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Advancing industrial sustainability in Pakistani smaller enterprises via industry 4.0: Awareness, challenges, and strategic readiness

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ABSTRACT

The literature on Industry 4.0 adoption has predominantly focused on large enterprises in developed economies, with limited empirical evidence from small and medium enterprises (SMEs) in developing economies, where organizational preparedness and resource constraints hinder technology incorporation. This study investigates the role of awareness, challenges, perceived benefits, and readiness in the adoption of Industry 4.0 technologies and their contribution to industrial sustainability among manufacturing SMEs in Pakistan. The objectives are to assess the relative influence of these factors on adoption status and to provide strategic recommendations for enhancing sustainable production and competitiveness. A descriptive cross-sectional research design was employed, and data were collected through an online survey of 200 SME managers in the manufacturing sector. Correlation and regression analyses were conducted using IBM SPSS to examine relationships between variables. The results indicate that awareness and understanding significantly influence the adoption of Industry 4.0, whereas challenges and perceived benefits show lower direct effects on adoption. The overall regression model explains 49.1% of the variance in adoption status, highlighting awareness as the primary driver. The findings emphasize the potential of Industry 4.0 to improve operational efficiency, optimize resource utilization, and support sustainable manufacturing in SMEs. The study offers actionable insights for policymakers and stakeholders by identifying low-cost, high-impact interventions such as targeted awareness campaigns, capacity building, and institutional support systems to accelerate digital transformation in developing economies.

Contribution/Originality: This paper examines Industry 4.0 adoption among manufacturing SMEs in Pakistan and highlights awareness as the primary driver of sustainable digital transformation. It advances understanding of technology adoption in resource-constrained contexts and provides empirical evidence and policy-relevant insights to accelerate sustainable industrial development in developing economies.

1. INTRODUCTION

Industry 4.0 is a transition toward digitally integrated and intelligent systems of production that allow real-time data exchange and decentralised decision-making (Xu, Lu, Vogel-Heuser, & Wang, 2021). The future of manufacturing is greatly challenged by mega-trends like shifting demographics, globalisation, shortage of resources, climate change, and the demand to manufacture (Feng, 2023). Such developments create uncertain, complex, volatile, and ambiguous environments of companies that affect their strategic situation (BasuMallick, 2024). Different efforts are highlighting the importance of high-technology manufacturing plans to address such issues and facilitate economic development (NSFAM, 2022). Almost 90 per cent of businesses in Pakistan are included in the SME sector, as it offers jobs to 80 per cent of the population and generates 40 per cent of the GDP (Qalati, Yuan, Khan, & Anwar, 2021). Almost 90 per cent of the business in Pakistan is made up of SMEs, offering 80 per cent of the labour force and contributing 40 per cent of the GDP (Bayraktar & Algan, 2019).

They are directly related to the economy, but they are confronted with a plethora of issues related to introducing Industry 4.0 technologies, which include automation, data sharing, and intelligent production (Iqbal & Ahmad, 2021). The manufacturing system made up of the small and medium-sized businesses will be adaptable to adopt newer technologies and shift to niche markets, but the large-scale corporations will be more effective in scale efficiencies, but lack the ability to adapt to newer technologies. Thus, it is required to research the difficulties in information technology implementation with regard to the concept of Industry 4.0 among small and medium-sized enterprises to hasten the proliferation of modern manufacturing (Prause, 2019). Industry 4.0 transforms the architectures of manufacturing by decentralising the control systems, instead of monolithic and centralised operations, to modular and self-regulating, digitally integrated networks spanning organisational boundaries. It supports responsive process control via agile product innovation through pervasive intelligent sensor-actuator systems (Ali, 2024). Bibliometric records of more than ten years confirm that smart manufacturing is a global developing area of priority, with the trends on automation, digitisation, and connectivity in SMEs. This strategy promotes context-related production and incorporation of the ICT-based processes in the value chain, network, and product lifecycle (Vaidya, Ambad, & Bhosle, 2018).

Industry 4.0 is one of the biggest challenges to businesses and, more so, the SMEs. Some SMEs are partly ready to implement the Industry 4.0 concept, though most of them are hindered by organisational and technical barriers. The bigger SMEs stand a higher risk of not capitalising on this revolution. The European SMEs can be identified as conscious of their lack of adaptation, the necessity to conduct further research, and can be tailored to not just raise their technical and organisational readiness (Grufman, Lyons, & Sneiders, 2020). Although there is an increasing trend towards Industry 4.0 around the world, the empirical data concerning its adoption by SMEs in the developing economy is scarce, especially in terms of the sustainability of the industrial performance (Jamwal, Palit, Kumari, Agrawal, & Sharma, 2026). The current literature has mostly concentrated on large organizations or developed economies, and in most cases, ignores the importance of awareness, organisational preparedness, and supportive strategies used in influencing adoption by the SME (Singhal, 2021). Besides, the existing studies in the Pakistani setting have focused more on the technological barriers individually, and have not incorporated the sustainability factors into the systems of adoption (Jamil, Zhang, Anwar, & Mustafa, 2025).

To fill this gap, the current research explores the topics of Industry 4.0 adoption among Pakistani SMEs through the prism of roles, problems, benefits, and preparation. This study, by associating Industry 4.0 implementation with industrial sustainability, provides novel empirical ideas and policy-based suggestions that help SMEs to digitize in developing economies. The existing literature underlines the strategic character of the connection between Industry 4.0 technologies and eco-friendly governance systems to ensure sustainability in the development of industries in developing economies.

The proposed study aims to contribute to the existing literature by considering specific features of Industry 4.0 information technologies and related issues, which require joint efforts and the introduction of variables such as the

role of government, financial support, infrastructure development, the establishment of incentives to acquire new skills, and the creation of an innovative culture. Industry 4.0 technologies can address these challenges, leading to successful implementation in SMEs in Pakistan. This will enhance productivity, competitiveness, and industry expansion in the global market.

2. LITERATURE REVIEW

2.1. Importance of Small and Medium Enterprises (SMEs)

By introducing economic growth and development, helping to reduce social poverty, and developing material and human resources effectively in the society where they engage with the formal economy, SMEs are effective (Maksum, Rahayu, & Kusumawardhani, 2020). Small and medium-sized firms (SMEs) are viewed as the predominant business organization subdivision across the world (Prasanna et al., 2019). The world has undergone great shocks that have affected small and medium-sized businesses (SMEs) and entrepreneurs (Erdiaw-Kwasie, Abunyewah, Yusif, & Arhin, 2023). The growing geopolitical tension, fluctuating effective monetary balance, rising inflation, and the tightening of monetary policy, through which we can analyze the mechanisms, instruments, rising trade obstacles, and the slowing pace at which the world is integrated in global value chains, are redefining the world economy. The OECD SMEs and Entrepreneurship offer greenfield-breaking evidence on the performance of SMEs, the evolving business environment, and policy implications. It puts further emphasis on SME integration into international networks, businesses that are led by women, and networks within knowledge and innovation (OECD SME, 2023).

SMEs have a critical strategic role in many emerging nations, most of which are in Asia. SMEs account for 99.7% of firms in Japan, 71% of employment, and 55.3% of GDP (Arshad et al., 2020). SMEs form 97 percent of businesses, 65 percent of jobs, and 36 percent of GDP in Malaysia. In Indonesia, the conformance rates are 99.8, 99.7, and 57 percent (Arshad et al., 2020). SMEs ownership constitutes 99 percent of total business setups, 70 percent of employment, and 60 percent of GDP in China (Motilewa, Ogbari, & Aka, 2015). The SMEs (90 percent of all businesses) in Pakistan contribute 40 percent of GDP, 35 percent of manufacturing output, and 30 percent of all product exports made by the manufacturers (SMEDA, 2023). Such businesses are vital to long-term economic development and provide more than 78 percent of the non-agricultural labour force. They also hire 90 percent of the companies in the industrial sector privately. SMEs provide 36 percent value addition of manufactured goods, 40 percent of the GDP, and 30 percent of manufactured goods exports, which necessitates the need to conduct more studies to establish the challenges that lead to distress (Arshad et al., 2020).

2.2. SME's Contributions to Pakistan's Economy

The SMEs have a record of significantly contributing to the growth of the industrial sector in Pakistan. The SMEDA report shows that in Pakistan, SMEs play a huge role in the economy and form 99 percent of the total number of business units, as well as have a 40 percent contribution in the national GDP. SMEs also create employment, which contributes 78 percent to the labor force, according to the position, which puts Pakistan above the South Asian average. However, SMEs need help accessing adequate financial resources, which affects their overall performance and growth potential in Sindh province (SMEDA, 2023). SMEs' contributions to Pakistan's economy include the creation of jobs, the Utilization of local resources, the Promotion of entrepreneurship, the Preservation of foreign exchange, the equitable allocation of earnings and assets, formation of capital. Small and Medium Enterprises (SMEs) play a crucial role in reducing unemployment rates by providing job opportunities for citizens in rural, semi-urban, and metropolitan regions, thus enhancing their way of life and contributing to the overall community (SMEDA, 2023; Zafar & Mustafa, 2017).

Small and medium enterprise sectors do not involve mass manufacturing but are engaged in the production of basic consumer goods by using local raw material, and both the food and beverage industry and the textile industry have a strong dependence on local resources (Karmaker, Al Aziz, Palit, & Bari, 2023). Due to the ease of working on

a small to medium scale with little funds and effort, the rise of SMEs has enabled the emergence of entrepreneurship to be important in the fact that the sector has inadequate production, therefore saving foreign exchange by displacing imports (Zafar, Waqas, & Butt, 2018). The lack of production has exacerbated the problem of exports, which, by saving forex through the reduction of imports, has preserved foreign exchange. But the products of SMEs can be considered substitutes for commodities that might have involved a substantial expense of foreign currency (Dey et al., 2022). The high rate of SMEs development has led to a fall in imports of some items, where people's production of the item is also on the rise (Surya et al., 2021). SMEs are a widespread phenomenon in the economy, with various types of businesses in every region (Surya et al., 2021). They share government resources and incentives, such as the establishment of small-scale industrial centers in each federation's states. This growth potential ensures a fair distribution of wealth and income to many, promoting economic growth and development (Henschel & Heinze, 2025).

SMEs are crucial providers of personal funds for productive uses and capital formation, using locally accessible raw materials and investing minimally in infrastructure. They can also generate foreign currency by creating goods for domestic and export markets. Pakistan's SMEs significantly contribute to GDP growth and national economy expansion, creating employment and driving economic growth. Nonetheless, the performance of Pakistan should be enhanced to reach its full potential, as the efficiency of SMEs is still low despite the fact (Manzoor, Wei, & Siraj, 2021). Pakistan is lagging behind its regional colleagues in terms of SME digital transformation. Although the ICT policies of Bangladesh have ensured that more SMEs adopt technology, and the MSME sector of India is estimated to inject a billion dollars via digitalization, the SMEs of Pakistan still have hurdles in terms of funding and infrastructure that hinder their competitiveness in the region.

2.3. Industry 4.0: Fourth Industrial Revolution

The fourth industrial revolution has significantly impacted the manufacturing sector, leading to great production (McKinsey & Company, 2022). To improve German manufacturing industry productivity, a group consisting of business politicians and academic specialists developed the term "Industry 4.0" as the fourth industrial revolution in 2011 (Kagermann, Wahlster, & Helbig, 2013; Phuyal, Bista, & Bista, 2020). Industry 4.0 is a technological advancement that integrates IoT and machine learning, focusing on real-time data analysis and integrating manufacturing systems. It includes artificial intelligence, automated robotics, flexible automation, additive manufacturing, and augmented reality, enabling informed decision-making and machine interaction (Zhang & Yang, 2020).

The first industrial revolution started in the 1800s to improve the quality of life with the mechanism and mechanical power generation. It was the transition from manual work to the manufacturing process. The second industrial revolution was aimed at electrification, which enabled industrialization and mass production in the 1900s. The third industrial revolution targeted the digitalization and introduced microelectronics and automation for flexible production in the 1960s. Now that the revolution is no longer concerned about flexible production. Currently, the fourth industrial revolution, known as Industry 4.0, targets smart innovations for information and communication technologies (ICT), cyber-physical systems, and the Internet of Things (IoT) functionalities. This appreciation of hierarchical development also presents flexibility of mass custom production and production quantity (Rojko, 2017).

2.4. Industry 4.0 Components for SMEs

Industry 4.0 is a broad term that covers different ideas and fields within the business industry. It represents rapidly progressing technological innovations, including big data, cyber-physical systems (CPS), the Internet of Things (IoT), interoperability, and intelligent manufacturing (Javaid, Haleem, Singh, & Suman, 2023; Suleiman, Shaikholla, Dikhanbayeva, Shehab, & Turkyilmaz, 2022). The advancement of technology highlights how technological advances may lead to an evolutionary change in production. Different manufacturing firms are in need of becoming independent of labor costs, especially in countries with high costs, by integrating new technologies,

which can be linked to Industry 4.0 (Strandhagen, Vallandingham, Alfnes, & Strandhagen, 2018). Industry 4.0 enhances the automation and information transfer among various industrial technologies, such as cloud computing, cyber-physical systems, cognitive computing, and the Internet of Things (Javaid et al., 2023).

The recent achievements of IoT-based sensor technologies, which have been discussed in the context of environmental and aquaculture applications, indicate the opportunities of real-time monitoring and adaptive control, which are essential prerequisites of smart manufacturing in SMEs (Ali et al., 2026). Industry 4.0 includes the utilization of digital technologies to gather, examine, and utilize enormous quantities of data, and the elements of big data (BD) play a vital role in enhancing performance. It is thought that the analytical way of handling big data helps in making informed decisions that consider the market trends and operational efficiencies, process optimization, and digital transformation (Müller, 2020; Sorger, Ralph, Hartl, Woschank, & Stockinger, 2021).

Table 1 presents the core technologies underlying Industry 4.0, outlining their definitions and highlighting their roles in supporting digital integration, automation, and data-driven manufacturing processes.

Table 1. Depicts the basic technologies used in IR 4.0. (Yang & Gu, 2021).

Terms	Explanation
Cyber-physical system (CPS)	The integration of physical processes with computational systems enables real-time monitoring and control.
Internet of Things (IoT)	A network of interconnected devices that communicate and share data through the internet.
Interoperability	The ability of different systems, devices, or applications to work together and exchange information seamlessly.
Intelligent manufacturing	Advanced manufacturing processes that leverage AI, automation, and real-time data for optimized production.
Technological advances	Innovation an improvement in technology that ensures efficiency, functionality, and capabilities.
Cognitive computing	Simulation of human thought processes in a computerized model using AI, Machine learning, and natural language.
Big data	Extremely large datasets are analyzed computationally to uncover patterns, trends, and insights.

Big data refers to various techniques used to manage vast amounts of data, including unstructured and structured data collection, transport, storage, analysis, curating, search, privacy, and visualization (Iqbal & Nawaz, 2021). Big data in SMEs is useful in predicting market trends, matching the choice with the purpose, and reducing the financial risks of fraudulent actions. It allows taking the initiative in managing risks and being agile and responsive to market forces (Adewusi et al., 2024).

It may be seen in the Industry 4.0 development that big data analytics contributes to the sustainability and competitiveness of small and medium-sized enterprises. However, these enterprises are not characterized by the use of big data technology, and the lack of resources and infrastructure is not a well-studied problem. There is insufficient expertise on the advantages of big data analytics among the entrepreneurs, financial limitations, and unskilled workers who can carry out strategic administration are the primary issues of applying big data analytics to small and medium-sized corporations (Udeh, Orieno, Daraojimba, Ndubuisi, & Oriekhoe, 2024). A study shows that Big Data has significant potential for SMEs, creating real-time solutions to industry challenges through open decision-making. SMEs are chosen due to their economic position and flexibility for efficiency adaptation. However, contentious issues like storage, processing capabilities, security, and privacy remain. This article proposes future research on Big Data for SMEs, addressing potential and threats, and recommends practices for capturing its full potential (Sen, Ozturk, & Vayvay, 2016).

A cyber-physical system is one in which people interact using various new models to combine their computer and physical skills. Future technological advancements are driven by the human ability to engage and extend the capabilities of the natural environment through computing and communication (Hamzah et al., 2023). The major

software to connect the physical process system is IoT. Self-learning models are expected to take control of the system as intelligent systems that monitor the system (An, Tao, Xu, El Mansori, & Chen, 2020). Interoperability refers to the ability of people, cyber-physical networks, and smart factories to communicate via the Internet of Things (IoT), enabling high-quality information exchange among stakeholders and forming the basis for error-free translation and transmission (Yang, Kumara, Bukkapatnam, & Tsung, 2019).

Small and Medium Enterprises (SMEs) are facing major challenges and opportunities in deploying Industry 4.0 technologies (Grooss, Presser, & Tambo, 2022). Although a large company might be resourceful enough to seamlessly analyze these sophisticated technologies, SMEs may often face monetary barriers and the necessity of special knowledge. Irrespective of these challenges, Industry 4.0 is becoming a prerequisite for SMEs to survive within a fast-growing and emerging market (Khan et al., 2025). The integration of cyber-physical systems, IoT, and artificial intelligence can lead to increased efficiency of the operations, flexibility, and new business model generation. Policymakers and technology service providers should provide specific help to SMEs by making sure that any solution is responsive to the demands and constraints of such enterprises and place significant focus on the maximization of these advantages. All these difficulties can be successfully overcome with the help of interdisciplinary activity and assist SMEs on the successful way to the world 4.0, ensuring their availability on the world market (Hafeez, Shahzad, Helo, & Mubarak, 2025).

2.5. Benefits of Industrial 4.0 Technologies

2.5.1. Industry 4.0 Technologies for Advancing Industrial Sustainability in SMEs

The inclusion of Industry 4.0 technologies improves the sustainable and ethical services of the SMEs. It has been shown that predictive analytics, machine learning, and real-time computing, as well as help to carefully sustain the performance of manufacturing SMEs in economies towards better operational efficacy and environmental sustainability (Pandya, Kumar, & Singh, 2024). The technologies contribute to the minimization of waste and the optimal use of resources, which is significant in the process of linking moral activities with economic ones. Moreover, the enhanced environmental performance and the transition into the net-zero world environment can also be spearheaded by the use of disruptive technology in SMEs, including IoT and additive manufacturing (Jamwal, Agrawal, & Sharma, 2023).

Hi-tech robotics and intelligent logistics would also be applied to make real-time performance adjustments in the production capacity that would reduce human interaction, increase sustainability, and efficiency in the working process (Gupta, Prathipati, Dangayach, Rao, & Jagtap, 2022). Further, sustained competitive advantages of SMEs through strategic management, through the manifested sustainable operations, emerge in the long term (i.e., interaction with compliance with environmental regulations) as demonstrated in the case involving SMEs in the UAE (Athooli, Dayanandan, & Elsaman, 2023). This is the disclosure of the lean culture as a prolific process of acquiring operational excellence in the wood and furniture production sector in Malaysia, which underlines the feasibility of the interrelated sustainability and digital transformation (Iranmanesh, Zailani, Hyun, Ali, & Kim, 2019). Finally, the Indian transition to Industry 4.0 (especially through automation and production process control) is evidence that increasing customer satisfaction and product quality may be the key aspects to obtain a sustainable result (Nazim, Sodhi, & Kumar, 2022). These technologies will be valuable towards aligning the efforts of the SME towards Sustainable Development Goals (SDGs), i.e., climate action, responsible consumption, and innovation in detail.

2.5.2. Industry 4.0 Technology to Support SMEs' Sustainable Production

Industry 4.0 technologies offer SMEs sustainable production opportunities, but their successful implementation requires reasonable matters of specific technological and operational factors (Alkhodair & Alkhudhayr, 2025). Studies have shown that Big Data Analytics, automation, and robots offer the most long-term benefits. These technologies facilitate the improvement of essential accomplishments in small and medium-sized enterprises (SMEs), such as

production planning, logistics, supply chain, quality, and maintenance management (Narkhede, Mahajan, Narkhede, & Chaudhari, 2024).

The paper will seek to make sense of how sustainability goals and Industry 4.0 (I-4.0) technology implementation by small and medium-sized firms (SMEs) relate to each other. The impact on the sustainability goals and successful implementation of I-4.0 is mediated by innovation traits, except the observability (Bharati & Chaudhury, 2012; Müller, Dotzauer, & Voigt, 2017). The research would suggest that SMEs ought to approach creating a good I-4.0, incorporating it, and building the potential to be innovative to address long-term ambitions. According to the studies, SMEs should promote innovative features and implement I-4.0 within their business to enhance performance and survive (Zainul, Iswanto, & Saifuddin, 2024). The evidence of this research could prove the potential to employ I4.0, as well as sustainable practices in SMEs. But of prime importance is the customisation of technologies concerning the special needs of SMEs. The research proposes certain applications of technologies that would address the economic, environmental, and social demands of SMEs. Besides that, a framework is outlined that highlights incorporating smart technologies as essential building blocks, with the help of which different aspects of sustainability can be considered (Santos, Becker, Ayala, & Sant'Anna, 2024).

The article reviews how Industry 4.0 technologies or sustainable production (SP) influence the number of 84 small and medium-sized European and Polish metalworking companies. The study had revealed that the implementation of physical systems and robots centred on cyber enhanced the levels of SP in the environments, economically and socially. A strong association was found between firm robot usage and SP levels, as well as the correlation between CPSs and SP. The study also found a high correlation between robot implementation and social factors, specifically workplace accidents. The findings are that SMEs in the metalworking industry have increased SP levels with the introduction of Industry 4.0 technology (Patalas-Maliszewska & Mrugalski, 2023).

2.6. Industry 4.0 Adoption Model and Barriers

Industry 4.0, as used in the development of the adoption of the technology model, is the digital integration of the manufacturing process with the business activities of the organization using technology for communication and information, together with self-regulatory sensor-actor networks (CPS), as illustrated in a conceptual framework. Figure 1 illustrates the core dimensions of Industry 4.0 adoption through CPS integration. It shows how adoption is operationalized through three interrelated mechanisms: autonomous regulation of logistics processes based on environmental changes, real-time access and use of data across key business areas such as marketing, sales, and R&D, and automated data transfer across organizational functions to enable seamless system integration. Together, these elements reflect the dynamic and interconnected nature of Industry 4.0 environments (Prause, 2019).

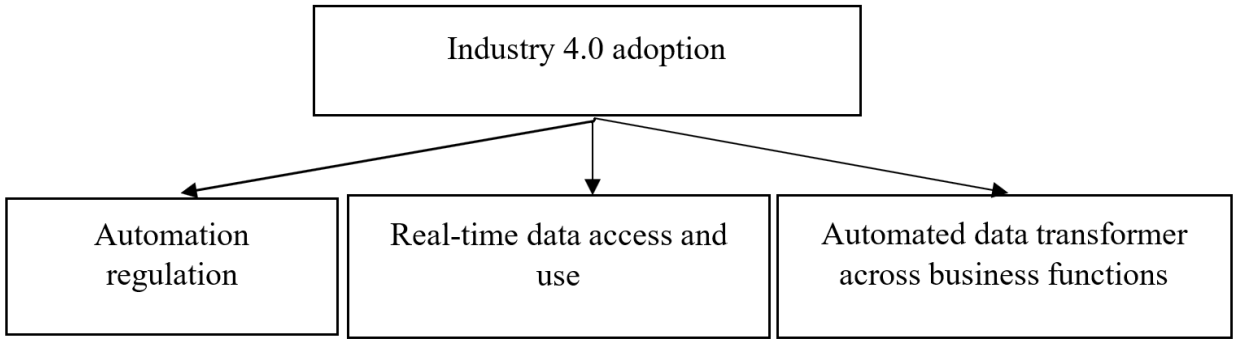

Figure 1. Conceptual framework for industry 4.0-driven technology adoption through CPS integration¨.

According to Rogers (2003), innovation diffusion theory (IDT), prospective adopters consider the following technical attributes when determining whether to adopt an innovation: First, the most important factors influencing adoption are the innovation's relative advantage over competitors and compatibility with the current infrastructure

(Bettoni, Matteri, Montini, Gładysz, & Carpanzano, 2021). In this context, IDT provides a hypothetical frame of the industry 4.0 technology perception of SMEs, particularly regarding the three concepts (awareness, readiness, and perceived positive results of adoption). To fit the concept of IDT into the research model, this study merges these concepts into the Technology-Organization-Environment (TOE) framework (Ghobakhloo & Ching, 2019). The TOE model identifies the technological, organizational, and environmental opportunities as affectors of the adoption decisions that SMEs make, whereas IDT elucidates how the attitude to adoption manifests in view of the recognition of obstacles to the adoption and perceived positive effects brought by the effects (Nguyen, Le, & Vu, 2022) In particular, the core qualities of IDT, its comparative advantage, and compatibility, expressed in perceived preparedness among SMEs, as well as acknowledgment of the capacity to improve productivity and operations efficiency of Industry 4.0 positive effects on productivity, are reflected in the research model (Wang, Gao, & Zhang, 2024). The Next Generation adoption is slow and is determined by the awareness, perceived benefits, and the organizational readiness through the concept of Innovation Diffusion Theory. Even though research on European SMEs has been conducted previously, it is also pertinent in the context of the Pakistani situation since the primary motivational factors behind its adoption, including infrastructure, financial capacity, and human capital, have the same impact (Müller et al., 2017). Combining IDT and the TOE framework, the given research represents a powerful prism through which we can analyze the mechanisms that influence the intention of SMEs to implement the Industry 4.0 technologies.

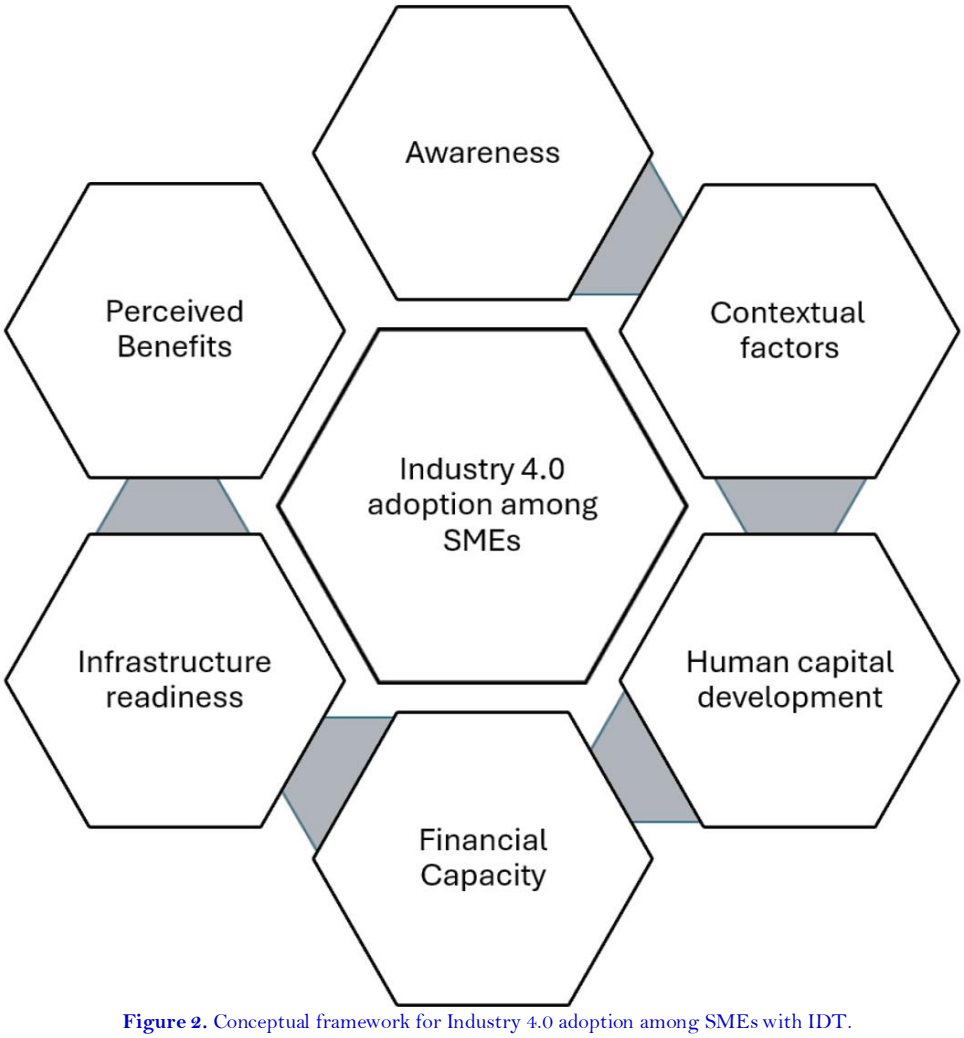

Figure 2. Conceptual framework for Industry 4.0 adoption among SMEs with IDT.

The present study is based on an Innovation Diffusion Theory (IDT)-based conceptual framework of Industry 4.0 implementation among SMEs, represented in Figure 2. Similarly, A type of readiness-based framework on Malaysian SMEs underscores the strategic role of organised maturity steps in the strategic planning and decision-making process throughout the Industry 4.0 adoption process. The conceptual framework approaches the understanding of adoption as gradual and a stage-by-stage process influenced by such crucial issues as organizational awareness, perceived benefits, readiness features of an infrastructure, financial capacity, and human capital development. Although these determinants have been discussed in the context of Europeans before, the paper believes that they can be generalised across the board and, accordingly, provides the infrastructure of the huge potential of the Pakistan SME efficacy, product quality, and skills transfer in the work of the Small Enterprise (SEs), especially in rural areas (Wischmann, Wangler, & Botthof, 2019). The results are, on the contrary, being approached cautiously due to the scarce case studies. However, more research should include additional case studies and consider the long-term patient consequences or scaling resolutions. The work presents a terrific roadmap of the introduction of Industry 4.0 to the SME sector (Havsgård, Ege, & Steinert, 2024).

This model highlights key socio-technical obstacles to the implementation of Industry 4.0, such as the presence of financial constraints, a lack of IT availability, and a shortage of human skills. The study has isolated less tested technological projects along with more recognisable challenges like funding and talent shortage. Literature research and interviews with practitioners identified 12 major barriers, the most important being a shortage of resources and experience. It suggests government change in capital disbursement and financial encouragement to enable training and sustainable supply chain convention, as well as planning of the implementation of Industry 4.0 and sustainability in SME (Shahzad et al., 2023).

2.7. History of Industry 4.0 in Pakistan

Industry 4.0 in Pakistan is a gradual process that will demand a lot of equipment upgrades and technological and labor force training. Although the world, including Asia, Europe, and North America, adheres to the Industry 4.0 model of Germany, Pakistani companies struggle with the integration of technologies, which restrains their competitiveness. Nevertheless, Pakistan is moving quickly in the technological sphere, as the expansion of the sphere of personal television started in the 1990s, and the usage of mobile communication reached 88 percent of the population by 2022, which means the gradual digitalization of daily life and business (World Bank, 2023).

Industry 4.0 in Pakistan shows a steady shift to developed manufacturing and digitalization, which is operated with the help of global innovations and domestic solutions. Adhere to the adoption of innovative technologies and the Internet of Things in the process of traditional manufacturing. The concept of Industry 4.0 was launched in Pakistan in the mid-2010s, the same as with worldwide progress in the automation and exchange of information in the production sphere. Robotics, IoT, and big data analytics are major technologies that are beginning to redesign the industrial environment, improving productivity and efficiency (Gunal, 2019; Umachandran, Jurčić, Della Corte, & Ferdinand-James, 2019).

2.8. Challenges and Opportunities of SMEs in Pakistan

There are also several crucial obstacles to the adoption of Industry 4.0 by the SMEs, such as the lack of access to outside knowledge, the low scope of innovative activity, the restrictive governmental policy, the increased levels of uncertainty and risk, the lack of intellectual resources, the lack of institutional assistance, the insufficient performance of the strategic business practices, and the poor business environment (Cassiman & Veugelers, 2006; Helfat & Peteraf, 2015). Other challenges that affect the SME sector in Pakistan are a lack of technical and management skills and inadequate technology, which could result in improved performance of the SMEs. The low level of technology has adversely affected the operational performance of SMEs in terms of their innovative operations.

Furthermore, many SMEs in Pakistan need a more educational background and cognitive abilities to run their companies. These have an impact on their capacity for efficient control and planning. Certain small-enterprise owners utilize the business financing they have secured for personal purposes (Khalique, Bontis, Abdul Nassir bin Shaari, & Isa, 2015). Inadequate intellectual capital undermines individuals' ability to maintain a competitive edge. Regrettably, academic institutions and government-supported organizations have not sufficiently taken on the mandate to develop professional and technical competencies critical to this field (Abiddin, Ibrahim, & Abdul Aziz, 2022). Pakistan's SMEs face significant challenges, with many halting operations within a year or five, others dying within six to ten years, and less than 5-10% remaining mature and developing (Khalique, Shaari, Isa, & Ageel, 2011). Thus, this suggests that Pakistan's SMEs have a high death rate and poor growth. As a result, Pakistan's SMEs' performance is worse than expected compared to other middle-income nations. Intellectual property is among the most essential success determinants of any company (Bilal, Khan, & Akoorie, 2016).

Pakistan's knowledge-based economy faces challenges in SMEs' performance due to a need for more knowledgeable and competent labor. To remain competitive, SMEs must understand intellectual capital and its practical applications. Innovation is also a significant issue for Pakistani SMEs. Despite 99% of Pakistan's over 3.2 million commercial firms being SMEs, their performance has declined due to non-competitive sectors losing market share in domestic and international markets. Pakistan ranks 108 out of 128 nations in the Global Innovation Index (Arshad & Arshad, 2018; Khalique et al., 2011). SMEs must be more actively and extensively involved in innovation activities or developing innovation capabilities. This is because they need more funds and expertise, which is a barrier to SMEs' ability to operate effectively and generate value. Environmental turbulence is another factor contributing to Pakistan's SMEs' poor performance. The country's unstable climate is the primary obstacle preventing businesses in Pakistan from doing well and seizing opportunities (Harram & Fozia, 2015).

The fall of the Pakistan textile industry has been notorious for the last few years, going further down the slump into obscurity in the world market share. In the first half of the fiscal year 2023-24, the textile export of the country declined by 5% to $8.283 billion compared to $8.716 billion during the same period of the previous year (Shahram, 2024). A similar situation was observed in the related textile sections, where knitted garments also underwent damage of 10.71% and 8.93%, respectively (The Textile Think Tank, 2024). Need for advanced technology and more innovation, intellectual capital, and absorptive capacity in the sector. December 2023 saw a notable recovery in exports, reaching $2.82 billion, a 22.2 % year-on-year increase despite an otherwise turbulent year marked by global economic pressures and domestic challenges (Khan & Mustafa, 2024). Pakistan has a shortage of contemporary technologies and poor industrial infrastructure, which concerns the global competitiveness of the textile industry because the country is worse than regional rivals, including Bangladesh, India, and China (Pakistan Textile Journal, 2023). Financial limitations in most SMEs in Pakistan are one of the biggest barriers to investing in Industry 4.0 advanced technologies, including automation, IoT, and big data analytics (Liao, Deschamps, Loures, & Ramos, 2017). The main obstacles are large initial investments, lack of confidence in the payback, and insufficient infrastructure, specifically, unreliable internet connections and insufficient capacity of data centers, which all hinder the process of digital integration (Liao et al., 2017). Moreover, a shortage of skilled personnel proficient in AI, robotics, and machine learning exacerbates the technology adoption gap, compounded by a lack of targeted training programs (Weyer, Schmitt, Ohmer, & Gorecky, 2015). Conservatism and unwillingness to abandon manual and move to automated workflows also delay digitization. The policy measures are still sparse in approval, and there are few financial incentives and a lack of support facilities to adopt Industry 4.0, which curtails the SME development (Lu, 2017). Implementation of Industry 4.0 solutions has the potential to optimise the productivity of SMEs by automating processes, providing real-time monitoring, and using data to make decisions (Zhong, Xu, Klotz, & Newman, 2017). All these are aimed at enhancing competitiveness in the globe, product quality, personalisation, and innovation capabilities that enable it to integrate into global value chains (Tsai et al., 2024). It was also observed long ago that green logistics in food manufacturing SMEs tend to share a systemic learning problem comprising inefficiencies in

transport infrastructure, policy constraints, and low technology absorption, which must evolve to acquire the full benefits of Industry 4.0. An additional role of governmental support in the form of subsidies, training, and building of digital infrastructure is to encourage SME investments in advanced technologies (Lu, 2017). The aspects of digitalization also broaden access to markets through the e-commerce solutions, thereby giving SME an opportunity to access customers all over the world as well as diversify revenue sources. In addition, Industry 4.0 is environmentally friendly through resource utilization management and minimization of waste, which aligns SMEs with international environmental norms and attracts environmentally friendly markets (Alkhodair & Alkhudhayr, 2025).

2.9. Critical Literature Review and Implications on the Research Model

The literature review validates the strategic role of SMEs and mentions Industry 4.0 as one of the most important facilitators of productivity, sustainability, and global competitiveness. Nevertheless, regardless of the potential of the technology, its adoption in SMEs, especially in developing economies like Pakistan, is still low. A critical review of the past literature demonstrates that the limitation may not solely be described by the availability of technology, but instead is the result of a mixture of perceptual, organizational, and environmental factors. This highlights why an integrative theoretical perspective is required in explaining Industry 4.0 adoption behavior among SMEs.

The Innovation Diffusion Theory (IDT) will be useful in understanding the perception and evaluation of Industry 4.0 technologies by SMEs prior to adopting them. IDT states that innovations are adopted when they are seen to provide a relative advantage, compatibility with the existing systems, and visible benefits. Within the framework of Industry 4.0, the mentioned attributes can be translated into the knowledge of digital technologies, the perceived advantages in efficiency and sustainability, and the decrease in the level of uncertainty about the results. Empirical findings show that SMEs, the more aware of them, the more likely to see the strategic worthiness of Industry 4.0 and are less reluctant to take the idea of implementing it into consideration. Therefore, awareness comes up as a determinant cognitive variable that affects adoption intention.

Although IDT describes perceptual readiness, it does not entirely describe organizational and contextual constraints. The Technology-Organization-Environment (TOE) framework is a complement to IDT, which explains the impact of organizational readiness (financial capacity, skills, infrastructure) on adoption decisions, technological conditions (complexity and compatibility), and environmental pressures (government support, competitive intensity, regulatory environment). Understanding the SMEs, studies have always indicated that despite the existing awareness and perceived benefits, lack of organizational preparedness and unfavorable environment may be a major impediment to adoption. It is especially noticeable in Pakistan, where SMEs have been struggling with acute financial limitations, a lack of digital infrastructure, and a lack of skilled labor.

The combination of IDT and TOE is synthesised into a literature, according to which, the adoption of Industry 4.0 among SMEs is a multi-dimensional and multi-stage process. Awareness can help SMEs to grasp the concepts of Industry 4.0; it is the perceived benefits that can influence positive attitudes to be taken to adoption; the organizational readiness will indicate how far we can go in terms of actual adoption. Meanwhile, obstacles such as financial constraints, absence of expertise, and infrastructural vulnerabilities are inhibitory influences that could undermine the positive perceptions into actual adoption.

According to this synthesis, the current study frames the conceptualization of Industry 4.0 adoption among Pakistani SMEs as a construct determined by four major constructs: Awareness, Readiness, Perceived Benefits, and Barriers. The perceptions of benefits and the level of awareness are based on the IDT, which is the cognitive assessment of innovation, whereas readiness and barriers are found in the organizational and environmental levels of the TOE framework. Combining these views, the study creates a context-specific research model that not only explains whether SMEs implement Industry 4.0 but also why it is not a uniform phenomenon even when its benefits are acknowledged.

This is an important synthesis, which provides a clear theoretical rationale for the proposed research model and on which hypothesis development will be based in the later section. The literature review has also offered a suitable analytical basis to study how Industry 4.0 is adopted by SMEs in Pakistan, as it links existing adoption theories to measurable study variables.

3. METHODOLOGY

3.1. Measurement of Constructs

The survey instrument was developed by adapting measurement items from previously validated studies related to technology adoption, Industry 4.0, and SME digital transformation. Minor wording adjustments were made to ensure contextual relevance to Pakistani SMEs and industrial sustainability, without altering the original conceptual meaning of the items.

Awareness (AW) was measured using items adapted from innovation diffusion and Industry 4.0 awareness studies, e.g., (Horváth & Szabó, 2019; Rogers, 2003). One of the sample items is: Our organisation possesses enough knowledge of the Industry 4.0 technologies and their use.

Items obtained by adapting previous research on digitalisation of SMEs and industry 4.0 adoption (e.g., (Müller, Buliga, & Voigt, 2018; Sony & Naik, 2020)) were used to measure challenges (CH). One of the sample items is: "High cost of implementation is an obstacle towards our organisation adopting Industry 4.0 technologies.

Ready (RD) was assessed through the question of readiness that was modified by the organisational readiness and technology preparedness sources (e.g., (Mittal, Khan, Romero, & Wuest, 2018; Tornatzky, Fleischer, & Chakrabarti, 1990)). One of the sample questions is: Our organisation has the skills and infrastructure to adopt Industry 4.0 technologies. The domains of benefits (BF) were assessed with the help of the items modified in accordance with the research on the perceived benefits of smart manufacturing (e.g., (Frank, Dalenogare, & Ayala, 2019; Kagermann et al., 2013)). One of the samples is: "The adoption of Industry 4.0 can increase operational efficiency and sustainability performance. Items that were transformed into policy and institutional support literature (e.g., (Liao et al., 2017; OECD, 2017)) were used to measure recommendations (RC). An example is: "Training and financial incentives by the government would promote the use of Industry 4.0 by SMEs.

The aim of this study was to investigate small and medium enterprises (SMEs in the manufacturing-related industries in Pakistan, such as textile, food and beverage processing, light engineering, chemicals and allied manufacturing industries. These industries were chosen because they are economically significant and are becoming subject to more and more digital manufacturing and sustainability pressures. The sampling procedure used was purposive because Industry 4.0 adoption involves the respondent possessing some minimal knowledge of digital or manufacturing processes. The publicly available SME directories, professional business networks, industry associations, as well as chambers of commerce and SME-related online forums were used to develop the sample frame with the contacts. The data was gathered using an online structured questionnaire that was provided using Google Forms. The online survey was sent via email, LinkedIn, and WhatsApp business groups to the owners, managers, and technical employees in the SME industry. This was 200 valid responses out of the 260 responses that were screened on completeness and relevance.

All items were measured using a five-point Likert scale, where 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, and 5 = Strongly Agree (Kociu & Kodra, 2021). Data from 200 respondents collected via Google Forms and analyzed using correlation and regression techniques in IBM SPSS Statistics version 25 (Hu, 2018).

3.2. Measurement of Adoption Status (AS)

The Adoption Status (AS) was not a binary measure but a continuous composite measure. It represents the level of Industry 4.0 adoption in SMEs, which captures the reported use of digital manufacturing technologies, the level of implementation, and the level of integration.

The construct was operationalized using various Likert-scale items that determine how much Industry 4.0 technologies (automation, digital data use, and smart manufacturing practices) are adopted or implemented in the firm. The AS scores are higher, indicating greater Industry 4.0 adoption. The scale showed good internal consistency reliability (Cronbach's alpha = 0.737), making it acceptable for regression analysis.

4. RESULTS

Operationalization of all variables in the study was done in terms of composite constructs based on several questionnaire items. To achieve a consistent construct and a comparable score across constructs, each construct was averaged to come up with one composite index.

Awareness (AU) was calculated as the average of awareness-related items, with potential points ranging from 1 to 5. Adoption Status (AS) was derived as a mean score of adoption-related items assessing the degree of Industry 4.0 implementation, also on a 1-5 scale. The Challenges (C), Benefits/Readiness (BR), and Recommendations (R) were similarly computed as mean indices, where higher values indicate greater perceived challenges, benefits/readiness, and support mechanisms, respectively. Using averaged composite scores maintains the original Likert scale metric and enables meaningful interpretation of regression coefficients. The demographic profile of respondents is presented in Table 2.

Table 2. The respondent demographic profile shows diverse representation as depicted.

Demographic	Percentage (%)
Gender	
Male	62.5
Female	33.5
Prefer not to say	4.0
Age	
Below 25	42.5
25 – 34	28.5
35 – 44	19.5
45 and above	9.5
Educational level	
Matriculation	4.0
Intermediate	10.5
Bachelor's Degree	52.5
Master's Degree and above	33.0
Position	
Owner\founder	14.5
Manager	23.5
Employee	62.0
Number of employees	
Micro (1 - 9 employees)	24.0
Small (10 – 49 employees)	42.5
Medium (50 – 249 employees)	33.5
Location	
Urban	51.5
Semi-Urban	21.5
Rural	2.70

Most respondents are male (62.5%), aged below 25 (42.5%), with the majority holding a Bachelor's degree (52.5%). In terms of roles, employees dominate (62%), and businesses are primarily small enterprises (42.5%), followed by medium (33.5%) and micro (24%). Urban areas (51.5%) are the most common location, with the remainder split between semi-urban (21.5%) and rural (27%). The Tests of Normality indicate that the dependent variable, Adoption Status (AS), does not follow a normal distribution, as both the Kolmogorov-Smirnov ($p<0.001 p < 0.001$) and Shapiro-Wilk ($p<0.001 p < 0.001$) tests are statistically significant, as depicted in Table 3.

Table 3. Normality results.

	Kolmogorov-Smirnova			Shapiro-Wilk		
	Statistic	Df	Sig.	Statistic	df	Sig.
AS	0.222	200	<0.001	0.909	200	<0.001

Note: Lilliefors significance correction. Kolmogorov-Smirnov and Shapiro-Wilk tests indicate that AS is not normally distributed ($p < 0.001$).

This indicates that there are parametric assumptions of normality, and other analysis methods like non-parametric tests or transformations might be required in further analysis if normality is paramount. The reliability results demonstrate that the five items have a Cronbach's alpha of .737, which indicates acceptable internal consistency reliability. This implies that there is reasonable consistency among the items used to measure the constructs in determining the adoption status. Assessment of normality was conducted before the regression analysis, but normality was not evaluated on the dependent variable, rather on the standardized residuals. The apparent normal distribution of the regression residuals was confirmed by histogram and normal probability (P-P) plots, which showed that the multiple regression analysis did not violate the normality assumption.

Descriptive statistics show that the respondents had the highest score on Recommendations (R) (Mean = 11.69, SD = 2.01) and then on Benefits and Readiness (BR) with a mean score of 10.72 (SD = 2.08). Challenges (C) were at the highest level with a mean of 10.09 (SD = 1.93), whereas Adoption status (AS) and Awareness and Understanding (AU) had lower values, with a mean of 7.54 (SD = 1.78) and 6.88 (SD = 1.69), respectively, as shown in Table 4.

Table 4. Descriptive statistics.

Variables	Mean	Std. deviation
Awareness and understanding	6.88	1.68
Adoption status	7.54	1.77
Challenges	10.08	1.92
Benefits and readiness	10.72	2.07
Recommendations	11.68	2.01
Valid N (Listwise)	200	

The correlation results in a significant positive relationship among most variables, as depicted in Table 5.

Table 5. Correlation results.

Variables	AU	AS	C	BR	R
Awareness and understanding (AU)	1	0.664**	0.141*	0.356**	0.362**
Adoption status (AS)	0.664**	1	0.224**	0.355**	0.434**
Challenges (C)	0.141*	0.224**	1	0.324**	0.324**
Benefits and readiness (BR)	0.356**	0.355**	0.324**	1	0.450**
Recommendations (R)	0.362**	0.434**	0.324**	0.450**	1

Note: **. Correlation is significant at the 0.01 level (1-tailed).
*. Correlation is significant at the 0.05 level (1-tailed).

Awareness and Understanding (AU) is strongly correlated with Adoption Status (AS) ($r=0.664$, $p<0.01r = 0.664$, $p < 0.01$), indicating that higher awareness strongly relates to higher adoption. Recommendations (R) also show a moderate correlation with AS ($r=0.434$, $p<.01r = 0.434$, $p < 0.01$), as do Benefits and Readiness (BR) ($r=0.355$, $p<0.01r = 0.355$, $p < 0.01$) and Challenges (C) ($r=0.224$, $p<0.01r = .224$, $p < 0.01$), albeit weaker. Also, inter-variable correlations are significant, the biggest one is between Recommendations (R) and Benefits and Readiness (BR) ($r=0.450$, $p<.01r =0.450$, $p <0.01$). The above-mentioned findings indicate the paramount importance of awareness and recommendations in influencing the adoption, which is backed up by the following benefits and challenges in smaller degree. Table 6-9 regression analyses show that Awareness and Understanding (AU) has a significant impact on Adoption Status (AS) ($B=0.602$, $p<.001B =0.602$, $p <0.001$), which means that higher awareness and understanding have a strong effect on promoting adoption.

Table 6. R-squared result.

Model summary				
Model	**R**	**R square**	**Adjusted R-squared**	**Std. error of the estimate**
1	0.701[a]	0.491	0.481	1.281

Note: a. Predictors: (Constant), Recommendation (R), Challenges (C), Awareness and Understanding (AU), Benefits and Readiness (BR). Dependent variable: Adoption Status (AS).

The value of R (0.701) indicates that the predictors (awareness, challenges, readiness, etc.) have a strong positive relationship with Industry 4.0 adoption among SMEs. The R value of 0.701 is an indicator that the independent variables taken as a group of variables hold a significant influence on adoption. R-squared (R 2) = 0.491 represents 49.1 per cent of the variation in the industry 4.0 adoption. In other words, nearly half of the change in the adoption status is explicable by the aspects that are in the model. Adjusted R 2 0.481 corrects the predictors in the model and makes it still have 48.1 per cent of the predictive ability, even with the supervision that there is no over-fitting. Standard Error of the Estimate = 1.28148 is used to indicate the average deviation between the actual values and those that were estimated. In practice, the vast majority of the predictions will be in the window of +-1.28 units to the actual figures.

The relatively high R^2 in Pakistan's challenging environment suggests that raising awareness and enhancing readiness can be low-cost, high-impact interventions for Industry 4.0 adoption among SMEs. Unlike developed contexts, where financial infrastructure is key, soft factors like awareness and support play a more crucial role. Policymakers should prioritize awareness campaigns and training over direct financial aid to drive adoption effectively.

Table 7. ANOVA result.

ANOVA[a]						
Model		**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
1	Regression	309.451	4	77.363	47.109	<0.001[b]
	Residual	320.229	195	1.642		
	Total	629.680	199			

Note: a. Dependent variable: Adoption Status (AS).
b. Predictors: (Constant), Recommendation (R), Challenges (C), Awareness and Understanding (AU), Benefits and Readiness (BR).

Table 8. Regression coefficients results.

Coefficients[a]						
		Unstandardized coefficients		**Standardized coefficients**		
Model		**B**	**Std. Error**	**Beta**	**t**	**Sig.**
1	(Constant)	0.427	0.670	—	0.637	0.525
	AU	0.602	0.059	0.571	10.144	<0.001
	C	0.063	0.051	0.069	1.245	0.215
	BR	0.040	0.052	0.047	0.781	0.436
	R	0.163	0.053	0.184	3.049	0.003

Note: a. Dependent variable: Adoption Status (AS).
B = Unstandardized regression coefficient.
Beta = Standardized regression coefficient.
t = t-statistic for hypothesis testing.
Sig. = Significance level (p-value).
b. Values significant at $p < 0.001$.

Table 9. Multiple linear regression analysis.

Variables	B	Std. error	Beta	t	Sig.
Constant	−2.839	1.635	—	−1.736	0.085
Awareness (AU)	0.602	0.079	0.518	7.571	**0.000**
Challenges (C)	0.021	0.065	0.018	0.327	0.744
Benefits/Readiness (BR)	0.089	0.071	0.076	1.254	0.211
Recommendations (R)	0.163	0.054	0.198	2.964	**0.003**

The regression findings also show that Awareness (AU) has a statistically significant positive influence on Adoption Status (B = 0.602, p < 0.001). This means that, where SME awareness of Industry 4.0 technologies is increased by one unit, the level of Industry 4.0 adoption is expected to increase by 0.602 units, other things held constant.

Recommendations (R) also demonstrate a strong positive correlation with Adoption Status (B = 0.163, p = 0.003), indicating that more meaningful adoption outcomes are caused by improved policy support, training programs, and institutional counseling.

Conversely, Challenges (C) and Benefits/Readiness (BR) do not exhibit statistically significant effects, which proves the opinion that the role of awareness and strategic support in promoting Industry 4.0 adoption among SMEs is more decisive than perceived barriers and readiness as individual factors.

5. DISCUSSION

This study aligns with recent advancements in the understanding of Industry 4.0 adoption, particularly within the context of SMEs. By focusing on factors like awareness, readiness, and external support, the study extends the technology organization environment framework, which emphasizes the interaction between internal organizational capabilities and external enablers in fostering technological adoption (Yang & Gu, 2021). The originality of the study is that it considers Building on the TOE framework, the study focuses on the three variables which are organizational preparedness, external support, and awareness in the context of Industry 4.0 adoption by Pakistani SMEs along with discussing sustainability-benefits relations and recommending specific interventions such as government backing and training within the framework of transcending the existing obstacles of financial and cultural character of the country (Khan, Arif, Sahar, Ali, & Abbasi, 2022). The results confirm the realization that technological adoption at SME is largely affected by their knowledge and awareness about benefits, which is consistent with earlier studies that recognized knowledge as a significant eventual influence of innovation diffusion (Udeh et al., 2024). Further, this article highlights the implications of custom-made support programmes in our quest to overcome the obstacles presented by such issues as financial and technical limitations, which echo contemporary debate on policy to enable digital change (Shahzad et al., 2023).

The findings are that awareness and understanding are most crucial to Industry 4.0 adoption in SMEs, which are both strong predictors of readiness and implementation. Though the predicaments, which included obesity, such as lack of finances and technical incompetence, were widespread, their effects were not so direct as the enabling ones that comprised awareness and advice. The findings show organisational willingness, optimistic business awareness, and a strategic support system are the crucial factors to foretell industrial transformation tools of SMEs in Pakistan, and key drivers of policy to transform the industrial transformation in Pakistan.

Stunningly enough, the SMEs, which announced more intensive contact with the supportive programs (in other words, becoming members of training conventions organised by status bodies or collaborating with educational institutions), turned out to be more prepared and with a positive attitude towards using the technologies (Faiz, Le, & Masli, 2024). Such solutions suggest that the ecosystems have to be constructed in a supportive way in response to the conservative nature of the ecosystems, which tends to maintain pace with the technological change in the conditions where nothing is free. It revealed the need to engage more proactive measures to address the managerial resistance, as well as the cultural resistance to change that is likely to diminish despite the introduction of external support.

5.1. Practical Implications

The findings of the research provide a platform through which Pakistan can implement certain policies that will allow the uptake of Industry 4.0 technologies by the SMEs. This may take the form of tax wins, offers and subsidies to make possible the acquisition of digital equipment. Improving digital infrastructure, such as the introduction of

high-speed internet connectivity and stable electricity supply in rural areas and pockets, will also be important (Khan et al., 2022). Technical schools can provide workforce development programs enabling employees with the fundamental knowledge they should have in automation processes, data analytics and Internet of Things (IoT) processes (Kakar & Khan, 2022). Besides, the workshops and seminars related to the awareness about what Industry 4.0 technologies can provide, and how to apply them, have to be encouraged. However, the last but not least is the ability to empower the SMEs to adopt pilot projects and reduce the risk of adoption and expanded use of these advanced manufacturing technologies. Findings suggest that the nationwide solutions that include arms stimulus, blame in the resolution of training, and investment in the technological infrastructures are needed. This would help directly the SDG 8 (Decent work), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 12 (Responsible Consumption) through the inclusion of Industry 4.0 in the Sudan policy framework of Pakistan.

5.2. Theoretical Implications

By expanding the Technology-Organization-Environment (TOE) paradigm and highlighting the importance of knowledge, preparedness, and outside assistance, this research provides theoretical insights into Industry 4.0 adoption among SMEs in Pakistan (Shahzad et al., 2023). Following the theory of Innovation Diffusion proposed by Rogers (2003), it focuses on awareness as one of the aspects of adoption and lists socio-technical barriers to adoption, such as financial constraints and cultural resistance, as the biggest obstacles (Al-Razgan et al., 2021). The analysis also indicates that special interventions, including government support and training programs, are needed to eliminate such barriers (Zickafoose et al., 2024). The current work contributes to the existing literature concerning sustainability-oriented innovation by connecting the industry 4.0 adoption to the sustainability-related objectives, indicating the benefits of environmental and productivity objectives in their interdependence. The findings can provide a theoretical framework of strategies that can assist SMEs in bridging any gaps, adopting modern technologies and in the long-term growth.

6. CONCLUSION

The paper has explored the adoption of Industry 4.0 among Pakistani SMEs with a narrow scope of awareness, challenges, preparedness, advantages, as well as strategic suggestions, and their effects on industrial sustainability. The combination of the Technology-Organization-Environment (TOE) model and the Innovation Diffusion Theory (IDT) enables the research to offer novel empirical data, which suggests that awareness is the key factor in Industry 4.0 adoption, and policy-related recommendations and institutional support systems should also be considered in an enabling role. These results provide new insights into the literature on adoption, indicating that cognitive and strategic factors are more significant than technological or financial ones in developing-country SME situations. Although this study has made contributions, it has some limitations. First, because of the cross-sectional research design, one cannot conclude causality between variables. Second, common method bias and respondent subjectivity may also affect the use of self-reported survey data. Third, the research is restricted to Pakistani SMEs only, which can narrow the scope in terms of generalization of the results to other economies with various institutional and technological settings, whether developing or developed.

These limitations can be a subject of future research through the adoption of longitudinal research designs to indicate how changes in Industry 4.0 adoption change over time and determine causal relationships. Internal validity may be improved through comparison between countries or regions; internal understanding can be gained through this. It is also possible to add objective performance measures, qualitative, or mixed methodologies in the future to triangulate the results and identify the peculiarities of sector adoption. These extensions would also help reinforce the theoretical advancement and offer more specific policy recommendations on how to promote sustainable digital transformation in SMEs.

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