Big data currently plays a big role in transitioning towards a digital economy and an information society which contributors to I5.0 implementation
Blockchain	3	Blockchain aids in achieving the resilience criteria of I5.0 as an effective way of transactions as seen in crypto currencies and safeguarding inter and intra company communication, even EU have undertaken an initiative to use its tamper proof properties in achieving resilience goals.
IoT	5	IoT is an enabling and supporting technology which aids all other functions hence an important technology in achieving I5.0
Cyber physical production systems	5	CPS can be considered an integrator of various I4.0 technology, CPS plays an important support role in an I4.0 framework, by helping to digitize physical systems thus impacting human centricity, sustainability and resilience of manufacturing systems.
Additive manufacturing	2	Additive manufacturing supports sustainability criteria of I5.0 by minimizing waste during manufacturing. Since it's relatively less standardized and yet to be a part of conventional manufacturing due to its slow speed of manufacturing it's still got a lot of unexplored potential.
ML	5	Application of ML can be used in achieving all three I5.0 goals. By applying ML, we can analyse data corresponding to each branch of manufacturing to find optimized methods which make a manufacturing process human centric by reducing workload, sustainable by eliminating waste and resilient by predicting threats to disruptions before they occur. Although ML needs robust data collection, it's a codependent technique.
Robotics and automation	3	Robotics and automation aid in making manufacturing safer for humans as tedious and repetitive tasks, they also make processes more efficient hence environmentally sustainable.
Digital twin	4	Digital twin has been widely applied virtual experimentation which has helped in optimizing and controlling of processes, this aids in achieving sustainability and human centricity goals as digital twin analysis can help process designs factor in ergonomics too.
RFID	2	Use of RFID aids in better inventory control from raw material to finished goods, helps build a resilient supply chain.
5G/6G	5	A fast reliable internet connection is paramount need for majority I5.0 technologies hence important.
Edge computing	4	Edge computing refers to the computational and networking operations carried out by IoT devices at the network's periphery while communicating with the distant cloud. Edge computing plays a crucial role in I5.0 by enabling the implementation of AI algorithms and models directly at the edge. This helps quicker processing of data and hence reducing energy consumption
Energy harvesting	2	Energy harvesting helps firms achieve their sustainability goals and achieving I5.0 transition in that aspect

Quantum computing	2	Quantum computing being another supportive function, helps in boosting security of conventional systems boosting their resistance to cyber attacks
IoS	3	Internet services (IoS) is a key component in service based remote working that has taken center stage over the recent years, the infrastructure of IoS supports remote working opportunities, which are human centric to promote better work life balance
Computer vision	3	Technology revolves around acquiring and analyzing data with the help of cameras and computers. Computer vision can help in assisting operators as in various ways including their safety and reducing the defects and consequently waste, hence improving sustainability
AR/VR	3	These function as supporting technologies for various wearables devices, this can be used in understanding processes better thereby

5. Conclusion

We have identified key insights that hold significant implications for both researchers and practitioners working toward Industry 5.0 implementation in SMEs. Our structured ranking of barriers helps differentiate between surface-level challenges and deeper root causes. For example, issues such as digital skill shortages and resistance to AI adoption are closely linked to broader problems like lack of training and limited economic resources. By grouping these into four core categories, we provide a clearer view of the leverage points that policymakers and SME support programs should prioritize.

Our evaluation of enabling technologies also offers practical guidance. While much of the existing literature provides qualitative insights, our impact-based scoring highlights which technologies align most strongly with Industry 5.0 objectives—human-centricity, sustainability, and resilience—and which are more feasible for SMEs to adopt. Retrofitting and machine learning, for instance, stood out as high impact yet accessible starting points for transformation.

Importantly, this study bridges the gap between high-level Industry 5.0 frameworks and the practical realities of SMEs, which are often constrained by financial, technical, and organizational limitations. While many transformation frameworks paint idealistic scenarios, our work grounds the discussion in literature-based evidence and realistic priorities.

Ultimately, we argue that progress toward Industry 5.0 does not require a perfect or complete overhaul. Even incremental changes, whether through software tools, retrofitting, or targeted upskilling, can move SMEs in the right direction. But to achieve a truly inclusive and resilient industrial future, there is an urgent need for affordable, adaptable frameworks that reflect the diverse contexts of SMEs. Future research should continue to address these gaps and refine actionable pathways that support SMEs in this critical transition.

References

Abdoli, S. and Djukic, L., Industry 4.0 in Labor Intensive Industries, Opportunities and Challenges. Procedia CIRP, 136, pp.201-206. 2025

Abdoli, S., "Experimentable digital twin for virtual validation of manufacturing systems." In Proceedings of the 2023 10th international conference on industrial engineering and applications, pp. 91-97. 2023

Abdoli, S., A framework for analysing the environmental impact and support decision making in sustainable development context. Environment Systems and Decisions, 43(2), pp.281-297. 2023

Abdoli, S., Kara, S., and Hauschild, M., Green paradox and the role of life cycle engineering. Procedia CIRP, 90, 159-164. 2020

Breque, M., De Nul, L. and Petridis, A., Industry 5.0: towards a sustainable, human-centric and resilient European industry. Luxembourg, LU: European Commission, Directorate-General for Research and Innovation, 46. 2021

Cagliano, R., et al., The interplay between smart manufacturing technologies and work organization: the role of technological complexity. International Journal of Operations Production Management, 39(6/7/8): p. 913-934. 2019

de Mendonça Santos, A., & Sant'Anna, Â. M. O., Industry 4.0 technologies for sustainability within small and medium enterprises: A systematic literature review and future directions. Journal of Cleaner Production, 143023. 2024 de Sousa Jabbour, A.B.L., Ndubisi, N.O. and Seles, B.M.R.P., Sustainable development in Asian manufacturing SMEs: Progress and directions. International Journal of Production Economics, 225, p.107567. 2020

Garetti, M. and Taisch, M., Sustainable manufacturing: trends and research challenges. Production planning & control, 23(2-3), pp.83-104. 2012

Golovianko, M., Terziyan, V., Branytskyi, V. and Malyk, D., Industry 4.0 vs. Industry 5.0: Co-existence, transition, or a hybrid. Procedia Computer Science, 217, pp.102-113. 2023

Grosse, E.H., et al., Human-centric production and logistics system design and management: transitioning from Industry 4.0 to Industry 5.0. International Journal of Production Research, 61(22):p.7749-7759. 2023.

Ivanov, D., The Industry 5.0 framework: viability-based integration of the resilience, sustainability, and human-centricity perspectives. International Journal of Production Research, 61(5), pp.1683-1695. 2023

Javaid, M., Haleem, A., Singh, R.P., Khan, S. and Suman, R., Sustainability 4.0 and its applications in the field of manufacturing. Internet of Things and Cyber-Physical Systems, 2, pp.82-90. 2022

Ji, X. and Abdoli, S., Challenges and opportunities in product life cycle management in the context of industry 4.0. Procedia CIRP, 119, pp.29-34. 2023

Kumar, R., Sangwan, K.S., Herrmann, C. and Bera, T.C., Development of a Human Centric Cyber Physical Production System Framework for Enhanced Social Sustainability. Procedia CIRP, 122, pp.581-586. 2024

Leng, J., et al., Industry 5.0: Prospect and retrospect. Journal of Manufacturing Systems, 65: p. 279-295. 2022

Lou, S., Hu, Z., Zhang, Y., Feng, Y., Zhou, M. and Lv, C., Human-cyber-physical system for Industry 5.0: A review from a human-centric perspective. IEEE Transactions on Automation Science and Engineering, 22, pp.494-511. 2024

Lu, Y., et al., Outlook on human-centric manufacturing towards Industry 5.0. Journal of Manufacturing Systems, 62: p. 612-627. 2022

Malaibari, M., Siddiqui, M., Xie, S., Bahramimianrood, B., Abdoli, S. and Djukic, L., Digital Twin as A New Approach to Data Management: A Review. Procedia CIRP, 128, pp.375-380. 2024

Martínez-Peláez, R., Escobar, M.A., Félix, V.G., Ostos, R., Parra-Michel, J., García, V., Ochoa-Brust, A., Velarde-Alvarado, P., Félix, R.A., Olivares-Bautista, S. and Flores, V., Sustainable digital transformation for SMEs: A comprehensive framework for informed decision-making. Sustainability, 16(11), p.4447. 2024

Mohammadian, H.D., Bakhtiari, A.K., Castro, M., Wittberg, V. and Brüggemann, T., March. The development of a readiness assessment framework for tomorrow's SMEs/SME 5.0 for adopting the educational components of future of I4. 0. In 2022 IEEE Global Engineering Education Conference (EDUCON) (pp. 1699-1708). IEEE. 2022

Nahavandi, S., Industry 5.0—A human-centric solution. Sustainability, 11(16), p.4371. 2019

Nazarejova, J., Soltysova, Z. and Rudeichuk, T., Requirements and Barriers for Human-Centered SMEs. Sensors, 24(14), p.4681. 2024

Oláh, J., Aburumman, N., Popp, J., Khan, M.A., Haddad, H. and Kitukutha, N., Impact of Industry 4.0 on environmental sustainability. Sustainability, 12(11), p.4674. 2020

Prasanna, R.P.I.R., Jayasundara, J.M.S.B., Naradda Gamage, S.K., Ekanayake, E.M.S., Rajapakshe, P.S.K. and Abeyrathne, G.A.K.N.J., Sustainability of SMEs in the competition: A systemic review on technological challenges and SME performance. Journal of Open Innovation: Technology, Market, and Complexity, 5(4), p.100. 2019

Puniani, B. and Abdoli, S., Development of Capability for Integrated Smart Production-Spare Part Warehouse System for SMEs in Fast-Moving Consumer Goods sector. Procedia CIRP, 136, pp.159-164. 2025

Stock, T. and Seliger, G., Opportunities of sustainable manufacturing in industry 4.0. procedia CIRP, 40, pp.536-541. 2016

Tóth, A., Nagy, L., Kennedy, R., Bohuš, B., Abonyi, J. and Ruppert, T., The human-centric Industry 5.0 collaboration architecture. MethodsX, 11, pp.102260. 2023

Turner, C. and Oyekan, J., Manufacturing in the age of human-centric and sustainable industry 5.0: application to holonic, flexible, reconfigurable and smart manufacturing systems. Sustainability, 15(13), p.10169. 2023

Vongchaisaree, R. and Abdoli, S., August. A Human Digital Twin Approach to Physical Hazard Management in the Manufacturing Environment: An Extensive Literature Review with a Conceptual Framework. In IFIP International Conference on Advances in Production Management Systems (pp. 498-512). Cham: Springer Nature Switzerland. 2025

Xie, S., Bahramimianrood, B., Malaibari, M., Abdoli, S. and Dietrich, F., 2024. Navigating Complexities In Closed-Loop Supply Chains: A Review Of Objectives, Uncertainties And Decision Variables. ESSN: 2701-6277, pp.753-765. 2024.

