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IoT adoption for sustainable performance in SMEs using an SEM-ANN approach

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Abstract

This research examines the adoption of the Internet of Things (IoT) by small and medium enterprises (SMEs) in Bangladesh using the Technology-Organization-Environment (TOE) model and the Resource-Based View (RBV) theory. This study integrates these frameworks to assess the factors influencing IoT adoption and its impact on firm performance. Furthermore, it seeks to gauge the economic dimensions of IoT-integrated SMEs in developing countries and investigates the effects of IoT adoption on organizational and environmental sustainability. A sample of 149 Bangladeshi professionals from agro-processing, consumer products, e-commerce, leather, and other IoT-based SME sectors was analyzed. A hybrid Structural Equation Modeling–Artificial Neural Network approach was employed to capture complex linear and non-linear relationships among variables. To ensure robustness, the Partial Least Squares model was applied, followed by the bootstrapping method for resampling. The findings indicate that complexity, competitive pressure, top management support, external vendor support, and regulatory frameworks significantly drive IoT adoption in SMEs. Moreover, IoT adoption positively influences both financial and environmental performance, fostering sustainability within SMEs. Hence, this study offers valuable insights for policymakers and researchers regarding the key factors necessary for the successful adoption of IoT in SMEs, particularly in developing economies. The findings also highlight how IoT technologies enable end-to-end monitoring and optimization of environmental performance, improving resource efficiency, reducing operational costs, and enhancing corporate reputation among consumers and stakeholders. Thus, IoT adoption not only aligns with global environmental protection initiatives but also spawns economic benefits.

Article highlights

- IoT serves as a means of utilizing resources, reducing costs, and better reputation in developing economy SMEs.
- The adoption of IoT promotes the financial and environmental performance of the SMEs and leads to sustainable growth.
- Policymakers can use IoT to boost efficiency and strengthen corporate environmental responsibility.



Keywords IoT adoption, TOE model, RBV theory, Developing countries, Financial sustainability, Environmental sustainability

1 Introduction

Fourth industrial revolution has introduced the paradigm shift in the business environment of today by the means of incorporating digital technologies [86]. The purpose of this technological integration is to increase productivity, quality, and efficiency [65, 75]. Internet of Things (IoT) is now and has been an influential factor in the contemporary business landscape that has altered how organizations conduct business and makes decisions [66]. This is a technological revolution that has been marked by the growing connectivity of the common objects, devices and systems such that they are able to gather and exchange data in real time. The emergence of IoT can be attributed to the combination of a number of factors, such as the fact that prices of sensors have dropped, the high-speed internet has become more accessible, and improvements in data analytics and cloud computing. The possibilities to collect and process a great deal of information between the devices that are connected provide business with unprecedented opportunities to streamline its processes, improve customer experiences, and create new sources of revenues. The traditional manufacturing has been revolutionized into smart systems by these technologies [34, 40], that focus on the implementation of new business models that influence the whole value chain, the society, and the environment (Fonseca, 2018).

IoT is a significant business prospect to enhance productivity and competitiveness by introducing novel solutions in the case of small and medium-sized businesses (SMEs) [82]. IoT technologies can help SMEs to restructure their operations [34], lower costs [82], and provide better customer service [92]. The use of IoT solutions can help the SMEs have a competitive advantage in the market and a sustainable growth.

IoT applications used in manufacturing SMEs are the low-cost smart instruction and live process monitoring system in assembly, the real-time expert help and enterprise knowledge platforms [29]. Moeuf et al. [53] identified that 90% of the experts are certain that IoT plays a significant role in the industrial performance of SMEs to redesign production processes and implement new business models. IoT implementation may result in the improvement of the management of resources, improved decision-making, and the creation of new products and services according to the needs of the customers. Such transformation can assist not only to survive but also to succeed in a more competitive global market by SMEs.

Nevertheless, SMEs are often faced with resource limitations and market-specific issues that make the acquisition of new technologies difficult [30]. They may be hindered by limited financial resources, limited technical expertise [29], inadequate infrastructure [26], and data security [44] to invest and implement new and innovative technological solutions such as IoT. Moreover, SMEs are usually in the competition with bigger businesses possessing more resources and it is hard to implement new technologies or to preserve the market position. These issues are forcing SMEs to be prudent in all their technology investments and have strategies that would ensure maximum returns on their investment.

Moreover, business organizations no longer can survive simply by struggling to survive financially in the 21st century. Rather, businesses have to strive to balance between

environmental sustainability and financial sustainability. Environmental sustainability is currently one of the primary sources of organizational behaviors and performance in the contemporary business environment. The adoption of sustainable business practices in business organizations is part of SDGs, which underscores the role of the United Nations in promoting resource efficiency and minimizing environmental effects. This does not only contribute to the international environmental protection agenda, but it also generates business performance, which shows how sustainability could become a business priority that is enhancing the overall ecological and economic outcomes.

The SMEs in most developing countries are significant producers of the Gross Domestic Product (GDP) [16]. SMEs in Bangladesh form 50.9% of all manufacturing plants, 35.5% of employment, and 47% of the gross value added (GVA) of the industry [14] and are a major source of generating economic growth and foreign exchange by promoting and increasing business operations. This makes the implementation of IoT into Bangladesh an excellent socio-economic expansion prospect in different industries, such as agriculture, manufacturing, health care, and transportation [64]. IoT implementation has the capacity to inject significant changes in the SME sector which is a key driver of the Bangladesh economy which has offered encouraging use cases that can support socio-economic development objectives of the country.

In spite of these advantages, the number of studies about the adoption of IoT and its implications is low. The existing studies on the topic of IoT have primarily concentrated on particular industries, including manufacturing SMEs [76, 82] or online education systems [58]. Likewise, Majstorovic et al. [45] examined the IoT in manufacturing and production. The majority of the studies analyzed the role of IoT in the performance of the organization alone (Mukherjee et al., [56]; Mashat et al., [51]). Thus, this paper discusses the implementation of the IoT in particular in improving sustainable organizational and environmental performance among SMEs in developing nations with the specific regard to Bangladesh. In contrast to the literature that mentions general benefits and challenges, the current paper focuses on the ability of IoT to promote financial and environmental sustainability in SMEs through better resource management, operational efficiency, and environmental impact on the environment with references to SDG 12 on Responsible Consumption and Production and SDG 13 on Climate Action.

IoT is a capability for firms and organizations must have internal resources to develop this capability. The association between capability and internal resources is well described by the Resource-Based View (RBV) theory. In contrast, the Technology-Organization-Environment (TOE) model provides prominent elements for IoT adoption. Previous literature adopted only TOE (Al-Badghish & Soomro [11], Al-Sharafi et al., [2]) to explore technology adoption drivers. However, Bag et al. [12] combined TOE and RBV to explore factors affecting blockchain adoption. To the best of the authors' knowledge, no studies in the SME context have integrated these two models to measure factors influencing IoT adoption. To address the gap, this study integrates the TOE model with RBV theory to investigate the drivers of IoT adoption in SME firms in Bangladesh. Moreover, SMEs in this country operate under resource constraints, highlighting the suitability of RBV theory in assessing the internal capability for IoT adoption. Similarly, the TOE framework provides a holistic approach to identifying external capabilities that interact with organizational capabilities rooted in RBV to impact IoT adoption. Therefore, the specific research objectives are:

RO1: To explore the drivers of IoT adoption in SMEs.

RO2: To examine the sensitivity of the drivers in predicting IoT adoption in SMEs.

RO3: To investigate the impact of IoT adoption on sustainable performance in SMEs.

The study focuses on the above objectives and can be differentiated with the current researches due to various reasons. First, the study combines TOE and RBV in the study of the drivers of IoT adoption and the effects of the adoption on sustainable performance, which adds to the body of literature on the topic of IoT adoption. Second, this paper was specifically interested in the context of SMEs in Bangladesh with a specific emphasis made on the changing technological ecosystem. Third, the current study is also methodologically dissimilar as the sample is also symmetric and asymmetric analysis, concentrating on the multifaceted connection of the enablers and results of the IoT adoption.

This research adds to the prevailing literature on the adoption of IoT identically through investigation on the forces, which affect the integration of the IoT to the SMEs in the developing nations. It also touches on how IoT can be used to ensure that the environment is sustainable which has emerged as a major regulatory responsibility of companies. The study classifies the influence of factors on the uptake of IoT by the SMEs into three dimensions, namely, the technological, organizational, and environmental, and evaluates their impact in the adoption process.

The implications of this research will make policymakers have a better idea of the key components that are required to successfully implement the IoT in SMEs, especially in developing countries with little internal capabilities such as Bangladesh. Additionally, it demonstrates the possibilities of SMEs to attain sustainable performance as a result of proper application of IoT technologies.

The remainder of the study is structured in the following manner: Sect. 2 of the study provides the literature review and hypothesis development, Sect. 3 of the study refers to discussion of the methodology used, and finally Sects. 4 and 5 refer to analysis and discussion respectively. Lastly, in Sects. 6 and 7, the implications, conclusion and future directions are discussed.

2 Literature review and hypothesis development

2.1 IoT application and adoption in SMEs

IoT, or the SME industry calls it the Industrial Internet of Things (IIoT), is a complicated set of interconnected devices [73]. Although the IoT optimizes data analytics and automates business processes, offering SMEs with potent means of optimizing their work [80]. It allows the SMEs to learn market trends, customer preferences and make better decisions based on real-time monitoring [54] and automation [98], which makes the data exchange across a network to realize smart business operation [48, 63]. Cloud computing offers SMEs scalable and affordable IT infrastructure to assist them in their efforts to transform digitally [44]. As such, through the implementation of IoT enabled systems, SMEs can get to automate their activities, cut down wastes, and even optimize the use of resources. This will enable them to enhance their bottom line and have sustainable growth, despite the small resources. Moreover, the IoT technologies can also be used to create the social value through improving the working conditions, enhancing diversity and inclusion, and facilitating the community development. The SMEs will be able to

generate both economic and social value by incorporating sustainability in their digital transformation strategies, and building a more sustainable and equitable future [96].

In the past, the COVID-19 served as a major catalyst to the heightened requirements to embrace the use of IoT among SMEs [60]. Nevertheless, the adoption process is complicated and usually may be entailed with numerous technological, organizational, and environmental aspects (Parra and Guerrero, 2020). Moreover, this adoption may be inhibited by financial and technical constraints, as it can be resolved with the help of the government [62].

Nevertheless, the SME industry embraces IoT because it has many advantages. Nevertheless, Asian nations continue to lag in the use of IoT in SMEs. When implemented, IoT positively influences the enhancement of operational efficiency (Priyashan and Thilakarathne, [67]), enhances inventory management and supply chain coordination [28], and sustainable growth [92].

IoT penetration in Bangladesh is on the rise in all sectors such as hospitality, manufacturing and farming. Therefore, IoT has been identified by The government of Bangladesh as a key facilitator of economic development, as described in the National IoT Strategy [64], since it can improve the experiences of the guests with tailored services and optimize the effectiveness of operations in the hospitality industries [32] and can increase productivity and resource management in the agricultural business [85].

Nevertheless, the use of IoT in Bangladesh has been associated with many challenges, e.g., absence of technical skills, expensive nature, and privacy issues, among which the need to overcome has been identified to implement it successfully [32]. Moreover, the manufacturing industry in Bangladesh encounters severe problems such as the absence of the top management decision, high initial implementations, and threats of adopting new models of business [83]. It is important to consider these barriers to improve the industry in terms of competitiveness and sustainability. Despite the fact that SMEs are playing an important role in the economic development of the country, they receive a low priority as far as the use of IoT is concerned.

2.2 Sustainable performance in SMEs

The sphere of sustainable performance is multifaceted, including economic, social, and environmental aspects, which makes business targets consistent with the needs of the entire society and contributes to its long-term sustainability [71]. When applied to SMEs, sustainable performance implies not only profitability and increase but also helping the society and reducing any adverse effects on the environment (Rahman and Sadik, 2025;[93]. This holistic model demands that SMEs, especially entrepreneurs, should take into account triple bottom lines of people, planet, and profit in their business strategy and practices (Asad, Fryan, and Shomo [5, 8]. Incorporating sustainability into their businesses will help SMEs to improve their image and reputation, attract socially responsible consumers, as well as generate value that would be realized over a long period of time [78]. Consequently, stakeholder and social involvement has a partial role in the businesses that are part of the sustainable performance [4, 21, 72].

In the case of SMEs, sustainable performance does not only imply attaining profitability but also adding to social well-being and reducing environmental impact, and thus providing a balanced and responsible approach to business [79]. Fair labor practice, community involvement, and provision of healthy and safe working environment can be

implemented to augment social well-being. The reduction of environmental impact can be reduced by minimizing waste, saving resources, and using environmentally friendly technologies. Green innovation in products and processes, driven, in large part, by technology discoveries, and the presence of entrepreneur networks, is also positively impacting the environment [6, 10, 94]. Emphasizing these factors, SMEs will be able to demonstrate their desire to be sustainable and leave the positive impact on the society and environment.

IoT has become a significant factor in the development of sustainable performance because it allows mobilizing and using resources efficiently and promotes transparency and data-driven decision-making [93, 100]. The IoT sensors can be used to track the energy consumption, water usage, and waste produced by the SMEs, and data analytics can be utilized to find areas in which the company can improve and move towards more sustainable operations. Moreover, the IoT can be used to improve supply chain transparency so that SMEs can monitor the environmental and social impact of their products and services throughout their lifecycle. This enhanced transparency will make SMEs gain the trust of their customers and stakeholders and will show the willingness to be sustainable.

2.3 Theory and research framework

Various theories have been used in the SME industry to assess technology adoption, including the Technology Acceptance Model (TAM), the RBV theory approach, and the TOE framework. RBV theory emphasizes identifying a firm's sources of competitive advantage and how it can maximize its performance by utilizing internal and external resources (Dionysus & Arifin, 2020).

Studies on technology acceptance in SMEs have used TAM, emphasizing collectively qualitative and quantitative approaches (Purnomo et al., 2022). TAM has been applied in SMEs for adopting knowledge management systems (Inayatulloh, 2020), e-business (Sani et al., 2022), and social media marketing (Makmor, 2024). However, TAM overlooks organizational and environmental impacts, despite the significance of both human and non-human perspectives in technology adoption within firms [70].

The TOE framework takes into account the technological, organizational and environmental aspects that determine the adoption of technological innovations by firms [82]. It has therefore been extensively applied in studying the drivers in the adoption of various technology, including e-commerce (Hanafiah et al., 2021), cloud computing [2], artificial intelligence [11], and blockchain [41, 72] within the SMEs and financial industry. TOE framework is especially useful when it comes to learning, applying, and integrating IoT in companies to make sure that its implementation is successful (Zin, 2024). Bhuiyan [17] pays attention to the long-term TOE model based on such dimensions as technology preparedness, governmental support, and decision-making within the manufacturing industry in Bangladesh. TOE and RBV frameworks are connected to each other as they tackle technological, organizational, and environmental aspects, which drive the use of IoT. The frameworks are mostly applicable to Bangladeshi SMEs in recognizing the contextual issue, including top management support and organizational culture, which play key roles in boosting technology adaptation and leveraging internal resources or capabilities to improve the environmental performance when responding to local market dynamics and other external pressures [43]. In this research, TOE will supply a

contextual background to this problem, as it elaborates the effect of TOE factors on the adoption of IoT and RBV will supplement it by focusing on the internal resources within the firm.

Although integrating TOE and RBV provides an all-encompassing approach to the concept of technology adoption, it is imperative to take into account substantial individualities of the context of Bangladeshi SMEs, including resource limitations and different extents of technological preparedness. Such complexity might be an obstacle to the direct use of these frameworks which imply that more specific strategies should be implemented that should respond to the local circumstances.

In an attempt to study thoroughly the factors that influence the implementation of the IoT and their effects on the sustainability of the business performance of SMEs, this paper applies both the RBV theory and the TOE framework. Effect of eight variables, such as relative advantage (RA), compatibility (COM), complexity (CMP), top management support (TMS), organizational readiness (OR), competitive pressure (COP), external support provided by vendors (EXS) and regulations and legislations (REL) on the adoption of IoT (IoTA) in the SME industry of Bangladesh will be tested. This paper also addresses the consequential sustainability of these companies after adopting the use of IoT with regards to alterations in their environmental performance (EP) and financial performance (FIN). The conceptual model is shown in Fig. 1.

2.4 Hypothesis development

2.4.1 Technological factors

2.4.1.1 Relative advantage Relative advantage (RA) denotes the extent to which an emerging technology will benefit more than existing systems in businesses. IoT provides multi-facet benefits to SMEs such as seamless communication among devices, improved productivity and decision-making, better management of inventory and supply chain, and reduced cost [42]. RA has been demonstrated to have a substantial positive effect on SMEs in terms of adopting technologies such as social media in Pakistan [69] and blockchain in Malaysia and Australia [47, 99]. Therefore, the hypotheses are:

H1. RA has a positive impact on the IoT adoption intention of SMEs.

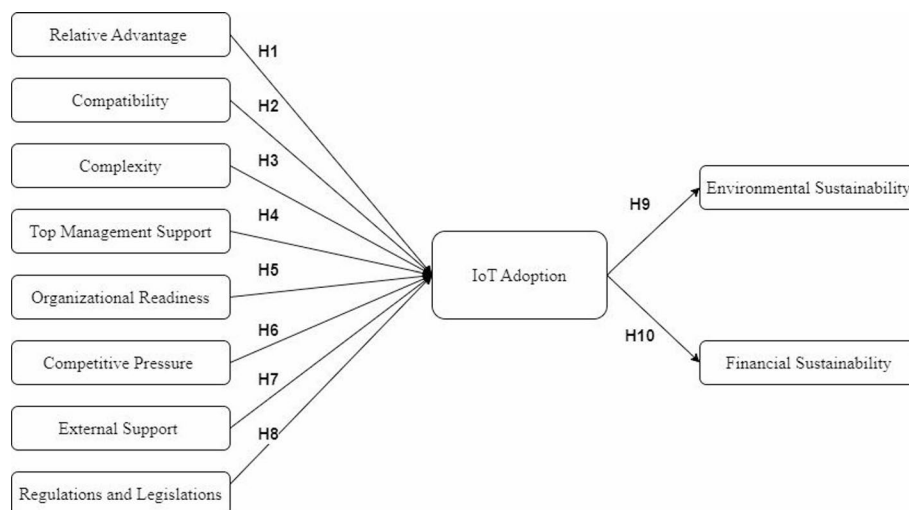


Fig. 1 Conceptual Model

2.4.1.2 Compatibility Compatibility (COM) explains how one system works well with the other infrastructures and objectives of the companies [20] [47]. emphasized that firms intend to adopt new technology if the technology is compatible with the existing IT environment. COM has been found to have a significant positive influence on SMEs' adoption of social media [13, 69]. Contrarily, among SMEs in Lebanon, COM has been found to have an insignificant impact on innovation adoption [89]. Therefore, it can be hypothesized that:

H2. COM has a positive impact on the IoT adoption intention of SMEs.

2.4.1.3 Complexity Complexity (CMP) in the SME context means the level of difficulty in comprehending and implementing new technology in the firm, and it has been proven to have a significant negative impact on adopting innovation in SMEs in Lebanon [12, 89]. Ahmetoglu et al. [1] also found CMP as a barrier to IoT adoption. Therefore, this study hypothesized that:

H3. CMP has a negative impact on the IoT adoption intention of SMEs.

2.4.2 Organizational factors

2.4.2.1 Top management support Top management support (TMS) is a vital factor in implementing any technology, as it requires a fundamental change in business [37] [68]. revealed top managers' support as a significant determinant of the adoption of IoT in the creative sector of the SME industry in West Java, Indonesia. Moreover, previous studies found a significant and constructive association between TMS and intentions to adopt innovation in SMEs [70]. Therefore, the hypothesis is:

H4. TMS has a positive impact on the IoT adoption intention of SMEs.

2.4.2.2 Organizational readiness Organizational readiness (RA) can be interpreted as the availability of required resources in the firm for the desired operation through innovation [91]. Studies found a positive relationship between RA and IoT adoption in the SME industry [68, 91]. However, a study conducted among the SMEs of South Africa has shown an insignificant relation between RA and IoT adoption intentions [2].

H5. RA has a favorable impact on the IoT adoption intention of SMEs.

2.4.3 Environmental factors

2.4.3.1 Competitive pressure Competitive pressure (COP) means the potential distress of losing the competitive advantage of a firm due to the presence of its competitors in the market. This kind of external pressure compels organizations to adopt technologies such as IoT [33]. COP has a significant and positive impact on the proper adoption of innovation in SMEs in Pakistan [70], as well as in Indonesia [68]. Therefore, it can be hypothesized that:

H6. COP has a positive impact on the IoT adoption intention of SMEs.

2.4.3.2 External support from vendors Firms can successfully adopt innovation into their business processes if they get the proper external support from their vendors (EXS) [12]. Vendors deal with the difficulties of installing novel technologies and provide technical support and help with infrastructural maintenance [50]. On the other hand, a lack of support from local vendors may lead to disruption of operations if firms face technical

difficulties. Therefore, support from suppliers plays a vital role in adopting innovations such as IoT. Thus, it can be hypothesized that:

H7. EXS has a positive impact on the IoT adoption intention of SMEs.

2.4.3.3 Regulations and legislations Regulations and legislations (REL) mean the laws set by responsible authorities in the country, as well as those that exist in the industry. Government policies can make firms adopt innovation in their business processes [55]. When it comes to developing countries, REL is extremely significant in the case of adopting innovation in SMEs [68]. Therefore, we can hypothesize that:

H8. REL has a positive impact on the IoT adoption intention of SMEs.

2.4.4 IoT and smes' sustainable business performance

The sustainable business performance of an SME can be measured in terms of its environmental performance (EP) and financial performance (FIN) [12]. Literature has proven that adopting various innovations, cloud computing [2], AI [11], and blockchain [41], has a significant positive impact on the overall execution of different SMEs all over the world. Similarly, IoT, being another innovation of Industry 4.0 [90], the following hypotheses can be made.

H9. IoT adoption has a beneficial impact on the EP of SMEs in Bangladesh.

H10. IoT adoption has a favorable impact on the FIN of SMEs in Bangladesh.

3 Methodology

3.1 Population, sampling, and data collection

The target population of the study comprises the employees working in SME companies in Bangladesh. The study follows the purposive sampling technique. The rationale for using purposive sampling, as suggested by Campbell et al. [18], is that purposive sampling facilitates researchers in finding target respondents based on specific criteria or perspectives. Two important aspects have been considered in selecting samples. Firstly, the respondents must be employees in any SME firm that utilizes IoT. Secondly, ease of reach is another criterion of selection. Hence, the target respondents were from IoT-based SME organizations who could be reached conveniently.

The authors distributed Google Form links to 215 target respondents working in SME companies that use IoT technologies. The distribution list consisted of respondents from five sectors of SME companies in Bangladesh: 57 from agro and agro-processing, 45 from consumer products, 80 from e-commerce, 12 from leather, and 21 from other categories, e.g., Fashion, Foods, and Handicrafts. As this study collected data from 5 major sectors of SME companies, the findings from the data can be representative of the SME sectors of Bangladesh. The research team distributed the questionnaire at the beginning of June 2024. By the end of July, only 106 respondents filled up the questionnaire. Then the team made several follow-ups through online reminders and received an additional 43 questionnaires by September 2024. Finally, the analysis has been done with 149 responses, reflecting an effective response rate of 69.30%. The list of sectors from which respondents took part in this study is listed in Table 1.

There has been extensive research to determine the appropriate sample size for different types of statistical analyses. Although a sample size of 200 is considered reasonable [38], a sample size below 200 can be used for robust statistical analysis using the

Table 1 Respondents from different sectors

Sectors	Frequency	Percentage
Agro and Agro Processing	41	27.52%
Consumer Products	38	25.50%
E-Commerce	52	34.90%
Leather	7	4.70%
Others (Fashion, Foods, and Handicrafts)	11	7.38%
Total	149	100%

PLS-SEM approach [77]. Studies on IoT, cloud, and digital technology adoption in SMEs frequently employ sample sizes in the range of 100 to 200. For example, with the application of SEM, Malesios et al. [46] assessed supply chain sustainability in SMEs using a sample of 120 firms, demonstrating that medium-sized samples can produce robust results when the study is carefully designed. Likewise, Alshahrani et al. [3] investigated IoT-based sustainable energy solutions for SMEs with a sample of 50 firms. From a statistical perspective, a sample of 149 provides adequate power for regression and SEM, meeting the recommended minimum ratio of 5 to 10 observations per estimated parameter [9]. Besides, still, there are still limited companies that are using IoT, particularly in the SME sector, which is another reason for having a small sample size. However, the bootstrapping technique with a sub-sample validates the results with a small sample size, as suggested by Mariri & Scheepers [49]. Hence, the final SEM analysis used bootstrapping with 5000 samples, which certified the strengths of the relationships between variables.

3.2 Study instruments

To assess each variable and achieve the research objectives, relevant scales were employed. Respondents were required to provide their observations on a 5-point Likert scale, where 1 represents “Strongly Disagree” and 5 represents “Strongly Agree.” The measurement items have been formulated based on the literature. The items for each construct have been presented in Table 2 with the justifications.

In order to keep theory-driven variables at a high level of conceptual precision, the control variables were intentionally excluded from the TOE and RBV frameworks. While this study sample is relatively homogeneous, the variance accounted for by typical controls (such as firm age, size, sector) may be minimal [24, 61]. The SME sample’s homogeneity in industry and geography made it unnecessary to include control variables like firm size or age. Therefore, no controls were necessary. Also, in SEM-ANN hybrid models with restricted sample sizes, control variables may inflate the model [52, 87]. Hence, the final structural model did not include any control variables to maintain model parsimony. Furthermore, controls may not be necessary in exploratory or theory-building research, particularly when the objective is to identify key drivers rather than distinguishing causality.

3.3 Respondents’ consent and ethical assessment

In Bangladesh, social science research is not subject to requiring ethical approval under institutional policies or national legislation. Only sensitive scientific and medical research, such as animal trials, requires ethical evaluation. Nonetheless, ethical approval was obtained from the Ethics Committee for Research Involving Human Subjects of the

Table 2 Study instruments

Constructs	Constructing Items	Sources	Justification for Using Variables in the Current Study
RA	RA1: IoT adoption elevates the quality of work. RA2: IoT adoption streamlines work more efficiently. RA3: IoT adoption has resulted in positive reviews from customers.	[59]	This study assumes that IoT adoption presents SMEs with better opportunities, leading to RA in the business.
COM	COM1: IoT adoption goes well with our business practices. COM2: IoT adoption is relevant according to our organizational culture, COM3: It is easy to adopt IoT in the business.	[97]	The current study believes that organizational COM is required to measure IoT adoption.
CMP	CMP1: Training on IoT adoption is difficult for the employees. CMP2: The resultant system after IoT adoption in the business is difficult to operate. CMP3: The resultant system after IoT adoption in the business is difficult to maintain.	[50, 74, 95, 97]	The study aims to examine the CMP of IoT, which could potentially be a barrier to IoT adoption in SMEs, particularly in Bangladesh, due to a lack of infrastructural support and skilled employees.
TMS	TMS1: The top management of our organization supports the adoption of IoT in the business. TMS2: Our top management regards IoT adoption as a matter of strategic priority in the organization. TMS3: Top management has taken steps to adopt IoT into the business.	[50]	The particular study perceives that TMS is crucial for IoT adoption, as previous research shows that leadership commitment is essential for the successful implementation of emerging technologies.
OR	OR1: IoT adoption in our organization is not possible because of a lack of relevant IT infrastructure. OR2: The organization does not have enough funds to invest in IoT adoption. OR3: You feel prepared to adopt IoT in your business.	[22]	The paper measures OR for IoT adoption as it presumes that adequate infrastructure and funds are needed for the proper adoption of the technology.
COP	COP1: We remain aware of our competitors when it comes to IoT adoption. COP2: We feel pressured to adopt IoT due to our competitors doing it. COP3: Our decision to adopt IoT is dependent on our competitors' decision in this matter.	[50]	Hypothesizing that competition among businesses can drive innovation, the study investigates the relationship between COP and IoT adoption of SMEs.
EXS	EXS1: There are available vendors to help with setting up IoT in the business. EXS2: Vendors can provide relevant training to the staff about the newly implemented system. EXS3: The business can afford the service of a vendor to help with its IoT adoption. EXS4: Support from vendors would make IoT adoption and maintenance much easier.	[50]	This paper explores the role of EXS in IoT adoption, considering them as key facilitators of IoT adoption in SMEs.
REL	REL1: The government policies support IoT adoption in our business. REL2: The government offers incentives for adopting IoT in the business. REL3: There are safety policies for secure IoT adoption and maintenance in the business.	[50]	Assuming that supportive laws and regulations benefit technological adoption, this paper aims to analyze the relationship between REL and IoT adoption in SMEs.

Table 2 (continued)

Constructs	Constructing Items	Sources	Justification for Using Variables in the Current Study
IoT	IoT1: Our company has adopted IoT to adapt to the changing market. IoT2: Our company has adopted IoT to gain a competitive advantage. IoT3: Our company has adopted IoT to reduce operational costs. IoT4: Our company has adopted IoT to reduce communication costs. IoT5: Our company has adopted IoT to improve employee productivity. IoT6: Our company has adopted IoT to improve transaction accuracy.	[50]	The authors wish to examine different motivations that drive SMEs' intentions to adopt IoT in their businesses.
EP	EP1: IoT adoption in the business has helped reduce wastewater. EP2: IoT adoption in the business has helped reduce the production of solid waste. EP3: Due to IoT adoption, the consumption of hazardous materials has decreased.	[50]	The study assesses the environmental performance of SMEs post-IoT adoption, considering IoT's role in favor of sustainable business practices.
FIN	FIN1: Compared with our competitors, our customer retention has improved in the last 2 years. FIN2: Compared with our competitors, our sales have improved in the last 2 years. FIN3: Compared with our competitors, our profitability has improved in the last 2 years.	[50]	IoT adoption in SMEs is speculated to have a promising effect on the FIN of businesses.

University of Dhaka (Reference Number: IBDUREC-2024-23) prior to the commencement of data collection for this study. Moreover, informed consent was also obtained from the respondents, and they were assured that their participation in the research was exclusively voluntary. Furthermore, participants were informed that their responses would remain entirely anonymous and would be used solely for academic research purposes.

3.4 Data Preparation and analysis

This study applied a hybrid approach to data analysis. SPSS 28 was employed to conduct the descriptive statistical analysis of the collected data. In addition, SmartPLS 4 was used to calculate the data, analyze the proposed research model, and develop hypotheses using SEM. The Partial Least Squares (PLS) model was used to test the robustness and value of the statistical evaluation, and the bootstrapping method was applied to draw many sub-samples from the original data. Before testing the structural model, reliability and validity of measurement model have been assessed. Composite reliability, and Cronbach's Alpha with a threshold of 0.70 has been used for measuring reliability. Convergent validity has been assessed using item loading and Average Variance Extracted (AVE) with a cut-off value of 0.50, while discriminant validity has been measured using only HTMT ratio with a threshold value of < 0.90. Outcomes from SEM analysis have been complemented through Artificial Neural Network (ANN) analysis to measure the predictability of the model and to rank the predictors. Therefore, this study adopted the SEM-ANN approach for IoT and SME research, as previous studies either used SEM [57, 88] or other methods [36].

4 Research findings

4.1 Demographic information of the respondents

A survey was conducted for this study, and Table 3 includes an overview of the general information regarding the respondents and their affiliated SME companies. The majority of the respondents (45.64%) are middle managers, whereas 28.86% and 25.50% are top managers and operational managers, respectively. SME companies operating in Bangladesh have been classified into five categories. The majority (34.90%) of the respondents belong to the e-commerce group. There are 27.52%, 25.50%, and 4.70% respondents from agro-business, consumer product selling companies, and leather companies, respectively. Most of the companies (35.57%) have less than 2 years of experience in using IoT technology for business operations, and only 8.72% have more than 10 years of experience.

4.2 Measurement model and discriminant analysis

4.2.1 Common method bias

Common Method Bias (CMB) measures the bias in the collected dataset due to using a simple mode of data collection. Kock [39] recommends that a Variance Inflation Factor (VIF) below 3.3 affirms the absence of CMB. All VIF values reflected in the Table are less than 3.3, confirming that no single factor dominates the dataset. Hence, there is no CMB issue.

4.2.2 Measurement model analysis

Measurement model analysis confirms the reliability, the construct, and the discriminant validity of the constructs used. To achieve construct reliability, Cronbach's Alpha and Composite Reliability values must be greater than 0.70 [27]. The Cronbach's Alpha and Composite Reliability values of the suggested constructs are higher than 0.728 and 0.780, respectively, as shown in Table 4, assuring construct reliability. Convergent validity is evaluated using item loading and Average Variance Extracted (AVE) with a cut-off value of 0.50 [27]. Table 4 also depicts that the item loading and AVE values exceed the threshold value, satisfying the convergent validity of the variables.

According to Henseler et al. [31], the Heterotrait-Monotrait (HTMT) ratio is a valuable measure for ensuring the discriminant validity of the latent variables. To affirm the discriminant validity, only HTMT ratios have been used and HTMT ratio is assessed using a threshold value of less than 0.90 [31]. Table 5 displays the HTMT ratio, and all values

Table 3 Demographic information

Variables	Description	Frequency	Percentage
Designation	Top manager	43	28.86%
	Middle manager	68	45.64%
	Operational manager	38	25.50%
Types of SME companies	Agro and Agro Processing	41	27.52%
	Consumer Products	38	25.50%
	E-Commerce	52	34.90%
	Leather	7	4.70%
	Others (Fashion, Foods, and Handicrafts)	11	7.38%
Experience of using IoT	Less than 2 years	53	35.57%
	2–5 years	49	32.89%
	5–10 years	34	22.82%
	More than 10 years	13	8.72%

Table 4 Measurement model

Constructs	Items	Loadings	Cronbach's Alpha	Composite Reliability	Average Variance Extracted (AVE)
RA	RA1	0.920	0.783	0.854	0.663
	RA2	0.695			
	RA3	0.813			
COM	COM1	0.773	0.729	0.801	0.573
	COM2	0.760			
	COM3	0.737			
CMP	CMP1	0.789	0.751	0.859	0.674
	CMP2	0.876			
	CMP3	0.882			
TMS	TMS1	0.872	0.849	0.909	0.768
	TMS2	0.886			
	TMS3	0.872			
OR	OR1	0.645	0.748	0.860	0.676
	OR2	0.903			
	OR3	0.892			
COP	COP1	0.904	0.820	0.892	0.734
	COP2	0.881			
	COP3	0.780			
EXS	EXS1	0.807	0.851	0.899	0.690
	EXS2	0.818			
	EXS3	0.852			
	EXS4	0.845			
REL	REL1	0.757	0.728	0.821	0.604
	REL2	0.801			
	REL3	0.773			
IoT	IoT1	0.756	0.849	0.889	0.572
	IoT2	0.763			
	IoT3	0.786			
	IoT4	0.710			
	IoT5	0.801			
	IoT6	0.809			
EP	EP1	0.751	0.767	0.780	0.649
	EP2	0.851			
	EP3	0.787			
FIN	FIN1	0.895	0.880	0.926	0.808
	FIN2	0.938			
	FIN3	0.862			

RA Relative Advantage, COM Compatibility, CMP Complexity, TMS Top Management Support, OR Organizational Readiness, COP Competitive Pressure, EXS External Support from Vendors, REL Regulations and Legislations, IoT Adoption of IoT, EP Environmental Performance, FIN Financial Performance

are below the suggested value, certifying the discriminant validity of constructs. Therefore, reliability, convergent validity, and discriminant validity have been established.

4.3 Structural model

A structural equation model has been established to identify the connections between the dependent and independent variables. The path coefficients have been assessed using the bootstrapping technique with a 5000-sample. Table 6; Fig. 2 show the results of the structural equation model. The t-values and P-values are used to identify acceptance and rejection of the hypotheses. Besides, Bias Corrected Confidence Intervals (BCI)

Table 5 Heterotrait-Monotrait ratio (HTMT)

Constructs	IoT	CMP	COM	COP	EP	EXS	FIN	OR	RA	REL
CMP	0.580									
COM	0.867	0.827								
COP	0.863	0.480	0.583							
EP	0.879	0.604	0.898	0.712						
EXS	0.780	0.493	0.759	0.411	0.771					
FIN	0.695	0.506	0.883	0.371	0.764	0.578				
OR	0.788	0.626	0.304	0.478	0.730	0.539	0.521			
RA	0.232	0.416	0.488	0.175	0.245	0.211	0.144	0.336		
REL	0.451	0.636	0.513	0.795	0.448	0.239	0.163	0.174	0.149	
TMS	0.687	0.535	0.602	0.363	0.740	0.442	0.409	0.292	0.194	0.641

RA Relative Advantage, COM Compatibility, CMP Complexity, TMS Top Management Support, OR Organizational Readiness, COP Competitive Pressure, EXS External Support from Vendors, REL Regulations and Legislations, IoT Adoption of IoT, EP Environmental Performance, FIN Financial Performance

Table 6 Structural model assessment for direct connections

H	Relations	Std Beta	Std Error	T values	P values*	BCI LL	BCI UL	f ²	VIF	Decision
1	RA ->IoT	0.027	0.034	0.809	0.419	-0.043	0.090	0.008	2.202	Not Supported
2	COM ->IoT	0.080	0.056	1.434	0.152	-0.032	0.190	0.014	2.104	Not Supported
3	CMP ->IoT	-0.057	0.028	2.022	0.043	-0.006	0.106	0.527	1.646	Supported
4	TMS ->IoT	0.867	0.125	6.950	0.000	-1.140	-0.646	0.502	2.181	Supported
5	OR ->IoT	0.109	0.076	1.436	0.151	-0.022	0.273	0.014	1.190	Not Supported
6	COP ->IoT	0.514	0.049	10.404	0.000	0.412	0.603	0.875	1.647	Supported
7	EXS ->IoT	0.911	0.134	6.796	0.000	0.692	1.220	0.838	1.354	Supported
8	REL ->IoT	0.268	0.067	3.987	0.000	0.149	0.413	0.795	1.220	Supported
9	IoT ->EP	0.821	0.030	7.191	0.000	0.744	0.868	0.867	1.520	Supported
10	IoT ->FIN	0.595	0.058	10.273	0.000	0.462	0.694	0.549	1.413	Supported

*At the significance level of <0.05

RA Relative Advantage, COM Compatibility, CMP Complexity, TMS Top Management Support, OR Organizational Readiness, COP Competitive Pressure, EXS External Support from Vendors, REL Regulations and Legislations, IoT Adoption of IoT, EP Environmental Performance, FIN Financial Performance

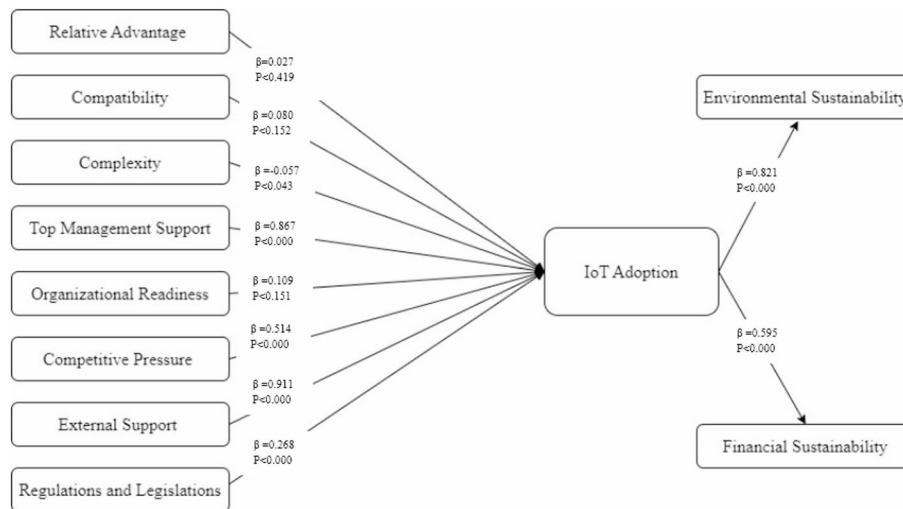


Fig. 2 Structural Model

lower limit and upper limit values measure the significance of the association between variables [27]. Except for hypotheses H1 (RA \rightarrow IoTA), H2 (COM \rightarrow IoTA), and H5 (OR \rightarrow IoTA), other hypotheses are found to be statistically significant at a 5% significance level as P values are less than 0.05. The hypotheses H3 ($p=0.04$, $t=2.02$), H4 ($p=0.00$, $t=6.95$), H6 ($p=0.00$, $t=10.40$), H7 ($p=0.00$, $t=6.79$), H8 ($p=0.00$, $t=3.99$), H9 ($p=0.00$, $t=7.19$), H10 ($p=0.00$, $t=10.27$) are accepted and H1, H2 and H5 are rejected.

Moreover, f^2 specifies the effect size, illustrating the degree to which an endogenous construct adds value to the R^2 of the exogenous construct [23]. According to Cohen [23], if the f^2 value exceeds 0.35, 0.15, and 0.02, the effect size is large, medium, and small, respectively. Here, all statistically significant hypotheses have a large effect as the f^2 values are within the range of 0.502 to 0.875. Furthermore, Fig. 3 presents the R^2 values of dependent variables. For this study, IoT and ES have substantial explanatory power with 72% variance in IoTA and 67% variance in ES, while FIN has moderate explanatory power (36%), as suggested by [27].

Therefore, complexity, top management support, competitive pressure, external support from vendors, regulations, and legislations significantly influence the adoption of IoT in SME sectors. Similarly, IoT adoption positively improves the environmental performance and financial performance of SME companies.

4.4 Results of the neural network analysis

A neural network analysis has been conducted to capture the non-linear relationship between the independent variables and dependent variables. ANN has three layers: input, output, and hidden layers. A 10-times cross-validation method has been applied to reduce the impact of data overfitting problems and errors on final results. Table 7 shows the findings from each network. 70% data has been used for training and 30% for testing the models as recommended by [35]. Root Mean Square error (RMSE) is the widely used validation measurement [84], which has been applied in this study. Small RMSE values, as portrayed in Table 7, confirm the predictability of the model in capturing the complex relationship between predictors and SMEs' IoT adoption intention.

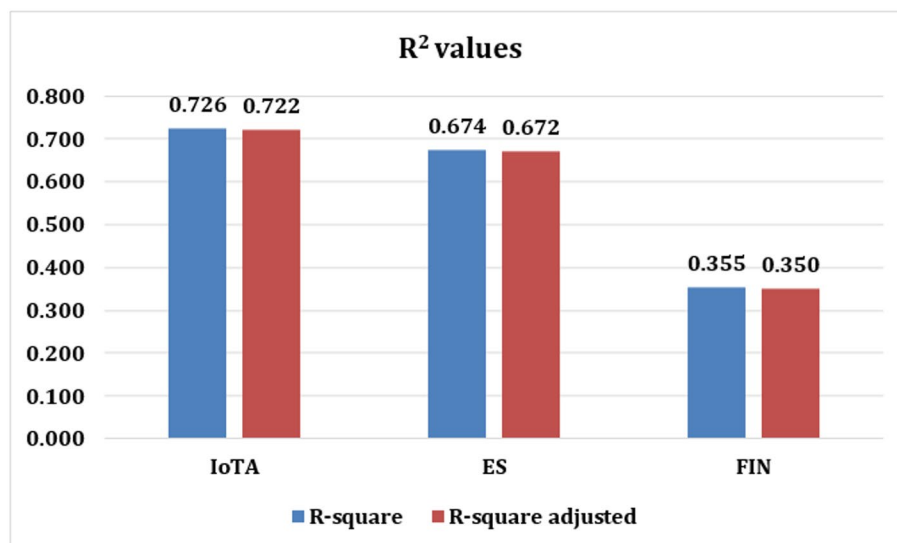


Fig. 3 R^2 values

Table 7 Validations of neural networks

ANN	Sum of square error (Training)	Sum of square error (Testing)	RMSE (Training)	RMSE (Testing)	RMSE (Training)-RMSE (Testing)	Sample size (Training)	Sample size (Testing)	Total sample size
1	4.240	2.050	0.203884	0.208847	0.005	102	47	149
2	4.948	0.841	0.211132	0.148767	0.062	111	38	149
3	3.394	1.856	0.178100	0.210215	0.032	107	42	149
4	4.555	1.196	0.220131	0.147463	0.073	94	55	149
5	3.980	1.957	0.202561	0.193996	0.009	97	52	149
6	4.589	1.011	0.203328	0.163111	0.040	111	38	149
7	4.188	1.153	0.192515	0.178963	0.014	113	36	149
8	4.643	1.998	0.207342	0.220753	0.013	108	41	149
9	3.599	1.919	0.183400	0.213753	0.030	107	42	149
10	4.125	1.587	0.127909	0.174698	0.047	97	52	149
Mean	4.226	1.557	0.193030	0.186057	0.032500			
SD	0.482	0.462	0.026116	0.027331	0.023162			

ANN Artificial Neural Network, RMSE Root Mean Square Error, SD Standard deviation

Sensitivity analysis has been presented in Table 8. According to ANN sensitivity results, EXS is the strongest predictor of IoTA, followed by COP, TMS, REL, and CMP. The ANN framework is shown in Fig. 4. Hence, EXS has the highest impact on IoTA, while CMP has the lowest impact

Table 8 Importance of constructs

ANN	EXS	COP	TMS	REL	CMP
1	0.348	0.217	0.223	0.195	0.017
2	0.317	0.231	0.225	0.210	0.016
3	0.345	0.244	0.213	0.177	0.021
4	0.332	0.228	0.214	0.211	0.015
5	0.326	0.224	0.220	0.192	0.037
6	0.328	0.258	0.211	0.152	0.051
7	0.333	0.291	0.204	0.166	0.006
8	0.326	0.233	0.214	0.181	0.046
9	0.319	0.267	0.209	0.159	0.049
10	0.316	0.226	0.222	0.181	0.055
Average Importance	0.33	0.24	0.22	0.19	0.03
Normalized Importance	1.00	0.72	0.66	0.56	0.09

ANN Artificial Neural Network, CMP Complexity, TMS Top Management Support, COP Competitive Pressure, EXS External Support from Vendors, REL Regulations and Legislations

5 Discussion

IoT enables a cyber-physical system that connects multiple devices, allowing them to exchange data automatically. It ensures efficiency in operations and automates tasks. Therefore, IoT contributes to cost savings for the SMEs. Especially for manufacturing SMEs, IoT improves the visibility as well as transparency of the supply chains and the production process, reducing the cost and yielding more profitability. Despite these benefits, business organizations face internal and external challenges in adopting IoT. Interoperability is a major problem for SMEs to reap benefits from IoT adoption [36].

Adopting emerging technologies, particularly in the context of developing countries, requires the availability of internal and external resources and a supportive environment [15]. Otherwise, companies cannot reap the potential benefits from technology adoption. However, for statistical analysis, primary data from 149 SME professionals in Bangladesh have been gathered. Although the sample size is adequate for statistical analysis and further strengthened using the bootstrapping technique for robustness, it remains

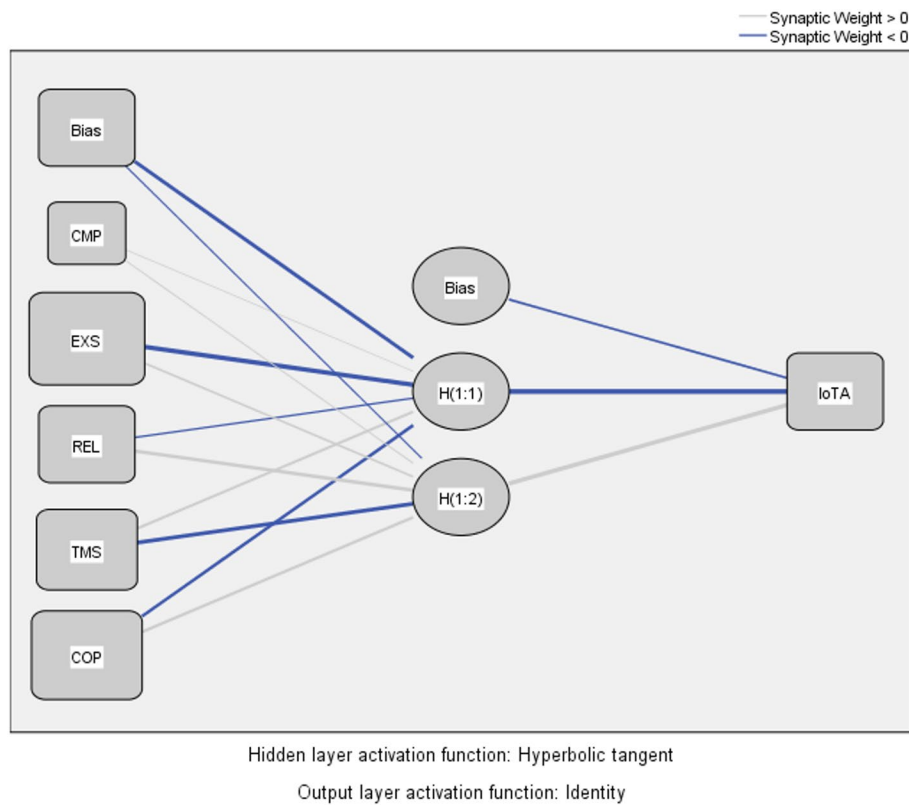


Fig. 4 ANN Model. ANN Artificial Neural Network, CMP Complexity, TMS Top Management Support, COP Competitive Pressure, EXS External Support from Vendors, REL Regulations and Legislations, IoTA Adoption of IoT

relatively small. This may limit the generalizability of the findings to the broader population and diverse contexts. As IoT is still an emerging technology for developing nations, the findings from studies in this field will guide policymakers and business leaders in the successful implementation of IoT, mostly in SMEs. Therefore, this study adopted the TOE framework and RBV models to determine the factors impacting the adoption of IoT in SMEs.

5.1 Discussion on SEM findings

5.1.1 Technological context

The study has found a relative advantage to be insignificant when it comes to IoT adoption in the SME industry in Bangladesh, rejecting H1. This result is consistent with the study conducted by Bakar et al. [13] in the UAE. The reason behind this finding can be that organizations sometimes adopt innovation because of competition in the market rather than making it part of the overall company strategy or considering it indispensable for better performance. IoT adoption is yet to gain popularity in the SMEs of Bangladesh, and so instead of adopting it voluntarily, due to the associated high risk, most firms choose to wait for other firms to test the waters first, and so ignore the opportunity to gain a relative advantage by adopting IoT.

Though compatibility is an important driver of innovation adoption in a firm [13, 70], this factor is insignificant for driving IoT adoption intentions by SMEs in the Bangladesh context. Thus, H2 is not accepted. The outcomes are aligned with the study conducted by Skafi et al. [89]. Many SMEs in Bangladesh are still in the early stages of technological

adoption, naturally lacking the required infrastructure or systems with which IoT technologies need to be compatible. Moreover, businesses in developing countries are yet struggling to develop a supportive IT environment [101]. Therefore, compatibility is an insignificant motivator in IoT adoption decision-making for SMEs.

Complexity has a significant negative relationship with IoT adoption intention in SMEs of Bangladesh, accepting H3, which is in line with the studies conducted by Bag et al. [12, 89]. The more the new technology is complex or difficult to understand and use, the fewer chances there are to have a successful adoption of that technology into the firm. Moreover, employees may resist IoTA due to complexities. Therefore, the study corroborates the literature and confirms that SMEs deter the adoption of IoT if complexity is high, particularly in developing countries.

5.1.2 Organizational context

Among the two organizational factors studied through this research, top management support (H4) has been proven to have a significant positive relationship with IoTA in the SME industry and this is also supported by previous studies conducted in SMEs of Pakistan [70], UAE [13], West Java, Indonesia [68]. ANN results also reveal TMS as an important predictor of IoTA in the SME sector. Therefore, managers in leading roles should consider IoTA as a strategic initiative and provide the necessary support for its functioning.

Organizational readiness, on the contrary, has been found to be an insignificant driver of IoTA for the SME industry, not supporting H5. The result corroborates the findings of [2, 56]. The possible reasons can be many. Firstly, the major reason for such a finding is the lack of adequate infrastructure and skilled employees. Secondly, most SMEs today adopt IoT to cope with competitive pressure, making organizational readiness insignificant. Thirdly, in most cases, IoT applications are simple and user-friendly. Fourthly, extensive support from vendors may allow SMEs to adopt IoT even though they are not internally ready. Furthermore, SMEs in developing countries are operating with small resources [19]. Therefore, organizational readiness and prior knowledge become insignificant for IoT adoption decisions.

5.1.3 Environmental context

All three hypotheses, H6, H7, and H8, related to environmental factors- competitive pressure, external support from vendors, and regulations and legislations have been found to have significant positive relationship with IoTA in the SME industry. The results are supported by studies on factors affecting technology adoption in SMEs conducted by [12, 55, 68, 70]. Mukherjee et al. [56] support that COM and EXS have a significant impact on IoT adoption in SMEs. The significance of these environmental factors in the Bangladeshi context emphasizes the necessity of creating a better business ecosystem where government initiatives complement market forces and external vendor support to accelerate the digital transformation of the SME sector. SME companies in developing countries with a scarcity of internal resources largely depend on the existing business environment to adopt new technologies. Therefore, it was discovered that the support from external vendors not only has the most significant impact on IoT adoption decisions, but also serves as a strategic tool for SMEs to compensate for the internal resource deficit. This finding underscores the capabilities of the SMEs to strategically leverage

vendors as a core external resource, thereby extending the TOE framework by emphasizing the external environment as a key enabler and deepening the RBV perspective. Moreover, the ANN model validates that all environmental factors, such as EXS, COP, and REL, strongly predict IoTA, with EXS being the strongest one.

5.1.4 Sustainable business performance

Regarding H9 and H10, the adoption of IoT technologies has shown a significant positive impact on both the environmental and financial performance of SMEs in Bangladesh, as confirmed by previous studies [11, 41, 90]. The findings also aligned with Asad et al. [5] as proactive innovation strategies, such as green market innovation [93], contribute to SME performance. IoTA acts as a technological enabler in this context to drive innovation and performance in SMEs. The integration of IoT has proven to be a key driver in enhancing both the economic and environmental sustainability of these SMEs, positioning them for long-term success in Bangladesh's increasingly technology-driven business settings.

5.2 Discussion on neural network analysis findings

Whereas SEM focuses on linear relationships, ANN uncovers non-linear and complex relationships that cannot be seen in SEM due to reliance on linearity and pre-specified pathways. Besides, ANN results indicate the importance of significant factors, which SEM does not give directly. The list of the order of ranking the predictors is determined by their total effect regardless of the nature of the relationship, be it positive or negative. In this regard, the ANN model has been embraced to complement the findings of the SEM analysis, highlighting the multifaceted connection between the factors that influence them through the adoption intentions [84]. Findings of ANN revealed that EXS is the prominent force of IoTA. Most of the SMEs in Bangladesh operate with fewer human and technology resources, with ineffective IT staff or the skills to manage complex systems within. This leads to the fact that companies heavily depend on external vendors to fill this gap, not only with regard to technical implementation but also decision-making and constant maintenance. Vendors in Bangladesh have also been known to be critical sources of knowledge, especially when it comes to newer or advanced technologies like IoT. Bangladeshi SMEs are wise when it comes to technological investments, as they are operating in a resource-constrained and often risk-averse setting. Heavy vendor support helps in the reduction of this perceived risk, whereby enterprises are guaranteed of successful installation and proper support of post-adoption. Thus, EXS has the highest predictive power of the IoT adoption in Bangladesh.

6 Research implications

6.1 Theoretical implications

This research makes an important contribution towards the theoretical development of digitalization and innovation adoption literature, as it considers the adoption of IoT technology among SMEs in the context of a developing country. By bridging the TOE framework with the RBV theory, the research creates an effective, multi-dimensional framework for explaining the dynamics of IoT adoption and its effects on the performance as well as the sustainability of the firm.

Besides, the research confirms and strengthens the TOE framework in terms of establishing complexity, competitive pressure, top management support, external support for vendors, and regulatory frameworks as important antecedents of IoT adoption in SMEs. These factors, previously tested in isolated or linear models, are examined holistically in this dynamic technological context for the first time. Notably, this research is among the few studies that utilize the TOE framework for IoT-specific adoption in resource-deficient, developing market contexts, thereby asserting the flexibility as well as cross-contextual validity of the TOE model. It advances empirical evidence of the applicability of the framework towards non-traditional, non-Western, or enterprise contexts.

Moreover, by incorporating RBV into the analysis, this research emphasizes how intangible assets, organizational capabilities, and external relational assets support a corporation's ability and preparedness for the adoption of IoT technologies. By adding elements like top management support and cross-vendor collaboration, these factors are framed as strategic assets that can support a corporation's technological as well as competitive agility. This adds to as well as modifies RBV theory as it demonstrates that in an era of digitalization, technological agility, and networked expertise are as important as tangible or capital assets in driving sustainable performance. By doing this, the research connects RBV's classic emphasis on internal assets with the growing networked reality of innovation environments. Therefore, the findings of the study show that strong support from external vendors may compensate for internal resource deficit, theoretically linking the TOE model with the RBV theory.

Likewise, a methodological contribution is the use of a hybrid SEM-ANN approach for IoT adoption literature. While SEM allows for the examination of linear relationships as well as hypothesis testing, the addition of ANN picks up on non-linear patterns as well as on variable interactions that were possibly neglected in conventional models. This combination of two different methods enhances the validity as well as the richness of the findings and is an inspiration for future studies aiming at analyzing complex technological adoption behaviors. It proves the applicability of the combination of predictive as well as explanatory modeling for achieving enhanced insights into decision-making in technology contexts.

Furthermore, one significant theoretical contribution is integrating dimensions of sustainability, both environmental as well as economic, into IoT adoption models. While the TOE, as well as RBV frameworks, generally emphasize performance as well as capability development, this research finds that IoT can act as an innovation spur for sustainability. It demonstrates that SMEs can attain cost efficiency as well as productivity improvements, but also enhance their environmental impact, resource efficiency, as well as stakeholder reputation. This broadens the scope of conventional frameworks by incorporating sustainability as well as social responsibility-oriented innovation within the digital transformation strategic rationale.

Finally, in placing the study within the context of Bangladesh, a lower-middle-income economy with a fast-developing SME sector, the research fills a significant gap in global digitalization research. Preeminent in most of the literature on IoT adoption are studies conducted in high-income or technologically sophisticated countries. This study delivers contextualized insights about how IoT is utilized in emerging economy SMEs in the face of infrastructural, funding, and regulatory challenges. It challenges researchers to take

into account institutional, cultural, and market-oriented constraints as well as facilitators, thus increasing the geographical and contextual scope of extant theory.

6.2 Practical and managerial implications

The present research study provides practical information to the SME leaders, technology suppliers, and policy makers to implement the IoT adoption and utilize its potential in developing economies such as Bangladesh. The combination of the TOE model and the RBV theory provides a comprehensive prism in the light of which strategic, operational, and environmental implications can be interpreted and implemented.

To begin with, it is important to note that top management support is vital in facilitating the adoption of IoT and hence the commitment of the top management. Managers ought to be at the forefront of speaking about digital transformation, a clear vision, sufficient resources, and create a culture of innovation. The role of decision-makers is to place the IoT not as a technical enrichment but as a performance and sustainability strategic facilitator of firms.

Second, IoT solutions may be perceived as complex, which may act as an adoption barrier. SMEs ought to make an investment on upskilling their workforce, streamlining the internal processes, and the integration and scalability of the IoT technologies. The technical difficulties can be mitigated by partnering with solution providers to provide training and assistance and decrease the perceived implementation risk.

Third, as a practitioner, the study recommends that SMEs that have small internal resources ought to be proactive in seeking collaboration with external vendors. Vendor support is a very important enabler that offers technical knowledge, infrastructural support, and training that can offset internal resource shortages and speed up the adoption of IoT. Besides, the SMEs need to establish strategic relationships with the providers of IoT who not only supply products but also provide end-to-end services, including customization, integration, and troubleshooting services. In turn, vendors will need to develop individually tailored support models that would work within the limitations and capabilities of SMEs within emerging markets such as Bangladesh. This can be through provision of bespoke training programs, especially those which are SME-focused, customizable service packages that enable SMEs to use IoT on a gradual basis and effective after-sales support that can give SMEs assurance and sustainability on the use of technology. Such types of vendor-focused strategic actions allow the IoT suppliers to reduce barriers and establish trust in the user and spread the technology diffusion in the environment of emerging economies, which is limited by resource availability.

Fourth, competitive pressure is also a factor that brings to fore the significance of market forces in driving technology adoption. Digital transformation is a competitive imperative that SMEs should take seriously, which can result in differentiation by means of enhanced efficiency, improved customer experience, and real-time data-driven decision-making.

Fifth, since regulatory frameworks have an influence on the introduction of adoption, SMEs would have to be aware of national policies of digitalization and regulatory demands. Managers ought to be proactive and be involved in the policymaking process and designation of the industry associations to jointly develop favorable regulations and capitalizing on the new incentives or existing infrastructure programs that enable IoT approval.

Therefore, the result that the increment of financial and environmental performance is supported by the presence of IoTA is especially helpful. The IoT solutions are to be implemented to reduce energy use, track environmental footprint, and ease operations. It can then achieve both the consumer and the international sustainability goals.

Since the sample encompasses agro-processing, consumer goods, e-commerce, and leather business SMEs, the study proposes that the IoT applications should be tailored to both business-to-industry issues and opportunities. Hence, various cases which can yield the highest possible benefits, such as smart logistics, inventory management, or predictive maintenance, need to be assessed in terms of needs.

Lastly, this study provides the SME managers with a roadmap to the adoption of IoT technologies in a strategic and sustainable manner. SMEs can be well-equipped to both be competitive in the long term and survive in the digital economy by considering internal strengths, collaborating with external parties, and with the environment simultaneously.

7 Conclusion, limitations, and future directions

7.1 Conclusion

The TOE model and RBV model were used in evaluating the drivers affecting the IoTA in SMEs of developing nations. The TOE model determines technological, organizational, and environmental variables, which affect the IoTA. In the same manner the RBV model analyses the internal and external resources, including financial resources and highly skilled employees, which are the drivers of IoTA.

IoTA among SMEs, especially developing countries is in its early days. That is why, it is essential to evaluate the vital aspects that should be considered to be successful in implementing IoT. This work offers new insights into the existence of the empirical relationship between critical drivers and IoTA, the relationship between IoTA and sustainability of the firms. These lessons can be useful when leading policymakers and managers to use IoT successfully.

As evidenced by the reactions of 149 Bangladeshi professionals in the SMEs, our study findings reveal the relative advantage, compatibility, complexity, competitive pressure, organizational readiness, top management support, external support, and regulations and legislations affect IoTA.

The analysis shows that all the factors mentioned above except relative advantage, compatibility, and organizational readiness carry considerable influence on the process of the IoTA in the SMEs. Furthermore, the use of IoT has a positive effect on financial performance and environmental performance and enhances sustainability among SMEs.

7.2 Limitations and future directions

The study has several limitations, which call for further studies to address those shortcomings. First, this study is cross-sectional in nature. Thus, future studies could collect longitudinal data to assess IoT adoption over time, providing a more dynamic understanding of its impact. Besides, this study was conducted using data from only 149 employees working in SME firms in Bangladesh, representing multiple types of SMEs. Future studies could be conducted with a larger sample size, including additional firms and industries from different countries and cultural contexts to enhance the

generalizability of the findings. Furthermore, cross-cultural comparative analysis could be done through forthcoming studies.

Second, the conditions of TOE factors, such as relative advantage, compatibility, organizational readiness, and government incentives, are constantly evolving for firms. Therefore, future research on these evolving factors and their influence on IoT adoption could provide novel insights relevant to the changing business environment. Third, this study evaluates the impact of IoT on the sustainability of SMEs in terms of environmental and financial performance. However, future researchers could explore other outcomes, such as employee satisfaction, market expansion, and innovation capability, to gain a more comprehensive understanding of the impact of IoT adoption on SME firms. Besides, this research studied IoTA as a core variable only, suggesting for future studies on the mediating role of IoTA in driving SME performance. Fourth, in this study, SME firms' performance has been measured using subjective indicators, as there are no trustworthy sources of objective secondary data to assess performance, particularly financial performance. Employees perceive their organizations as superior to their competitors, leading to misleading outcomes. Therefore, future studies can measure performance based on reliable secondary data. Finally, exploring the synergistic effects of IoT with emerging technologies like artificial intelligence and blockchain on organizational performance could be a valuable avenue for future research.

Author contributions

R.A.R. and F.M. contributed to the conceptualization and methodology, data collection, data cleaning, data analysis, and the overall writing of the original manuscript. S.T. contributed to the questionnaire preparation, interpretation of the results, and the overall review and editing of the manuscript. A.N.M.S. contributed to the introduction, discussion, implication, conclusion, review, and editing. S.A. contributed to the discussion, conclusion, review, and editing. R.M. contributed to the interpretation of the results and the overall editing of the manuscript.

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Data availability

Data can be made available from the corresponding author upon reasonable request, subject to applicable regulations and institutional policies.

Declarations

Ethics approval and consent to participate

Ethical approval was obtained from the departmental Ethics Committee for Research Involving Human Subjects of the University of Dhaka (Reference Number: IBDUREC-2024-23) before the commencement of data collection. Informed consent was obtained from the respondents, and they were assured that their participation in the research was exclusively voluntary.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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