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Article

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Exploring IoT integration challenges: Causal relationships and strategic implications for business models[☆]

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ABSTRACT

Implementing the Internet of Things (IoT) into business models has become an influential catalyst, supporting novel revenue generation, improved operational efficiencies, and competitive dominance. Still, its implementation has been challenged by barriers to technological, organizational, and societal dimensions. The current study utilizes the Fuzzy Decision-Making Trial and Evaluation Laboratory (Fuzzy DEMATEL) technique to comprehensively identify and assess the interconnections among fundamental IoT integration challenges. Thirteen crucial components were analysed, influencing interoperability challenges, data security and privacy issues, standardized issues, high initial investment, scaling obstacles, and adverse environmental effects. The results indicate a clear differentiation between seven cause variables such as lack of skilled workforce, interoperability issues, standardization gaps, high initial investment, regulatory issues, resistance to change, and data security and privacy issues were the most influential challenges and six effects (dependent) factors including vendor dependency risks were the most impacted effect factors. These findings highlight the necessity to tackle fundamental problems, including standardization, workforce development, and regulatory clarity. This research strengthens theoretical aspects in IoT using Fuzzy DEMATEL by delivering a robust decision-making roadmap. The results highlights actionable practical recommendations for regulators and businesses for effective resource utilization to improve their IoT adoption in compliance with sustainable development. Businesses can utilize the full potential of IoT by addressing such problems and promote innovative environment to ensure a sustainable and resilient future.

1. Introduction

The Internet of Things (IoT) has recently transformed the way of doing business for many organizations, creating new forms of business models, value propositions, and marketing channels (Ali et al., 2023). The technology that enabled this change is the IoT, which supports the idea of autonomous sensing and interaction, and data collection and exchange. It can enhance productivity, create new revenue streams, and innovate with the consumer at the centre of the value proposition when embedded into business systems (Mukherjee et al., 2024). There is an estimation that by the end of 2030 the number of devices using IoT will be around 25.44 billion, which shows the importance of using this technology world-wide (Krishna et al., 2021).

The worldwide IoT market valuation in 2023 was 595.73 billion USD which increased to 714.48 billion USD in 2024 and forecasted to reach 4062.34 billion USD till 2032 (Internet of Things (IoT) market, 2025). However, the integration of IoT within business operations is very challenging. The challenges such as data privacy, technical interoperability, scalability, stakeholders perceptions, resistance to change etc. continuously impacts the implementation of IoT. Some practical cases are evident to these challenges, for example LoRaWAN networks faced scalability issues, lack of trainings and lack of integrated solutions; Sigfox faced difficulties to match up with consumer expectations; helium lagged behind to deliver the implementable solutions and many other similar IoT service providers are facing such integration challenges (Nemish, 2024). To overcome this situation, it is necessary to explore

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these challenges effectively and investigate their relationship (Oke et al., 2022). The adoption of IoT within business models is not just a technological implementation, instead it highlights a potential digital transition into organizational activities, interactions with customers, and towards competitive approaches in digital economies. IoT-based business models uses real time data using different sensors within operational activities which provides modified interactions and enhanced decision making processes (Singh & Bhanot, 2020).

Maintenance prediction in production, automated management of supplies in the retail sector, and distant medical monitoring for healthcare highlight the transformative impact of IoT. But achieving this level is still challenging which required detailed exploration of potential solutions (Arnold & Voigt, 2019). A key component of integrating IoT includes solving significant technological challenges, including interoperability difficulties. The numerous ecological challenges associated with IoT hardware, software systems, and communication methods represent major hurdles to achieving seamless connectivity (Haaker et al., 2021). The lack of regulatory rules and standards influences the implementation of IoT on large scales and questions its reliability which leads to high operation cost and ineffectiveness. Also the concerns such as data privacy, security and quality also necessitate the need for IoT systems due to its dynamical capabilities to communicate and generate lot of data (Birkel & Hartmann, 2019). The organizations are facing challenges in maintaining safe and secure data communication between connected systems in compliance with strict rules and regulations. Thus the challenges faced by organizations with IoT implementation are significant. Small scaled businesses with limited resources needs huge investment in initial stages of technology adoption (Janssen et al., 2019). In IoT context, this investment is related with setting up the infrastructure, purchasing IoT hardware, and organizing trainings for workers. All these expenditures usually outweighed the potential benefits offered by IoT implementation which leads to developing unwillingness in stakeholders to adopt the technology (Taherdoost, 2023).

This situation complicates the adoption process, as businesses deals with stakeholders and cultural resistance to transition from traditional methods to IoT based systems. The main reason for this situation originates from the perception towards IoT systems, their capacity, potential benefits and upcoming changes in existing operational activities (Reyna et al., 2018). The lack of qualified workers trained in managing IoT projects adds considerable complications. IoT integration involves expertise in analysing data, security and privacy, and developing models architecture, which are frequently restricted inside businesses. The absence of such capabilities certainly impacts IoT adoption and also increases the risk of improper integration, so reducing the potential positive impacts of IoT (Yadav et al., 2024). These issues are associated with the information management as the various types of data is produced by IoT devices in huge volume which needs advanced analytical skills and tools to analyse the data.

Issues related to regulatory standards specifically with security and privacy of data puts additional legal burden on businesses. Investigating such legal systems usually needs significant fundings and efforts to ensure compliances to worldwide standards (Luthra et al., 2018). Infrastructural limitations additional complicates the adoption process especially in locations with limited access and irregular electricity. Such challenges influences the expected growth and capacity of IoT integration to enhance operational efficiency in businesses requires real time monitoring and continual connection. The implications of such issues are visible in key domains which are reliability and expansion to ensure sustainable future Tarmizi et al., 2020). The problems with scaling originate from high expenditure, infrastructural limitations, and compatibility challenges. Businesses often have challenges in expanding their IoT networks across many locations which leads to disorganized implementations that limits the potential benefits of IoT integration. Similarly, technological problems impact the reliability of IoT systems, which results in irregularity and disruptions in operations (Malik et al., 2023). Such reliability problems decrease customer trust and enhance

expenses associated with IoT management. The complicated nature of managing data represents a major impact caused by the relationship of technological and business variables. IoT systems generate considerable data, requiring extensive storage, processing, and analytical capabilities (Hassoun et al., 2023). Inconsistency with business's objectives is a constant challenging situations, resulting from resistance to transformation, limited resources, and ineffective organizational strategy. Environmental issues add complexity to the challenges of IoT integration. The energy consumption and electronic waste associated with IoT devices raise major concerns over the adverse environmental effects of their widespread implementation. As businesses wants to comply with sustainable development goals, addressing these issues is critical (Hassoun et al., 2022a). Still, implementing sustainable IoT requires major investments in renewable energy technologies and recycling initiatives, resulting in a financial burden on businesses (, Hassoun et al., 2022b). Thus challenges such as technological, organizational, environmental and regulatory are significantly influencing IoT integration attempts (Aamer et al., 2021).

This scenario highlights the necessity for a holistic methodology to address the challenges properly (Grover & Ashraf, 2024). A primary bottleneck in current research is the identification of the relationships underlying these issues. Despite specific challenges have already been thoroughly analysed, their underlying causes and resulting consequences remains unexplored. Technological challenges, such as the lack of standards, sometimes increase organizational concerns, particularly unwillingness to transformation and incompatibility with the business's objectives. Similarly, infrastructural limitations could increase uncertainties about expansion and validity. Recognizing these interconnections is crucial for developing holistic approaches that address specific problems while also addressing their broader consequences. Thus considering the research gap, the following research objectives were developed:

RO 1: To identify key challenges impacting integration of IoT in business models.

RO 2: To analyse relationship among identified challenges and their prioritization.

The present research addresses this gap by employing a thorough analytical method to identify and prioritize challenges in IoT integration based on their interrelations. Fuzzy DEMATEL approach was used to investigate the relationship among IoT integration challenges. The manuscript is subdivided into following sub-sections: Section 2 outlines existing literature, Section 3 presents the material and methods, Section 4 and 5 highlights the results and discusses the findings, and the final section concludes the research.

2. Literature analysis

The Internet of Things (IoT) is significantly changing business scenarios via improving participation, sharing information, and digitizing operational activities. IoT denotes a network of networked objects that independently interact and communicate, gathering and transferring data in real time (Hopkins, 2021). These abilities enable organizations to make data-informed decisions, improve productivity, and provide innovative goods and services. The transformational promise of IoT resides in its capacity to merge physical and digital realms, enabling dynamic interactions among objects, systems, and individuals (Wanasinghe et al., 2020). In production, IoT-enabled predictive maintenance systems evaluate equipment performance and detect probable issues before occurrence, minimizing downtime and maintenance expenses (Haaker et al., 2021). Transformations in inventory management using IoT based smart solutions enables continual monitoring to improve efficacy and reducing wastage (Caro & Sadr, 2019). The medical field implements IoT based systems to improve their operational activities. Such instances highlights the transformative capacities of IoT and its contribution towards their digital transformation (Chatterjee et al., 2021).

Implementing IoT into business models includes multiple problems that can be classified into technological, organizational, and environmental categories. Each of these categories involves particular challenges that restrict the straightforward integration of IoT technologies (Kumar et al., 2022). Several previous studies highlight various barriers impacting the integration of IoT in business models (Haaker et al., 2021; Sharma et al., 2020; Singh & Bhanot, 2020). The literature focused on segmented investigations related to IoT, while detailed investigations related to these challenges are limited. (Das, 2019) explored the factors impacting the adoption of IoT in retail outlets of oil and highlighted five significant factors, including technological, competitive, data security, etc. (Arnold & Voigt, 2019), employed the TOE framework to explore the enablers of IoT adoption in the manufacturing industry. (Pappas et al., 2021) Utilized fsQCA to investigate the willingness to adopt IoT in the hospitality industry. (Hsu & Yeh, 2017) adopted hybrid DEMATEL to explore IoT adoption in logistics, categorizing the factors into four major categories. Several other studies utilized different methodologies to examine the IoT enablers and barriers focused on operational activities (Ahmetoglu et al., 2022; Eskerod et al., 2019; Singh & Bhanot, 2020; Wang et al., 2021). Most of the studies focused on manufacturing and retail industries. The adoption of “Institutional Theory” can offer detailed understanding on how external factors such as regulations and industry norms influence IoT integration in business models (Xu et al., 2022). Similarly, the “Dynamic Capability Theory” can explore the requirement for businesses to adapt, modify, and improve their IoT capabilities to compete in digital transition among business competitors (Sullivan et al., 2023). Such theories can provide a systematic way to address challenges related to IoT integration in business models. However, limited research explored challenges related to the integration of IoT in businesses. The following sub-section highlights the significant barriers impacting IoT integration.

2.1. Key factors impacting IoT integration in business models

The implementation of IoT into business models is affected by multiple crucial components across technical, organizational, and environmental dimensions. Addressing these aspects and their interrelations is essential for formulating effective strategies for addressing challenges, allowing businesses to take advantage of IoT’s transformational capacity for effectiveness and innovation (Pappas et al., 2021). Although the adoption of IoT offers significant advantages, the technology remains in its early stages, and many barriers need to be addressed prior to its widespread adoption (Yadav et al., 2024). Such issues significantly contribute to the minimal adoption rate and prevent realizing IoT’s significant advantages. In this research, we identified 13 major challenges from the existing literature and expert opinion, as discussed in the following sub-sections and Table 1.

2.1.1. Lack of skilled workforce

Restricted technological proficiency constrains enterprises’ utilization of IoT. It is a complex technological field that includes vast data, devices, sensors, and many sources. Consequently, IoT requires individuals with expertise in data analytics and the ability to create value and perform content analysis through optimization and prediction applications (Ahmad Tarmizi et al., 2020). The challenge of knowledge deficiencies within enterprises pertains to management’s reluctance to oversee IoT, the inadequate skills of employees, and the scarcity of professionals such as data scientists. Consequently, to ensure the successful execution of IoT, organizations must hire experts with IoT expertise and invest in improving the digital skills of their employees to utilize IoT efficiently (Pillai & Sivathanu, 2020).

2.1.2. Interoperability issues

Managing a variety of differing equipment is, in fact, a challenging task. Also, challenges arise when creating a sync system among several different systems. Therefore, compatibility commonly poses a challenge

Table 1
Factors Impacting IoT Integrations.

Categories	Identified Challenges	Their Description	References
Technical Challenges	Reliability of IoT Systems	The adverse perception regarding performance of IoT systems and their reliability due to insecure connectivity is a significant factor.	(Kamble et al., 2019; Luthra et al., 2018; Mishra et al., 2022; Sharma et al., 2020)
	Scalability Challenges	Issues related to scale the integrated IoT system including various devices, huge datasets and increasing number of users.	(Brous et al., 2020; Das, 2019; Hopkins, 2021; Malik et al., 2023)
	Data Security and Privacy Issues	The large volumes of sensitive data transmitted and stored by IoT systems make them attractive targets for cyberattacks.	(Das, 2019; Mircea et al., 2021; Seetharaman et al., 2019)
	Interoperability Issues	The inability of IoT devices and platforms from various manufacturers to seamlessly communicate due to non-standardized protocols and frameworks.	(Arnold & Voigt, 2019; Ehie & Chilton, 2020; Satar et al., 2019)
	Standardization Gaps	The lack of universally accepted standards for IoT devices, communication protocols, and data formats contributes to inefficiencies.	(Eskerod et al., 2019; Hsu & Yeh, 2017; Oke et al., 2022; Singh & Bhanot, 2020)
Organizational Challenges	Lack of Skilled Workforce	There is a shortage of adequately trained personnel proficient in managing IoT technologies, such as data analytics, cybersecurity, and system integration.	(Ahmad Tarmizi et al., 2020; Hsu & Yeh, 2017; Ladasi et al., 2019; Pillai & Sivathanu, 2020; Tang & Ho, 2019)
	High Initial Investment	Considerable expenditure to purchase software, hardware, infrastructural environment, and trainings for stakeholders associated with IoT integrations is a key challenge.	(Hsu & Yeh, 2017; Ladasi et al., 2019; Rey et al., 2021)
	Resistance to Change	The willingness to change and resistance towards adoption of IoT systems from traditional operating systems is a key challenge.	(Brous et al., 2020; Jia, Komeily, Wang, & Srinivasan, 2019; Khanna & Kaur, 2019)
	Data Management Complexity	Huge volume of data produced by IoT systems needs advanced databases	(Ehie & Chilton, 2020; Kim & Kim, 2016; Lu et al., 2018)

(continued on next page)

Table 1 (continued)

Categories	Identified Challenges	Their Description	References
	Vendor Dependency Risks	and highly skilled analytical capacity. Over-reliance on specific vendors for IoT solutions can limit flexibility, increase costs, and create challenges in adapting to technological advancements.	(Caro & Sadr, 2019; Ladasi et al., 2019; Tang & Ho, 2019)
Environmental and External Challenges	Regulatory Issues	Complicated and unstandardized rules related to technological adoption particularly IoT related to information privacy and security.	(Hsu & Lin, 2018; Lee, 2019; Rejeb et al., 2021)
	Environmental Impacts	Diverse environmental impacts such as e-waste, energy reliant devices and carbon emission by IoT systems.	(Arnold & Voigt, 2019; Tu, 2018)
	Lack of Infrastructure	Issues such as irregular electricity and internet connections, high quality computational power and technology compatible infrastructure poses a significant challenge.	(Ehie & Chilton, 2020; Hawash et al., 2021; Tang & Ho, 2019)

with IoT. Integration of multidisciplinary disciplines, previous technologies, and the practical application of a basic, user-friendly service architecture all add to the complexities of implementing IoT (Satar et al., 2019). Business procedures may be constrained within an organization or extend across organizational boundaries, complicating process integration due to varying interfaces, technologies, methodologies, protocols, and distinct characteristics of each participating organization. Moreover, businesses' past technologies have evolved, characterized by isolated databases and restricted interconnectivity to outside systems, keeping them extremely limiting and making enhancing or extending their usefulness difficult (Ehie & Chilton, 2020).

2.1.3. Standardization gaps

Standards are integrated to facilitate various kinds of implementations. Despite the application of conceptual frameworks, machine-accessible regulations sometimes lead to contradictions and misconceptions arising from varying contexts faced throughout time. Establishing guidelines for the proper utilization of IoT across diverse applications (Singh & Bhanot, 2020).

2.1.4. High initial investment

The adoption of IoT technology within businesses necessitates a significant early investment in technological infrastructure assistance, components, programming, qualified employees, and education because of IoT's multidisciplinary nature and complexities, along with the associated maintenance and operational costs (Ladasi et al., 2019). The higher expense of IoT technology restricts businesses' plans to use it, especially small and medium-sized enterprises (SMEs) with constrained

financial resources. Also, businesses are hesitant about the potential for permanent financial and economic losses, and the return on investment (ROI) may require a longer duration than anticipated, hence extending the payback period (Khanna et al., 2022). Hence, implementation expenses are crucial in the decision-making process regarding IoT adoption. High implementation costs generally result in reduced IoT adoption inside enterprises.

2.1.5. Scalability challenges

An IoT network involves diverse devices interconnected in a collaborative setting utilizing various protocols and technologies. This characteristic caused IoT technology to be significantly deficient in interoperability and scalability because of the variability of connected devices. IoT devices will produce exponentially more significant volumes of big data in the future, necessitating an increased number of connected physical devices (Hopkins, 2021). Scalability will be critical as companies must adapt to the evolving complexities of data collecting and processing. Providing practical and scalable infrastructure to manage the complexities of IoT big data is crucial for realizing new commercial value (Malik et al., 2023).

2.1.6. Regulatory issues

Insufficient implementation of regulations and legal structures results in inadequate standards and difficulties in security, data exchange, protection, and questionable control (Hsu & Yeh, 2017). Authorities should assess methods to promote emerging technological advancements, such as the Internet of Things (IoT), and systematically implement this technology into business models to enhance economic competitiveness. Hence, governments need to create significant laws and guidelines to promote the adoption and advancement of IoT technology, thereby unlocking its complete economic and societal potential (Rejeb et al., 2021). This involves determining challenges and proposing approaches, establishing regulations for privacy and liability, promoting technology investment, and enhancing tax incentives for research and development. So, enhanced efforts are necessary to advance IoT applications by establishing national initiatives and legislative instruments that strengthen the IoT technology growth framework.

2.1.7. Environmental impacts

Integrating multiple IoT devices in various operational activities leads to energy consumption and e-waste and increases carbon emissions for businesses. Recent developments in the field of IoT highlight that energy-efficient devices lower energy consumption and carbon emissions (Arnold & Voigt, 2019). However, businesses that are heavily reliant on IoT infrastructure and complex systems face issues related to environmental sustainability, which leads to limited adoption of IoT technology (Ingemarsdotter et al., 2020).

2.1.8. Lack of infrastructure

Implementing an IoT-based system within any business requires significant infrastructure. The scale of business models affects this requirement, which poses a significant challenge when implementing IoT systems (Hawash et al., 2021). Other facilities, such as technological compatibility, power supply, computational resources, internet connectivity, etc., are required as infrastructure to manage the IoT integration effectively (Tang & Ho, 2019).

2.1.9. Reliability of IoT systems

The primary objective of higher reliability is to augment the effectiveness of IoT services through their capacity to communicate information effectively. Therefore, several inspections must be conducted on the network's architecture's hardware and software components (Kamble et al., 2019). The integrity of the framework in IoT is consistently challenged by limitations arising from system failures or risks of breach. Like previous technologies, IoT technology naturally encompasses both commercial and technological uncertainties (Sharma et al.,

2020). The rapid advancement of technology could damage the IoT by introducing a sophisticated new technology. Decision-makers are apprehensive about the unpredictability linked to technical advancement and the substantial investment expenditures of IoT, which may be surpassed by other developing technologies (Mishra et al., 2022).

Table 1 highlights the findings of the literature about the key barriers impacting IoT integrations in business models.

2.1.10. Resistance to change

Implementing novel approaches, machines, or approaches within businesses is a major initiative. A significant segment of workers is resistant to acquiring new technologies or modifying their daily activities. Employees experience comfort and alignment with the existing technologies (Brous et al., 2020). However, they express concern regarding their incapacity to utilize rising technology like IoT, leading to their rejection of these innovations. Also, integrating IoT technology in the workplace results in heightened automation and autonomy, creating fear among employees over job security and prompting resistance to IoT adoption. Consequently, employee attitudes substantially impact IoT deployment's technological efficiency and failure (Khanna & Kaur, 2019).

2.1.11. Data management complexity

Despite offering various potential applications like data analysis, forecasting, real-time monitoring, etc., IoT devices generate vast amounts of data. Businesses must deal with this information effectively to manage this small data. The requirements to manage this data include advanced data management systems and a skilled workforce, which pose a significant challenge in the case of IoT adoption (Ehie & Chilton, 2020).

2.1.12. Vendor dependency risks

Nowadays, IoT devices and accessories from major manufacturers are incapable of intercommunication because of their distinct platform structure. Unfortunately, competitive dynamics and market restrictions among IoT providers and technology vendors have limited IoT adoption (Caro & Sadr, 2019). Additionally, there is inadequate technical support from manufacturers and suppliers during the implementation of IoT applications. Since IoT is an emerging technology with complicated characteristics, it needs considerable vendor assistance during and after installation. Also, business models encounter challenges in identifying suitable vendors and suppliers capable of providing high scaling, resilience, and optimum outcomes while ensuring efficiency and accuracy (Ladasi et al., 2019). Consequently, identifying the appropriate IoT provider that can deliver optimal IoT solutions and support is challenging.

2.1.13. Data security and privacy issues

Although IoT enhances the business's performance and efficiency, it also presents numerous safety and confidentiality issues as an expanding number of interconnected equipment become integrated into businesses. Privacy issues linked to IoT are evident through the illegal execution of functions and the exposure of confidential and sensitive customer information (Das, 2019). IoT security concerns encompass many assaults against software, hardware, and networks, including denial of service, hacked or damaged devices, and data or information alteration/loss. Additionally, the adoption of IoT necessitates collaboration among multiple stakeholders, which raises issues related to data ownership and security. As a result, the security implications of IoT are presenting substantial obstacles to broader organizational adoption for several reasons (Mircea et al., 2021). The potential security threat intensifies owing to the absence of standardized protocols and architecture for IoT security. Secondly, IoT networks consist of diverse devices, platforms, communication channels, and protocols, resulting in multiple layers requiring distinct security methods. Thirdly, most IoT communications are wireless, facilitating the ease of potential attacks (Singh &

Bhanot, 2020).

2.2. Gaps in existing research

Even though the challenges related to IoT integration were considered, literature primarily focuses on specific sectors in combinations. This fragmented framework insufficiently handles the related complications of IoT integration challenges preventing the establishment of broad strategies. Technological challenges such as compatibility with existing systems and scalability, are integrally linked to business-related challenges such as unwillingness to transformation and expensive pricing. Rules and regulations increases issues related to privacy and security of information. Thus a critical need emerges for structured methods of decision-making that addresses these interconnected components and provide meaningful findings. The Fuzzy DEMATEL offers a robust approach for recognizing and ranking these identified challenges based on their causal relationships. Addressing these challenges requires an advanced understanding of their interconnections and a methodical approach to prioritization. The present research seeks to enhance prior studies by formulating novel strategies for IoT adoption, enabling enterprises to fully leverage its transformative potential.

3. Materials and methods

The study analysed existing studies and expert opinions to identify IoT integration challenges within business models. Using Fuzzy-DEMATEL, we explored the causal relationship between these challenges. This section highlighted the adopted approach for the research demonstrated in Fig. 1.

Fig. 1 shows the detailed systematic research methodology utilized to explore IoT integration challenges within businesses.

3.1. Data collection

The current study uses a questionnaire to collect data from experts with backgrounds aligning with the current research theme. The questionnaire consisted of three parts, i.e., the objective of the study and demographic information such as expertise, role of expert in the business model's ecosystem, and experience; a brief description of IoT and the factors influencing its implementation; linguistic and influence scale; respondents were requested to fill the responses using given scale.

The Fuzzy-DEMATEL method advises that the team of experts, consisting of six to eleven experienced individuals with expertise in a research area, is enough to give feedback according to a formalized structure (Khatun et al., 2023). This method does not involve data on a big scale, as it takes place in general questionnaire studies (Islam et al., 2018; Parmar & Desai, 2020). The method assists in evaluating the interconnections and causal relationships among specified components. The questionnaire was developed and pre-tested with the help of experts, including academicians and senior technology developers. Among the experts, three experts from the industry have more than fifteen years of experience, and the other two have experience more than ten years.

Three experts with experience as senior IoT experts were selected from technological backgrounds with more than ten years of experience. Three experts from academia possess more than fifteen years of experience in the related research area. Final data was gathered from ten respondents from different businesses. The data were collected through personal visits and online. The selection of respondents for this study depended on the number of participants, expertise in the subject area, and year of experience. Fifteen experts were requested to obtain the data for this study, and ten experts acknowledged an interest in providing their time and expertise to analyse the factors. The experts utilized a linguistic and influence scale to provide their responses.

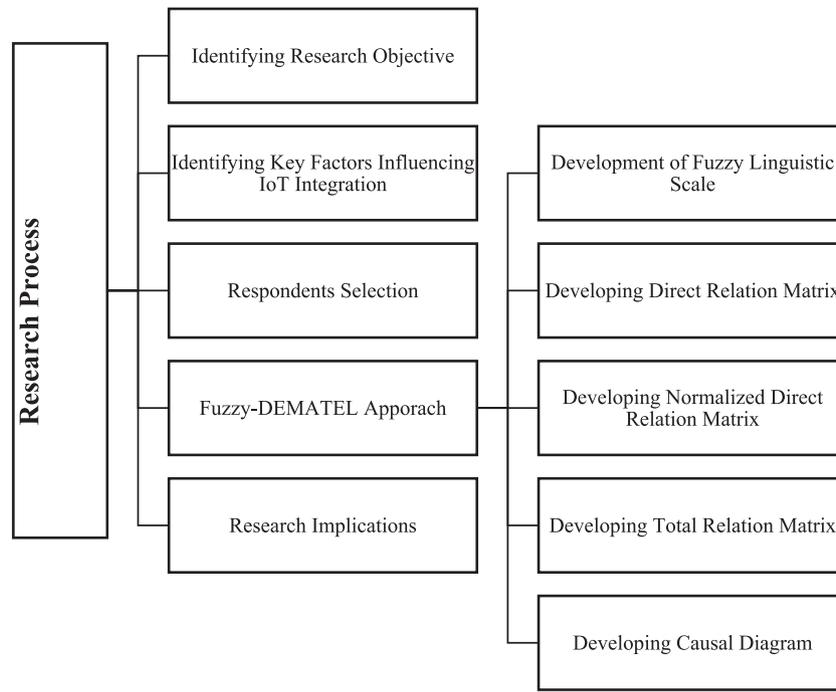


Fig. 1. Research Flowchart. (Source: The Authors)

3.2. Fuzzy-DEMATEL approach

DEMATEL is an efficient approach for exploring interactions among factors influencing IoT integration by integrating collective experience. The primary significance of this approach is based on its application to multi-criteria decision-making, namely in establishing a connection and framework among many elements. Including the fuzzy concept with this method will be beneficial because of the uncertainties in participants responses. The present research implemented the DEMATEL method for the following two reasons: initially, to calculate the matrix of interactions between the key challenges, and second, to identify the primary challenges that influences others. Similar methodology was adopted in various domains such as investigating the willingness to adopt IoT in manufacturing industry (Sumrit, 2024), assessing and demonstrating business models (Carvajal et al., 2019), and exploring the integration of lean six sigma practices with industry 4.0 (Ibrahim & Kumar, 2024). Parmar and Desai (2020) used this technique to investigate the drivers of six sigma practices in a sustainable manner. Kumar et al., (2024) developed a framework to improves competitive edge and social efficiency of Indian SMEs using Fuzzy DEMATEL. Likewise, Mohapatra et al., (2023) adopted similar approach to address lean barriers highlighting its relevance in business transitions. Gaur et al., (2020) explored the major drivers impacting the productivity of retail websites. Many other authors adopted Fuzzy DEMATEL approach solely and combined with other approaches such as Fuzzy AHP to investigate and prioritize variables influencing IoT adoption in businesses (Nezhad et al., 2023; Mousakhani et al. (2022)). Similar methodology was adopted to investigate the Blockchain-integrated IoT (B-IoT) models to optimize the efficiency and improving traceability (Singh, Khan, Dsilva, & Centobelli, 2023).

The hybrid fuzzy-DEMATEL technique is preferred in this investigation because it can quantify and assess association strength. It is explained by Farooque et al., (2020) which independent variables influence which dependent variables. According to Islam et al., (2019), the integrated approach helps manage variation that is influenced by human subjective opinions (Islam et al., 2019). Fig. 1 presents the step-by-step process for Fuzzy-DEMATEL. Eqs. 1 to 5 below were used to calculate

and develop the normalized direct relation matrix, where Z_{ij} is given as crisp values (Islam et al., 2018).

$$x_{ij}^k = (l_{ij}^k - \min l_{ij}^k) / \Delta_{\min}^{\max}$$

$$x_{m_{ij}}^k = (m_{ij}^k - \min m_{ij}^k) / \Delta_{\min}^{\max}$$

$$x_{r_{ij}}^k = (r_{ij}^k - \min r_{ij}^k) / \Delta_{\min}^{\max}$$

Where.

$$\Delta_{\min}^{\max} = \max (r_{ij}^k - \min l_{ij}^k) \tag{1}$$

To calculate right side (rs) and left side (ls) normalized values using:

$$x_{ls_{ij}}^k = x_{m_{ij}}^k / (1 + x_{m_{ij}}^k - x_{l_{ij}}^k) \tag{2}$$

$$x_{rs_{ij}}^k = x_{r_{ij}}^k / (1 + x_{r_{ij}}^k - x_{m_{ij}}^k) \tag{2}$$

To calculate the crisp values, use:

$$z_{ij}^k = [x_{ls_{ij}}^k (1 - x_{ls_{ij}}^k) + (x_{ls_{ij}}^k)^2] / [1 - x_{ls_{ij}}^k + x_{rs_{ij}}^k] \tag{3}$$

To calculate total normalized crisp values using:

$$z_{ij}^k = \min l_{ij}^k + x_{ij}^k \cdot \Delta_{\min}^{\max} \tag{4}$$

To integrate crisp values using:

$$Z_{ij} = \frac{1}{p} (z_{ij}^1 + z_{ij}^2 + \dots + z_{ij}^p) \tag{5}$$

here, p denotes number of decision makers.

$$R = N(I - N)^{-1} \tag{6}$$

here I denote the identity matrix.

Eq. 6 was used to calculate the total relation matrix, and values of $D - R$ and $D + R$ were used to develop the causal diagram. If the values in $D - R$

R are positive, that group is categorized as cause, and if the values are negative, then that group is categorized as effect group. It will provide a clear representation of the relationship and the impact of factors on each other.

4. Results and discussion

A total of thirteen factors influencing IoT integration in business models were identified. The selected experts were asked to provide their perceptions using linguistic terms and influence values/scales. The linguistic terms and influence values used are given in Table 2, presented as positive triangular fuzzy numbers (TFN) denoted as L_{ij} , M_{ij} , and N_{ij} .

The collected responses were initially in the form of a direct relationship matrix (DRM), presented in Table 3. Similarly, responses from each expert were collected in the form of similar DRM.

The data collected from all experts were converted into fuzzy assessment matrix structures TFNs to represent the uncertainty in the decisions precisely. The fuzzy information was transformed into precise values, and the resulting accurate data was expressed as DRM. The normalized DRM was calculated by eqs. 1–5. The matrix R was calculated using eq. 6 and presented in Table 4.

The sum of all element rows was denoted by D, and the column elements were denoted by R. The axis D + R is indicated as “prominence” and D-R as “relation.” Table 5 represents the values of D, R, D + R, and D-R. The factors were categorized into “Cause” and “Effect” as positive and negative values of D-R, respectively.

We analysed the significant challenges and IoT integration’s impact within business models utilizing the Fuzzy-DEMATEL method to identify the main responsible factors. The D-R and D + R values were evaluated to get a causal relationship diagram demonstrated in Fig. 2. It highlighted that cause factors are F1: Lack of Skilled Workforce, F2: Interoperability Issues, F3: Standardization Gaps, F4: High Initial Investment, F6: Regulatory Issues, F10: Resistance to Change, and F13: Data Security and Privacy Issues whereas effect factors are F5: Scalability Challenges, F7: Environmental Impacts, F8: Lack of Infrastructure, F9: Reliability of IoT Systems, F11: Data Management Complexity, and F12: Vendor Dependency Risks. These challenges were categorized as cause factors that significantly impact the decision-making process while integrating IoT.

In the cause factors, F10: Resistance to Change, with a D – R value of 1.5054, indicates the most significant challenge with a degree of impact of 5.2, making it at first rank. Resistance to change signifies an organizational unwillingness and hesitance towards accepting IoT caused by concerns about disruption, insufficient knowledge, or uncertainty of a return on investment. The resistance restricts IoT adoption and decreases effectiveness. Approaches for managing change, such as worker engagement and straightforward disclosure of IoT advantages, are crucial for navigating this challenge. Hence, it is a major challenge impacting the integration of IoT within business models. The causal factor F2: Interoperability Issues, with the second highest D – R value of 0.9804, indicates its significant impact at degree 5.5. Previous research also emphasized interoperability challenges caused by different protocols and methods, which restrict uninterrupted interaction among IoT devices and systems. This component restricts system integration and impacts scalability. Businesses spend supplementary expenses for customized integrations and confront challenges with operations. The implementation of standardization initiatives and universal protocols

can address these challenges, facilitating seamless communication among devices and systems. The analysis shows that F2 significantly affects other factors. Therefore, F2 is a major challenge impacting IoT integration.

These findings support the research carried out by Kuzminykh et al., (2022). The factor F3 having 5.1 degree of impact and value 0.6562 for D – R highlighting absence of related rules and regulations standardized for IoT systems. This component is primarily linked to problems over compatibility and durability. Different standards raise complexities and costs in the implementation of IoT. Businesses have to work together with professional groups to push for regulations, ensuring consistent and cost-effective IoT implementation. Janiesch et al., (2020) examine the relationship of IoT with Business Process Management, emphasizing the requirement for standardization to effectively handle applications for the IoT.

The F6: Regulatory Issues, a cause factor with 0.5726 D-R value signifies that legal complexities, including compliance with privacy, security, and operational norms, present significant barriers to IoT implementation. This factor influences multiple dependent factors, such as data security and reliability. Businesses experience disruptions and increased costs for adherence. Properly established and effective regulatory structures could promote an environment suitable to IoT adoption, enhancing trust and inventiveness. Kuzminykh et al. (2022) emphasized the necessity for comprehensive safety regulations to adhere to legislation. F13 which is “Data Security and Privacy Issues”, a cause factor with 0.4341 D-R value emphasized the concerns related to drawbacks of IoT systems and data management issues due to these drawbacks. Such issues influences the stakeholders trust and compliance because data leaks can cause financial loses, business image damage and legal implications. Developing strong counter measure to prevent such cyber issues is the valid methodology. Factor F4 related to high investment, a cause factor with 0.2225 D-R value highlights the requirement of huge initial payment to adopt IoT systems for all facilities such as hardware, infrastructure, trainings etc. This challenge is directly linked with scale of business and impacted SMEs mostly. Therefore factors F3, F4, F6, and F13 are primary cause factors. F1 which is “Lack of Skilled Workforce” has 0.0448 D-R value and pointed towards the unavailability of IoT experts and skilled manpower for advanced data analytics. Adoption and implementation of IoT systems is very challenging for businesses due to lack of skilled employees. These situations can postpone their IoT integrations and can impact financially. Thus engaging in educational events, training workshops, and association with academia can addresses such issues to support effective IoT integrating.

The effect factor F8 which is “Lack of Infrastructure” having value –0.1626 of D-R, highlights the lack of IoT related facilities, including electricity, advanced computational power, infrastructure, internet connectivity etc. and their influence on IoT integration. Expansion of IoT systems and their operating capacity directly affected by limited infrastructural facilities. Thus collabs with technology developers and adequate investment can address these challenges. The effect factor F5 “Scalability Challenges” having –0.3873 value of D-R emphasized scaling issues related to IoT integration and their impact on potential applications of IoT systems. The effect factor F11 “Data Management Complexity” has –0.5520 D-R value highlighting the requirement for advanced technology to deal with high volume of data generated by IoT systems and skilled manpower. Adopting advanced data management techniques and employing skilled manpower can mitigate such issues. The effect factor F7 “Environmental Impacts” with –0.8984 value of D-R indicates towards increasing ecological impacts of a IoT system implemented on large scale which generates e-waste, high electricity consumption and producing carbon footprints. Such adverse ecological issues can impact business’s brand image and legal complications. Adoption of green IoT systems and low energy based hardware can overcome such issues and ensure sustainable future. The factor F9 “Reliability of IoT Systems” is in effect group with –0.9331 D-R value highlighting the role of efficient and productive IoT systems in

Table 2
Linguistic Scale.

Linguistic Term	Influence Value/Score	Triangular Fuzzy Numbers
No Influence	0	(0.0, 0.0, 0.25)
Very Low Influence	1	(0.0, 0.25, 0.50)
Low Influence	2	(0.25, 0.50, 0.75)
High Influence	3	(0.50, 0.75, 1.0)
Very High Influence	4	(0.75, 1.0, 1.0)

Table 3
Direct Relation Matrix (DRM).

Factors	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13
F1	1	L	L	VH	H	H	VH	H	VH	No	H	H	VH
F2	L	1	H	VH	VH	H	VH	L	H	H	H	VH	VH
F3	VH	H	1	L	VH	H	VH	H	H	L	H	VL	H
F4	VH	H	H	1	VH	VL	H	No	VL	VH	No	VH	VH
F5	VH	VL	VH	H	1	VH	VH	VH	No	VL	VH	No	H
F6	H	VH	VH	VH	VH	1	H	No	VL	H	H	H	H
F7	H	VL	L	H	VL	VL	1	No	No	VL	No	No	VL
F8	H	No	VL	H	VH	H	VL	1	H	L	L	VH	VH
F9	VL	VL	L	VL	L	VL	No	VL	1	No	VL	VH	VL
F10	VH	VH	H	VH	VH	VH	H	VH	H	1	VH	VH	H
F11	L	VH	H	No	H	H	No	H	VL	VL	1	VL	VL
F12	H	No	VL	VH	VH	VL	No	VL	No	VL	No	1	VL
F13	VH	H	VH	H	VL	H	VH	VH	VH	VL	L	H	1

Table 4
Total Relation Matrix (TRM).

Factors	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13
F1	0.2121	0.1913	0.1532	0.1752	0.1984	0.1834	0.2033	0.1921	0.1759	0.1291	0.2129	0.2052	0.1948
F2	0.2321	0.2618	0.2357	0.2354	0.2639	0.2624	0.2482	0.2444	0.2552	0.2181	0.2569	0.2787	0.2495
F3	0.2224	0.2245	0.2409	0.1781	0.2364	0.2412	0.2403	0.2382	0.2363	0.1632	0.2402	0.2255	0.2213
F4	0.2102	0.1970	0.1702	0.2078	0.1745	0.1470	0.2086	0.1498	0.1679	0.1868	0.2064	0.2336	0.2104
F5	0.1402	0.1424	0.1775	0.1565	0.2065	0.1711	0.1752	0.1632	0.1342	0.1159	0.1666	0.1534	0.1585
F6	0.2346	0.2290	0.2301	0.2157	0.2518	0.2566	0.2467	0.1655	0.1917	0.2052	0.2419	0.2495	0.2306
F7	0.1433	0.0900	0.1044	0.1465	0.1043	0.1068	0.1742	0.0833	0.0929	0.0782	0.1226	0.1316	0.0980
F8	0.1714	0.1117	0.1398	0.1706	0.1657	0.1648	0.1326	0.2081	0.1829	0.1269	0.1621	0.1970	0.1560
F9	0.0917	0.0942	0.1035	0.0970	0.1073	0.1024	0.0819	0.0891	0.1660	0.0655	0.1185	0.1557	0.1007
F10	0.2438	0.2666	0.2587	0.2513	0.2782	0.2687	0.2259	0.2610	0.2630	0.2445	0.2809	0.2865	0.2511
F11	0.1571	0.1526	0.1583	0.1156	0.1703	0.1725	0.1533	0.1471	0.1397	0.1161	0.2093	0.1540	0.1267
F12	0.1134	0.0766	0.0707	0.1331	0.1109	0.0695	0.0614	0.0834	0.0765	0.0727	0.0843	0.1689	0.0748
F13	0.2099	0.2244	0.2094	0.1648	0.1805	0.2298	0.2228	0.2271	0.2242	0.1525	0.2221	0.2389	0.2298

Table 5
Values of D + R and D-R.

Notation	Factors	D	R	D + R	D-R	
F1	Lack of Skilled Workforce	2.4267	2.3820	4.8087	0.0448	Cause
F2	Interoperability Issues	3.2422	2.2618	5.5040	0.9804	Cause
F3	Standardization Gaps	2.9086	2.2524	5.1610	0.6562	Cause
F4	High Initial Investment	2.4703	2.2478	4.7182	0.2225	Cause
F5	Scalability Challenges	2.0613	2.4486	4.5099	-0.3873	Effect
F6	Regulatory Issues	2.9488	2.3762	5.3251	0.5726	Cause
F7	Environmental Impacts	1.4761	2.3745	3.8506	-0.8984	Effect
F8	Lack of Infrastructure	2.0898	2.2524	4.3422	-0.1626	Effect
F9	Reliability of IoT Systems	1.3734	2.3064	3.6798	-0.9331	Effect
F10	Resistance to Change	3.3802	1.8748	5.2550	1.5054	Cause
F11	Data Management Complexity	1.9726	2.5247	4.4973	-0.5520	Effect
F12	Vendor Dependency Risks	1.1961	2.6786	3.8747	-1.4825	Effect
F13	Data Security and Privacy Issues	2.7364	2.3023	5.0387	0.4341	Cause

improving business operations. Major issues such as irregular performances and compatibility with existing operation activities can question the reliability of IoT integration. The effect factor F12 “Vendor Dependency Risks” has -1.4825 value for D-R which pointed towards the importance of reliable IoT technology providers and risk related to vendors limited availability. Businesses usually dependent on these technological providers and lack of such vendors impacts the IoT integration.

Addressing major challenges such as Interoperability Issues (F2), Regulatory Issues (F6), and Resistance to Change (F10) positively impact the effected variables such as Scalability Challenges (F5) and Vendor Dependency Risks (F12). Business stakeholders needs to focus on all such aspects to support smooth IoT integration, enhance performance and maximize the capacity of IoT-enabled business models. Thus the findings categorized the main challenges into cause and effect factors highlighting primary challenges which influences IoT integration which are Interoperability Issues (F2), Standardization Gaps (F3), High Initial

Investment (F4), Regulatory Issues (F6), Resistance to Change (F10), and Data Security and Privacy Issues (F13). From the effect group the factors including Scalability Challenges (F5), Environmental Impacts (F7), and Vendor Dependency Risks (F12) are key challenges impacted by primary cause factors. Therefore, businesses should focus on dealing with primary challenges such as Interoperability Issues (F2), Standardization Gaps (F3), Regulatory Issues (F6), and Resistance to Change (F10). Managing these challenges can enhance IoT adoption and integration into business models.

5. Implications of the research

This section highlights the theoretical and practical implications of the study. The research identified several factors affecting IoT integration within businesses divided into cause-effect groups based on their influence on each other. The factors included in the cause positively impact other factors and are influential challenges associated with IoT

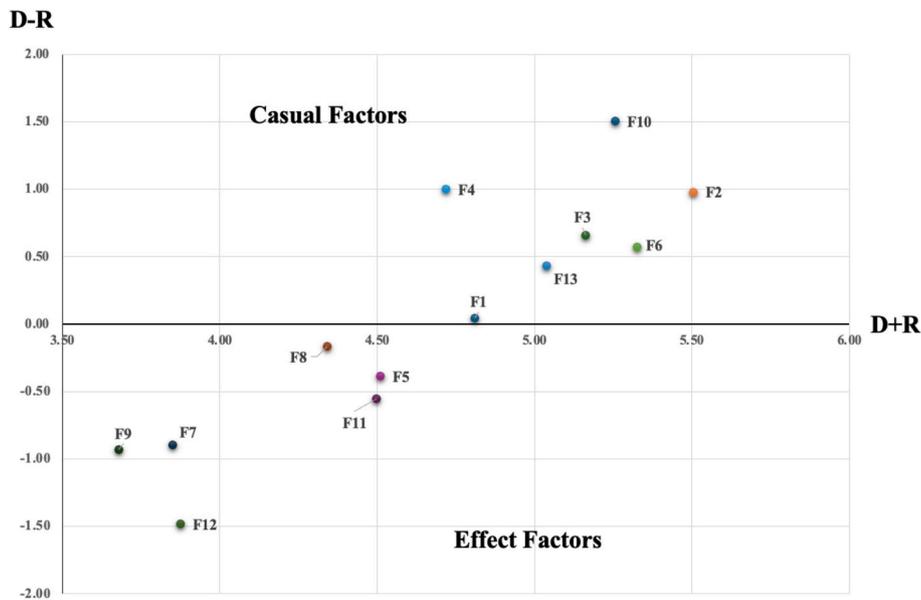


Fig. 2. Cause-Effect Matrix (Source: Authors).

integration. Conversely, effects are impacted more by cause factors. Resistance to Change, Interoperability Issues, Standardization Gaps, Regulatory Issues, Data Security and Privacy Issues, High Initial Investment, and Lack of Skilled Workforce are all the most inflexional challenges associated with IoT integration. These challenges are essential in transforming the IoT ecosystem and enhancing automation, productivity, and sustainability of business models. The results highlight the complex causal relationships and transition in the adoption of IoT in different businesses, demonstrating the importance of addressing such challenges and focusing on key challenges for a sustainable future.

5.1. Theoretical contributions

The current research considerably improves the theoretical perception of integrating IoT and innovation in business models. It contributes to the exiting literature on advancing the integration of IoT, digital transformations and decision making frameworks in business models. This research improves the conceptual discussion among scientific research and actual business issues. It utilizes the Fuzzy DEMATEL methodology to overcome conventional descriptive investigations of challenges and investigate their interrelated dynamics. The results underscore the necessity of overcoming the complicated nature and interconnections of challenges to IoT adoption. The present study offers a comprehensive analytical methodology for classifying IoT integration issues into technological, organizational, and environmental categories. This approach provides a systematic framework that allows researchers to analyse IoT uptake from several perspectives. Furthermore, pinpointing motivating and reliant factors broadens the discussion on causal connections, extending the traditional emphasis on individual challenges. Such holistic approach serves as a foundation for future investigations related to how specific challenges influence the complete IoT systems. This perspective provides an overview of similar multifaceted challenges related to supply chain and technical transitions. The current research highlights specific recommendations to navigate the existing challenges despite solely focus in identification of these challenges. This linkage of theoretical perspectives with practical recommendations strengthens the importance of IoT studies for academic and business partners. It provides the opportunities to explore these theoretical findings using the established theories.

5.2. Practical recommendations

The current research provides practical information for entrepreneurs, policymakers, and other stakeholder stakeholders attempting to successfully handle IoT integration challenges. Essential prerequisites involve establishing standards as a business objective, motivating businesses along with industry organizations to effectively create and implement uniform regulations and standards. Standardization addresses concerns about interoperability, enabling uninterrupted interaction between systems and devices. Managing the lack of skilled employees is crucial for the successful integration of IoT. Businesses should collaborate with academic institutions for awareness and training programs and to develop IoT ecosystem. Authorities could establish benefits or tax refunds that decrease the cost imposed on businesses leads to boost the adoption process. Policymakers need to find a balance among supporting development and maintaining data privacy and security. Clear, regular, and flexible laws and regulations may build confidence in businesses to adopt IoT technologies while ensuring compliance with privacy rules or industry-specific guidelines. Resistance to transformation represents a significant organizational challenge. Businesses have to implement comprehensive transformation management strategies that include straightforward discussions about the benefits of IoT, engagement from stakeholders, and phased implementation techniques. Integrating workers with education and supporting imaginative thinking may create an atmosphere of acceptability and adaptability. With increment in IoT adoption, its socioeconomic and environmental implications should be investigated. Businesses need to encourage the adoption of low-energy gadgets, promote reuse and recycling programs for IoT technology, and adopt circular economy ideas.

The overall results of this research highlight the significance of addressing IoT integration issues through a strategic and cooperative approach. Through incorporating perspectives from the Fuzzy DEMATEL approach, businesses and authorities can devise individual approaches that address core issues, thus allowing effective and sustainable IoT implementation. The continuous advancement of IoT requires the integration of these pragmatic strategies for effectively using its potential to transform business models and support sustainable value creation.

6. Conclusion

Integrating IoT into business models requires major changes in business procedures, inventiveness, and economic development. The current study investigates and evaluates 13 significant issues linked to IoT integration, categorized within technological, organizational, and environmental categories, utilizing the Fuzzy DEMATEL method. The investigation highlights the primary causes, including interoperability challenges, significant initial investment, rules and regulations, and the effects of factors such as scaling constraints, alignment with business goals, and data management complexities. The findings highlight the importance of compatibility concerns and the reliability of IoT systems as key variables influencing several secondary issues. Addressing such essential factors might have a significant influence on related concerns, enabling businesses to overcome the barriers of IoT adoption. Managing legal uncertainty, overcoming regulatory gaps, and enhancing workforce development are crucial for establishing a conducive environment for the transformation of IoT-enabled business models. The conclusions of the current research clearly address the issues related to IoT integration and their interconnectivity. By addressing the identified root causes and implementing the recommended practical suggestions businesses and governments can create a more resilient, expandable, and sustained IoT environment. These findings offer a vital foundation for further research, aiding businesses in navigating the complicated landscape of IoT adoption and embracing its revolutionary capacity for business model transformation.

6.1. Limitations

Considering its positive factors, the research presents considerable limitations including the methodological limitations, focus of research limited to broader IoT adoption challenges avoiding any industry specific investigation. Examining the integration of IoT in highly-regulated industries such as medical or banking could identify specific challenges and alternatives.

6.2. Future research opportunities

The long-term research documenting the evolution of IoT challenges over an extended period could provide important information on how businesses adapt to technological developments and changing legal frameworks. Likewise, integrating quantitative data from IoT installations with expert evaluations could enhance the analysis's robustness. The researchers can adopt mix method approaches to enhance the findings and develop high quality decision making frameworks. These findings can be used to further develop established frameworks such as TOE, TAM etc.

CRedit authorship contribution statement

Parveen Siwach: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis. **Disha Gulia:** Writing – review & editing, Visualization, Validation, Software, Methodology. **Dhiraj Kumar Yadav:** Writing – review & editing, Visualization, Methodology, Data curation, Conceptualization. **Mohit Malik:** Writing – review & editing, Writing – original draft, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Vijay Kumar Gahlawat:** Writing – review & editing, Visualization, Validation, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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