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Investigating the nexus of environmental turbulence, technological learning, and innovation dynamics: empirical evidence from Turkish manufacturing firms

Ali Ekber Akgün[1] · Halit Keskin[1] · Ekrem Tatoglu[2,3] · Büşra Müceldili[1] · Ayşenur Mavuş[1]

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Abstract
Technological learning is paramount for the success of firms in a highly competitive environment. This study, rooted in the absorptive capacity perspective, explores how technological turbulence influences product and process innovation within manufacturing firms through the lens of technological learning. Furthermore, we examine the moderating impact of market turbulence on the relationship between technological turbulence and technological learning in the context of manufacturing. Empirical analysis was conducted via a survey-based approach, and Partial Least Square (PLS) analysis was employed to test our research hypotheses using data collected from 142 manufacturing firms in Turkey. The findings reveal that technological turbulence significantly impacts technological learning, and technological learning mediates the link between technological turbulence and firm innovation in the manufacturing sector. Notably, we also establish that market turbulence moderates the connection between technological turbulence and firm innovation, specifically in the domains of product and process innovation.

Keywords Market turbulence · Technological turbulence · Technological learning · Product innovation · Process innovation · Manufacturing firms · Turkey

1 Introduction

The transition from the industrial age to the digital age, accelerated by the Fourth Industrial Revolution and the post-COVID-19 era, has had profound implications for governments, businesses, and economies (Barata 2021; Pedota and Piscitello 2022; Yang et al. 2023). This transformation of the business landscape has been characterized by the rapid adoption of new technologies, such as the Internet, blockchain, big data, and artificial intelligence (AI) (AlNuaimi et al. 2022). In response to these changes, the success factors for firms have evolved significantly. Firms operating in an environment marked by unpredictable technological shifts, uncertainties, and rapidly changing market dynamics are compelled to

Extended author information available on the last page of the article

Table 1 A summary literature review on technological learning

Author	Definition	Purpose	Findings
Carayannis (2000)	Technological learning shows the systematic procedure via which a technology-oriented organization develops, revitalizes and enhances its inherent and demonstrated competencies, drawing upon its collection of explicit and tacit resources.	To examine the relationship among technological learning and market performance.	The findings of the study indicate a correlation among technological learning activities and market performance. Furthermore, the research has provided evidence that the association among learning and performance can change with contextual variations.
Zahra et al. (2000)	Technological learning is characterized by multifaceted, including breadth, depth and speed. The concept of breadth pertains to the identification of many domains in which one might acquire new technological abilities. Depth refers to the capacity to derive novel conclusions and build connections within the existing knowledge base. Lastly, speed denotes the ability to swiftly acquire fresh insights and skills.	To investigate the relationship among international expansion, technological learning, and financial performance.	The association among international diversity, mode of market entry, and the breadth, depth and speed of a firm's technological learning is moderated by formal knowledge integration.
Carayannis (2002)	Technological learning refers to the internalization of technical and administrative knowledge within the organizational transformation process, with the aim of enhancing decision-making capabilities and effective management of complexity and ambiguity.	To assess the correlation among technological learning and market performance within multi-industry firms.	The study shows that the correlation among technological learning and market performance, contingent upon firm-specific characteristics.
Chen and Qu (2003)	Technological learning encompasses the integration of operational, tactical, and strategic forms of learning.	To investigate the technological learning role in an aspect of operational, tactical, and strategic learning in a case study in China.	This study has introduced a novel approach to technological learning, integrating various phases of the traditional model.
Lin (2003)	Technological learning creates corporate-wide technology and production abilities and transforming them into competences that provide individual enterprises to effectively respond dynamic contexts.	To investigate the role of organizational intelligence and firm specificity.	The study's empirical results show that complexity and maturity are antecedents of firm specificity and employee qualification, and innovation orientation are antecedents of organizational intelligence. Firm specificity and organizational intelligence have a positive impact on technological learning performance.
Lee (2004)	Technological learning refers to a dynamic process in the organization which includes the integration of organizational processes and technical pathways for responding external environmental changes.	To examine the effect of technological learning in developing countries-Korea.	The study has demonstrated that national R&D activities are essential for technological learning mechanisms rather than firms' technological activities.

Table 1 (continued)

Author	Definition	Purpose	Findings
Kim and Inkpen (2005)	Technological learning shows the accumulation of technological knowledge to enhance a firm's competitive advantage.	To explore the role of technological learning in the chemical-pharmaceutical industry.	The longitudinal study showed that cross-border R&D alliances are positively related to technological learning and an inverted U shape relationship between technological learning.
Ignatius et al. (2012)	Technological learning comprises knowledge acquisition, distribution, interpretation, and organizational memory.	To test the role of technological learning in multinational companies.	The research indicates a positive relationship between innovation speed and product development success. However, organizational memory does not significantly correlate with product development outcome dimensions. The study also has shown the moderating effect of project complexity on the association among technological learning.
Ghazinnory et al. (2017)	Technological learning refers to the process through which an organization enhances its internal technical skills, successfully utilizes existing technologies, assimilates other technologies, and generates novel technological advancements in response to changing environmental conditions.	To examine technology road mapping's role in making technology, R&D, and innovation decisions.	The study indicated that in developing countries, technology planning is shaped by technological learning, with strategies being built upon technological capabilities.
Pan et al. (2019)	Technological learning refers to the process via which firms operating inside high-tech clusters engage in the exploration, evaluation and assimilation of both internal and external knowledge. Technological learning addresses technical challenges and solves them through critical thinking and refining.	To investigate how technological learning and innovation networks affect high-tech cluster firms' innovation performance.	The empirical result of the study shows that technology acquisition, technology digestion, and technology exploitation positively affect innovation performance. Also, the study has demonstrated that technology acquisition is the association among innovation networks and technological learning.
Guo et al. (2020)	Technological learning includes four kinds of knowledge processing activities, namely, knowledge acquisition, knowledge maintenance, and knowledge reactivation which are developed from absorptive capacity perspective.	To test knowledge attributes (knowledge tacitness and knowledge heterogeneity) on technological learning routines within industrial cluster firms.	The findings indicate a positive relationship between knowledge tacitness and intensity and variety of technological learning routines. Additionally, there is a negative relationship between knowledge heterogeneity and the types of technological learning routines.
Charmjuree et al. (2022)	External technology acquisition (ETA) includes activities such as finding, evaluating, acquiring and assimilating of practical technical knowledge obtained from external sources. External technology exploitation (ETE) indicates the firm's efforts to effectively commercialize its technological knowledge.	To investigate the relationship among ETA - ETE and process innovation performance.	The study has revealed the direct effects of ETA and ETE on process innovation performance. Furthermore, it has demonstrated the moderating role of unabsorbed slack in the relationship between ETA and ETE.

accelerate their technological growth. This growth is facilitated by the accumulation of technological knowledge and learning. As noted by Zahra et al. (2000), technological learning is imperative for achieving success in rapidly changing environmental conditions. In this context, a firm's capacity to proactively seek, discern, and assimilate both internal and external technology-driven insights, while adeptly navigating challenges (referred to as technological learning), emerges as a critical organizational capability that significantly influences firm operations, performance, and sustainability (Pan et al. 2019).

While past research has extensively explored technological learning as an aspect of organizational learning (Carayannis and Aleksender 2002) and its impact on innovation performance (Guo et al. 2020), competitive performance (Hitt et al. 2000), and research and development (R&D) efficiency (Yeh and Chang 2020), its effect on specific types of innovations, such as products and processes, as a firm capability rather than just a part of the organizational learning process, remains underexplored. Therefore, further empirical investigation is warranted (see Table 1 for a summary literature review). Additionally, the context-dependent nature of the association between technological learning and firm product and process innovation within manufacturing firms remains largely unexplored. This issue is particularly relevant for manufacturing firms that must adapt quickly to evolving operational demands and external conditions (Saad et al. 2017). For example, Bulut et al. (2022) found that acquiring and applying knowledge significantly improves innovation performance, especially in manufacturing settings. Consistent with this view, manufacturing firms regularly invest in advanced technologies to maintain a competitive edge by adopting innovative production methods (Tu et al. 2006).

With the increasing adoption of automation in the manufacturing industry, there is a demand for new technical knowledge. For example, Jabar et al. (2011) emphasized the importance of efficiently adopting suitable technology to enhance both product and process innovation in manufacturing firms. Moreover, Moughari and Daim (2023) developed a model specifically examining how technological innovation influences export development in emerging countries. Their findings highlighted the substantial impact of knowledge management on export development, emphasizing the importance of factors such as manufacturing capability, service innovation, marketing strategies, and the learning process in bolstering competitiveness in the global market. Additionally, Baccarella et al. (2022) shed light on the significant challenges confronting manufacturing firms, including the digitalization of machinery and the adoption of information technology, prompting a departure from traditional manufacturing approaches to strengthen their competitive positioning. Hence, investigating the dynamics of technological learning and their impact on both firm product and process innovation within manufacturing enterprises is imperative. This study endeavors to offer a comprehensive understanding of how organizations navigate the intricate landscape of acquiring, assimilating, transforming, and ultimately leveraging technology-related knowledge from external sources.

Foreign direct investment (FDI) has long served as an important mechanism for the transfer of technical knowledge across borders, particularly in manufacturing. In economies where firms face limitations in internal R&D capacity, FDI offers an alternative route for acquiring advanced technologies. This is especially relevant for countries like Turkey, where manufacturing industries increasingly rely on external partnerships to modernize production systems. Salim et al. (2017) note, the diffusion of technological know-how through FDI can improve the capabilities of local firms and promote broader industrial upgrading. Through these channels, firms are not only exposed to more efficient production methods but also to international standards and innovation practices (Konstandina and Gachino 2020). Hu et al. (2021) find that such exposure often results in higher productivity levels, particularly when local firms are able to internalize and apply the knowledge effectively. Sanchez-Sellero et al. (2014) also show that the extent of benefit from FDI depends on firms' absorptive capacity, especially in settings where product and process innovation are already part of ongoing development efforts.

In addition to exploring the connections between technological learning and product and process innovation, it is crucial to delve deeper into the antecedents of technological learning from a managerial perspective. Previous studies have examined various factors, such as international diversity and international mode of entry (Zahra et al. 2000), technology collaboration, and external networking (Pan, 2019), all of which contribute to the technological learning of firms.

Given the critical role that environmental turbulence plays in shaping firm operations and its extensive investigation within the technology management literature (Bicen and Johnson 2015; Jin et al. 2022; Wu et al. 2023; Zulu-Chisanga et al. 2016), it becomes essential to empirically examine the effect of turbulence on technological learning as a key antecedent. Researchers have predominantly concentrated on market and technological turbulence, both characterized by their speed and unpredictability, as the primary forms of environmental turbulence within the literature (Luo et al. 2024; Santos et al. 2020). As emphasized by Gemici and Zehir (2023), heightened levels of external awareness are an outcome of turbulence, prompting firms to gain a comprehensive understanding of market opportunities and obstacles. This, in turn, stimulates firms to engage in deeper technological learning to effectively adapt to their evolving environment.

In this study, we specifically address technological turbulence, defined as the rate of change in technology and its related know-how and implications in the industry (Jaworski and Kohli 1993), as the antecedent of technological learning. Although earlier research has indicated that technological turbulence moderates the association among firm performance, technology acquisition, and exploitation (Hung and Chou 2013; Jardim et al. 2021; Li et al. 2020; Wu et al. 2017), the direct effect of technological turbulence on technological learning remains unclear. Although some recent studies have explored how shifts in technological environments influence innovation outcomes (Chen et al. 2018; Huo et al. 2024), there is still limited empirical investigation into how such turbulence directly shapes firms' efforts to engage in technological learning.

By investigating how technological turbulence influences technological learning and subsequently enhances product and process innovation within manufacturing firms, we seek to elucidate the notion that the rapidly evolving technological landscape compels firms to acquire, comprehend, and apply technology-related knowledge from external sources. This, in turn, encourages them to amalgamate external technological expertise with their existing capabilities, fostering the development of improved products and processes.

Unlike technological turbulence, which serves as an antecedent variable for technological learning, we argue that market turbulence, referring to changes in customer preferences and market fluctuations (Kohli and Jaworski 1990), positively moderates the relationship between technological turbulence, technological learning, and product and process innovation. For instance, previous studies emphasize that firms' learning, and innovation are contingent upon the moderating role of market turbulence in relation to various variables within the literature (Chen et al. 2016; Kamasak et al. 2017; Zhou et al. 2019). However, the interaction between market turbulence and technological turbulence in influencing technological learning and product and process innovation has not been empirically examined. Past studies have often examined environmental turbulence variables separately without considering their interconnected effects. We propose that a higher level of market turbulence fosters technological learning and unveils new opportunities for developing new products, influenced by technological turbulence (Chen et al. 2016). Investigating the specific moderating effect of market turbulence will enable researchers to comprehend the diverse effects of distinct turbulent environmental conditions (market and technological turbulence) on a firm's technological learning capability and innovation endeavors. As highlighted by Rego et al. (2022), firms respond to competitors by adapting to market conditions and embracing technological advancements in a turbulent market.

Therefore, as outlined in Fig. 1, this study focuses on three inter-related relationships: (1) the effect of technological turbulence on technological learning; (2) the mediating effect of technological learning in the relationship between technological turbulence and product and process innovation; and (3) the moderating effect of market turbulence on the relationship between technological turbulence and technological learning as well as the indirect relationship between technological turbulence and product and process innovation through technological learning. Thus, this research substantially contributes to the literature by introducing a fresh perspective on the dynamics of technology and market turbulence. It sheds light on the interactions between these traditionally distinct variables, showcasing their combined influence on technological learning. Furthermore, our study advances the current understanding of how the interplay between technology and market turbulence shapes a firm's capability, technological learning, and enhances efforts towards product and process innovation. It underlines the central role of organizational capabilities in harnessing the positive aspects of turbulent environmental conditions within manufacturing firms.

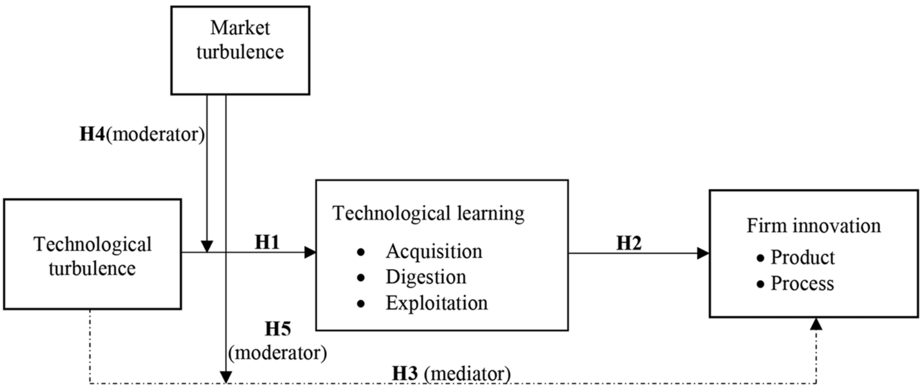

Fig. 1 Proposed research model

2 Theoretical background and hypotheses

2.1 Absorptive capacity perspective

In our research, we adopt the absorptive capacity perspective to elucidate the relationship among technology and market turbulence, technological learning, and product and process innovation. Absorptive capacity, as defined by Cohen and Levinthal (1990:128), refers to "a firm's ability to recognize the value of new external knowledge, assimilate it, and apply it for commercial purposes." Technological learning is a unique and vital aspect of absorptive capacity (Guo et al. 2018; Pan et al. 2019). Ghazinoory et al. (2017) has also emphasized that absorptive capacity and technological capacity can be used interchangeably. Additionally, Huang and Intarakumnerd (2019) have highlighted the essential role of absorptive capacity in enhancing technological learning.

Building on this, technological learning acts as a conduit for adaptation within a technologically intensive landscape. It involves the effective utilization of technology-related knowledge, the assimilation of external technology-related knowledge, and the creation of new knowledge to respond to environmental shifts through a comprehensive absorptive capacity process (Ghazinoory et al. 2017). Notably, external technology acquisition, as asserted by Kim and Inkpen (2005), is intrinsically linked to absorptive capacity, complementing internal development efforts.

Technological learning signifies a firm's ability to learn about new technology-related know-how and solve technical problems by utilizing and improving acquired technology and its related know-how from the external environment (Pan et al. 2019). Building upon the absorptive capacity framework, scholars have identified three intricately interconnected processes that constitute the essence of technological learning: technology acquisition, digestion, and exploitation (Pan et al. 2019). These processes collectively lay the groundwork for firms to enhance their ability to internalize and proficiently apply external technological advancements.

As the first step in this process, technology acquisition represents the initial phase of technological learning, determining the external landscape and facilitating novel connections (Jansen et al. 2005; Lei et al. 1996). It involves the utilization of external technology-related resources that are deficient within the firm, granting access to knowledge generated externally, which is instrumental in cultivating new knowledge (Xie et al. 2018a). Technology acquisition promotes access to technological knowledge, networks and resources (Kerstens and Langley 2025) and enabling firms to stay connected to new trends and opportunities in their industry.

Once external knowledge is acquired, firms engage in technology digestion process. Technology digestion denotes the process of internalizing acquired external knowledge and converting it into practical procedures and abilities (Pan et al. 2019). Primarily, technology digestion fosters the interpretation and dissemination of external technical resources, promoting the integration of technical knowledge among employees within an organization (Zobel 2017).

Following technology digestion, the final dimension of technological learning is technology exploitation. Technology exploitation involves creating and developing something new based on transformed technology-related knowledge. Specifically, it entails refining, expanding, and employing existing technologies to generate new products, enhance their productivity, and improve performance and sustainability through the utilization of acquired and transformed knowledge (Haro-Dominguez, 2007; Zhong et al. 2022).

It is important to note that, while technological learning process is crucial for enhancing innovation, firms operate within external environments that have direct and powerful influences on how technological knowledge is acquired and applied. Specifically, technological and market turbulence are important external factors that influence a firm's innovation outcomes. Additionally, absorptive capacity, external knowledge flows and innovation performance depend on key contingencies, such as environmental turbulences (Escribano et al. 2009).

Environmental turbulence encompasses random and infrequent changes and significant transformations in the market landscape and technology-related information and expertise, primarily including market and technology-related turbulences. Market turbulence signifies unpredictable and unforeseen changes in market demand, along with fluctuations in market trends (Senbeto and Hon 2020). Within this context, firms encounter disruptions in demand, leading to shifts in customer preferences and the rapid adoption of new products and services (Sun and Govind 2017; Turulja and Bajgoric 2019). Gölgeci and Kuivalainen (2020) noted that both the marketing and management literatures emphasize the crucial role of acquiring and processing new external knowledge from an absorptive capacity perspective, particularly for firms operating in highly turbulent environments.

In parallel, technological turbulence represents another dimension of environmental turbulence, indicating the pace at which unforeseeable technical advancements occur within a given environment (Folger et al., 2022). Moreover, technological turbulence signifies the emergence of new technological knowledge in a dynamic technological landscape, often accompanied by novel and distinctive development prospects. These prospects can result in new commercial applications that challenge established technological knowledge (Wang et al. 2022). Su et al. (2013a) noted the fundamental role of technological turbulence in shaping firm's knowledge creation and absorptive capacity development. Moreover, it is important to note that rapid and frequent changes in technology make current knowledge obsolete, therefore firms broaden their external information acquisition by absorptive capacity perspective (Li et al. 2022).

2.2 Hypothesis development

2.2.1 Technological turbulence and technological learning

Previous studies in the field of absorptive capacity have underscored the impact of turbulent environmental conditions on a firm's ability to acquire and integrate external knowledge to tackle operational and innovation challenges (Hussain et al. 2022; Lane et al. 2006). For instance, Liu et al. (2019:1377) emphasized the critical importance of a firm's absorptive capacity in complex and turbulent environments, highlighting its role in integrating, assimilating, and applying knowledge from both internal and external sources.

In alignment with the existing literature on the absorptive capacity framework, we propose that technological turbulence has a positive relationship with technological learning in our study. For instance, Ghazinoory et al. (2017) have noted that technological learning is intricately linked to various internal and external factors, with one such external factor being the technological turbulence prevalent in the environment. We argue that technological turbulence influences technological learning by compelling firms to cultivate new knowledge, forge new connections, and establish causal systems (Li et al. 2020).

Technological turbulence presents a dual nature. On one hand, it poses the risk of technological obsolescence, while on the other, it ushers in new and distinctive scientific, competitive, and technological dynamics that challenge the effectiveness of firms in adopting external technologies. Moreover, it drives firms to enrich both the breadth and depth of their existing knowledge and technical competencies (Xie et al. 2018a). Consequently, firms diversify their channels for acquiring and assimilating new specialized knowledge and innovative ideas, promoting a culture of innovative thinking and transformative changes in their operational strategies (Santos et al. 2020; Li et al. 2022). Thus, we propose the following hypothesis:

H1 Technological turbulence influences technological learning in manufacturing firms.

2.2.2 Technological learning and product & process innovation

Numerous prior studies have presented compelling evidence that absorptive capacity is positively linked to both product (Engelman et al. 2017; Su et al. 2013b) and process (Aliasghar et al. 2019) innovations. For instance, Akgün et al. (2019) empirically demonstrated the positive relationship between a firm's ability to acquire, assimilate, transform, and exploit external knowledge and product innovation by investigating 203 firms across various industries. Similarly, Aliasghar et al. (2023) found that a firm's absorptive capacity significantly influences the success of process innovation, based on their study of 124 small and medium-sized firms in the automotive industry. In alignment with the concept of absorptive capacity, we propose that technological learning, a specific facet of firm absorptive capacity, influences both product and process innovation by facilitating firms' access to external technological knowledge (Lai et al. 2011).

In particular, past studies have demonstrated that technology acquisition enhances a firm's technological innovation (e.g., Pan et al. 2019), resulting in breakthroughs, economic advantages, cost-related improvements, and greater success in new business development projects (Sullivan and Marvel 2011). Through technology acquisition, firms gain access to additional technology-related information, enrich their technical knowledge bases, and expand their exposure to new knowledge sources, all of which contribute to more effective new product and process innovation efforts (Tsai et al. 2011). In this context, Liao and Marsillac (2015) have suggested that acquiring externally generated knowledge through effective interactions between various knowledge sources is conducive to product innovation efforts.

Moreover, technological learning plays a role in shaping product and process innovation by aiding firms in the digestion of external technical knowledge (Lai et al. 2011). The process of technology digestion ensures an efficient internal knowledge transfer and enhances technological knowledge dissemination across different functional departments, thereby improving a firm's products and processes (Akgün et al. 2019; Liu et al. 2013; Xie et al. 2018b). For instance, Tzokas et al. (2015) have pointed out that evaluating and adapting new technologies promotes ambidexterity and enhances innovative performance. According to Grimpe and Kaiser (2010), the acquisition and integration of technological knowledge within a firm's knowledge base play a vital role in driving process innovation.

Additionally, technological learning contributes to both product and process innovation by assisting firms in effectively leveraging external technological knowledge (Lai et al. 2011). Rooted in the absorptive capacity perspective, the exploitation of technology enables firms to enhance their tools, techniques, methodologies (Charmjuree et al. 2022), and to update, modify, and refine their procedures, routines, and knowledge bases (Pan et al. 2019). For example, Kale et al. (2019) emphasized the importance of aggregating in-house information and transforming it into valuable insights to foster firm innovation endeavors. Furthermore, Zobel (2017) has demonstrated that exploitation positively affects competitive advantage in product innovation through the utilization of external technological resources. Thus, we hypothesize that:

H2 Technological learning influences innovation in manufacturing firms.

2.2.3 The mediating effect of technological learning

We posit that shifts in technological environments offer favorable opportunities for firms. For example, Sheng et al. (2011) emphasized that technological turbulence provides firms with opportunities to enhance their competitive positions through product modification or enhancement (Wu et al. 2017). Additionally, Puriwat and Hoonspon (2022) observed that technological turbulence significantly influences the success of product innovation by generating new and valuable ideas. In this context, the presence of technological turbulence requires firms to engage in learning about innovative technologies, gain deeper insights into product-related information, and infuse novelty into their product development activities (Deng et al., 2021).

Furthermore, we contend that technological learning is associated with both product and process innovation, as per H2. Therefore, we propose that technological learning serves as a mediator in the relationship between technological turbulence and both product and process innovation. This mediation implies that technological learning transforms the challenges posed by technological turbulence into favorable opportunities, fostering the development of enhanced products and processes. In this light, technological learning encourages firms to view technological turbulence as an external opportunity for advancing both product and process innovation.

As a result, technological opportunities encompass a spectrum of possibilities for advancing technology to improve the functionality or production aspects of a product (Lee et al. 2017). These opportunities act as incentives for increased investment in R&D (Nieto and Quevedo 2005). Additionally, technological learning introduces changes such as new technological knowledge, pathways, and relationships among technological components, all induced by technological turbulence and integrated into efforts related to product and process innovation (Li et al. 2020).

Consistent with the absorptive capacity perspective, technological learning opportunities inspire firms to effect new and significant improvements in organizational procedures, structures, and routines, subsequently influencing their endeavors in both new product and process innovation (Brem and Voigt 2009). Therefore, we posit the following hypothesis:

H3 Technological learning mediates the positive relationship between technological turbulence and innovation in manufacturing firms.

2.2.4 The moderating effect of market turbulence

In today's dynamic and competitive environments firms must adapt innovation strategies to respond to changing market conditions. To remain competitive in this turbulent environment firms must acquire new information and knowledge and develop better insight into the opportunities in emerging markets (Wu et al. 2023). For instance, Dost et al. (2019) emphasized the critical role of market turbulence to seek and assimilate both external and internal knowledge. In line with this argument, we suggest that the level of market turbulence that firms encounter corresponds to their ability to leverage technological turbulence to enhance their technological learning and innovation endeavors, all while employing technology push and market pull strategies (Guo et al. 2020). For instance, heightened market turbulence results in more complex and fluctuating customer tastes and preferences. In such scenarios, technological turbulence, characterized by rapidly evolving technological advancements, compels firms to actively acquire, assimilate, and leverage new external technologies, which is at the core of technological learning. This enables them to offer technologically superior products or services capable of addressing substantial shifts in customer requirements and volatile preferences.

Furthermore, technological turbulence necessitates that firms seek and acquire amplified market and technology-related insights from external environments. This is done to nurture new and creative perspectives that can adeptly navigate market pressures arising from customers who are sensitive to differences in products or seek variety (Cai et al. 2020; Sandos, 2020). In this way, firms strategically harness the advantages offered by technological turbulence to streamline the efficiency of the technological learning process and to conceive novel products that effectively respond to the evolving preferences of their customer base.

Moreover, heightened market turbulence creates ambiguity regarding firms' market-related strategies and operations. In such circumstances, firms require novel capabilities to effectively address the dynamic and intricate preferences of customers (Wong 2014). For instance, Wang et al. (2022) emphasized how market turbulence renders a firm's existing market knowledge obsolete. In response, technological turbulence prompts firms to grapple with technological shifts and concentrate on assimilating new external technological knowledge to cultivate new capabilities. Building on organizational change theory, Wang et al. (2023) introduced the concept of organizational unlearning, smart technologies, and environmental turbulence to explore strategies for promoting digital process innovation and improving performance. Their empirical findings revealed that digital process innovation mediated the relationship between organizational unlearning and enterprise performance. Additionally, smart technologies and environmental turbulence were found to positively moderate the mediation of digital process innovation on the association between organizational unlearning and enterprise performance.

Furthermore, the study by Larbi-Siaw et al. (2022) demonstrates the importance of market turbulence as a moderator in the relationship between technological turbulence and technological learning in manufacturing firms. Their findings suggest that market turbulence amplifies the positive effect of technological turbulence on firms' ability to learn and adapt to technological changes, thereby enhancing technological learning in turbulent market environments.

Indeed, the swiftly evolving demands and preferences of customers necessitate the integration of new technology-related knowledge components within the organization. This drives an augmented utilization of externally sourced technological knowledge and the exploitation of such knowledge in conjunction with pre-existing insights. This concerted effort serves to engender new and superior products and processes (Lee et al. 2019; Xie et al. 2018b). Based on this discussion, we propose the following hypotheses:

H4 Market turbulence moderates the relationship between technological turbulence and technological learning in manufacturing firms.

H5 Market turbulence moderates the mediated relationship between technological turbulence and innovation through technological learning in manufacturing firms.

3 Research methods

3.1 Research context

Although interest in technological learning has grown in recent years, empirical research that examines its antecedents and outcomes within the context of Turkey remains limited. This gap is particularly notable given Turkey's position as an emerging economy with a growing emphasis on industrial upgrading and innovation (Bouguerra et al. 2022). Previous studies have predominantly focused on firms in the USA, Europe, and Asia (Chen et al. 2021; Hansen and Lema 2019). However, it is crucial to explore Turkey as a key emerging economy to contribute to the literature on technological learning. As highlighted by Chen et al. (2021), the context of technological learning holds significant importance, and the unique conditions of large emerging economies can significantly impact the effectiveness of technological learning.

Turkey has recently initiated structural reforms and prioritized R&D, innovation, and entrepreneurship policies (Avunduk et al. 2023; Duran et al. 2022). As a result, firms are under pressure to reinvent themselves, exhibit flexibility in adapting to technological changes, and develop new capabilities (Yeniaras et al. 2020). Additionally, Turkey plays a significant economic role in bridging Southern Europe and the Middle East (Bolatan et al. 2022; Kleiner-Schäfer and Liefner 2021). This positioning is crucial for technology development and transfer. Particularly in Istanbul and the Marmara Region, firms place a high priority on technology transfer and technology management to integrate into the globalized economy (Kleiner-Schäfer and Liefner 2021; Kleiner-Schaefer et al. 2024).

3.2 Sample and data collection

In this study, we followed the approach outlined by Usunier (2011) for our research methodology. Initially, the questionnaire items were developed in English and later translated into Turkish. To ensure accuracy and consistency, a research team was involved in the translation process. The translated items were then back-translated into English. Additionally, we conducted a pilot study, which involved a carefully selected group of industry managers. The purpose of this pilot study was to identify and address any potential emic (pertaining to the local culture) and ethical issues that might arise during the research.

The data were collected through participants enrolled in Master of Business Administration (MBA) and other graduate-level programs at three universities in Istanbul, Turkey. This sampling method is consistent with approaches adopted in prior research (e.g., Akgün 2020). We specifically approached students, many of whom were managers in their respective firms and willing participants in our research. We inquired whether their firms were involved in developing new products, selling them in both domestic and global markets, and adhering to European quality standards. Subsequently, these students were requested to identify the managers within their firms who possessed the most knowledge about the firm's operations. These designated managers, referred to as "key informants", were then invited to respond to our survey questions, as commonly practiced (Kumar et al. 1993).

Our study was tailored to manufacturing firms. In total, we reached out to 185 manufacturing firms, and 161 of them agreed to participate in our research and returned the surveys. After assessing the reliability of the responses by examining the consistency of identical survey questions, we excluded 19 firms. As a result, our final analyzable sample comprised 142 manufacturing firms, each accompanied by a corresponding survey.

Within our sample, the respondents were made up of marketing managers (31%), manufacturing/production managers (28%), product/project managers (27%), and other top management roles (14%). The surveyed industries represented a diverse mix, including machinery (32%), materials (27%), automotive (22%), and electronics (19%).

The adequacy of the sample size and the suitability of the methodological approach were evaluated in accordance with established recommendations for Partial Least Squares Structural Equation Modeling (PLS-SEM). This method is particularly well-suited for analyzing models that involve multiple constructs and relatively small samples, and it avoids several limitations associated with covariance-based techniques (Chin 1998; Hair et al. 2014). The final sample of 142 manufacturing firms exceeds the commonly cited guideline of having at least ten cases per estimated path coefficient, ensuring sufficient statistical power for the analysis (Barclay et al. 1995). Given that the model incorporates reflective indicators and includes a second-order construct, the use of PLS-SEM is both methodologically justified and consistent with best practices in the literature (Hair et al. 2019). This approach has been frequently applied in research on innovation and technology management, particularly in studies based on firm-level data from emerging markets where access to large samples may be constrained. These factors collectively indicate that the sample size is appropriate for testing the proposed relationships and for drawing valid and interpretable conclusions.

3.3 Measurement of variables

To assess the hypotheses, we utilized multi-item scales sourced from previous research and measured them using 5-point Likert scales, ranging from "strongly disagree" (1) to "strongly agree" (5).

Technological turbulence represents unforeseeable technological advancements in the environment (Folger et al., 2022). We employed a five-item scale adapted from existing technological turbulence studies (Jaworski and Kohli 1993; Moorman and Miner 1997).

Market turbulence is conceptualized as changes in customer preferences and fluctuations in the market (Kohli and Jaworski 1990). A four-item scale adapted from Jaworski and Kohli (1993) and Moorman and Miner (1997) was used to measure this construct.

Technological learning is captured using three dimensions: technology acquisition, technology digestion, and technology exploitation. Technology acquisition allows firms to access knowledge that has not been generated internally and is available outside the firms. It also enables them to acquire new external technology-related expertise and technologies that foster the development of new knowledge (Xie et al. 2018a). Technology digestion involves the internalization of knowledge acquired from external sources and its conversion into operational procedures and skills (Pan et al. 2019). Technology exploitation pertains to creating and developing something new based on transformed technology-related knowledge. Consistent with Pan et al. (2019), we used an eleven-item scale to measure technological learning.

Product innovation. We utilized a six-item scale, adapted from Wang and Ahmed (2004), to measure product innovation.

Process innovation. For process innovation, a four-item scale adopted from the same source (Wang and Ahmed 2004) was used for measurement.

Control variables. Firm size and age were measured using a ratio scale.

The questionnaire items related to these variables, along with their sources, can be found in the Appendix 1.

4 Results

4.1 Validity and reliability of measures

We conducted a thorough assessment to evaluate the reliability and validity of our measurement scales. This process involved a meticulous data purification and testing procedure. Our measurement model incorporates both first-order and second-order reflective-reflective constructs, ensuring the most suitable modeling approach for all variables.

Our initial focus was on evaluating the first-order construct variables. To assess reliability, we employed composite scale reliability (CR), and average variance extracted (AVE) using the PLS technique, given the relatively small size of our study (less than 200 firms) (Chin 1998). The PLS-based CR exceeded 0.70, and AVE values exceeded 0.50, as recommended by Fornell and Larcker (1981). We also conducted a test for convergent validity by examining the standardized loadings of questionnaire items on their respective variables (Chin 1998), all of which exceeded 0.60. Specifically, based on the PLS-SEM, items with standardized loadings below the threshold of 0.60 were removed. Additionally, variance inflation factor (VIF) analysis was conducted in accordance with the guidelines proposed by Kock (2015), and all values were found to be below the threshold of 3.3, indicating no multicollinearity concerns.

Furthermore, in accordance with the guidance from Fornell and Larcker (1981), each construct's AVE exceeded the squared latent factor correlations between pairs of constructs (see Table 2). Moreover, our analysis showed that the Heterotrait-Monotrait correlation index values were all below 0.85, confirming that all variables exhibited adequate discriminant validity.

In this study, we operationalized technological learning as a second-order reflective-reflective construct, comprising the variables of technology acquisition, digestion, and exploitation. The second-order construct was analyzed using the repeated indicator method,

Table 2 Correlations and descriptive statistics

Variables	Mean	S.D.	1	2	3	4	5	6	7	8	9
1. Product innovation	3.84	0.75	(0.77)								
2. Process innovation	3.75	0.67	0.62***	(0.73)							
3. Technology acquisition	3.97	0.84	0.36***	0.28***	(0.83)						
4. Technology digestion	4.21	0.70	0.36***	0.31***	0.34***	(0.87)					
5. Technology exploitation	4.18	0.67	0.37***	0.39***	0.46***	0.64***	(0.81)				
6. Technological turbulence	3.84	0.81	0.30***	0.31***	0.26***	0.39***	0.30***	(0.82)			
7. Market turbulence	3.77	0.80	0.38***	0.29***	0.13	0.24***	0.24***	0.58***	(0.83)		
8. Firm age (logarithmic)	1.42	0.37	0.17**	0.21**	0.16*	0.39***	0.22**	0.33***	0.18**	--	
9. Firm size (logarithmic)	2.55	1.03	0.27***	0.26***	0.37***	0.36***	0.33***	0.35***	0.26***	0.62***	--
Composite reliability			0.88	0.81	0.89	0.90	0.88	0.91	0.90	NA	NA
Variance extracted			0.60	0.53	0.69	0.76	0.65	0.68	0.69	NA	NA
Cronbach's α			0.83	0.72	0.85	0.84	0.82	0.88	0.85	NA	NA

Notes: S.D.=Standard deviation

*p<.1, **p<.05, ***p<.01

Diagonals show the square root of AVEs

in which all the first-order constructs are simultaneously considered as a reflective measure of the second-order construct in the PLS model (Becker et al. 2012). Before establishing technological learning as a second-order reflective construct, we applied the Confirmatory Tetrad Analysis for PLS (CTA-PLS). Following the CTA-PLS process, as recommended by Gudergan et al. (2008), all tetrad values were non-significant. Additionally, we found that all values of the adjusted confidence interval lower limits were negative, while all values of the adjusted confidence interval upper limits were positive, demonstrating that all latent constructs were reflective.

4.2 Assessment of common method bias

To evaluate the presence of common method bias, we conducted the Harman One-factor Test, as recommended by Podsakoff and Organ (2003). Our study's results revealed that the unrotated principal component analysis explained 68.68% of the total variance by generating several factors. Among these factors, the one with the highest variance extracted accounted for 30.80%. These findings indicate that common method bias did not emerge as a statistically significant concern in our study.

4.3 Hypothesis testing

We conducted hypothesis testing using the PLS technique with Smart-PLS 3.0 and the bootstrapping resampling method, generating 500 subsamples of randomly selected cases. The choice was driven by several key considerations. First, PLS-SEM addresses several limitations of maximum likelihood estimation and minimizes the risk of improper solutions and factor indeterminacy (Akgün et al. 2015; Chin 1998). Second, PLS-SEM is also insensitive to sample size, it is proper for a small number of observations (Hair et al.,2014). Moreover, it allows researchers to estimate complex models even with smaller sample size (Hair et al. 2014).

To examine the direct and mediating relationships among the variables, the analysis was structured around three separate models, each outlined in detail below.

We observed that technological turbulence significantly and positively relates to technological learning (β = 0.42, $p < .01$), supporting H1. Moreover, technological learning exhibited positive relationships with both product (β = 0.38, $p < .01$) and process (β = 0.38, $p < .01$) innovation, thus confirming H2 (as displayed in Model 3 of Table 3).

To examine the mediating role of technological learning in the relationship between technological turbulence and firm product and process innovation, we adopted the procedure outlined by Baron and Kenny (1986). In this analysis, as depicted in Table 3, we implemented three distinct PLS models:

Model 1. This model included technological turbulence, firm product, and process innovation, along with control variables. Within this model, we observed that technological turbulence exhibited a positive relationship with both product (β = 0.25, $p < .01$) and process innovation (β = 0.24, $p < .01$), and the corresponding R^2 values were 0.14 for product innovation and 0.13 for process innovation.

Model 2. Focusing on technological turbulence and technological learning, this model indicated that technological turbulence significantly and positively related to technological learning (β = 0.43, $p < .01$), resulting in an R^2 of 0.19 for technological learning.

Model 3. In this third model, while adjusting for technological turbulence, we observed a statistically significant relationship between technological learning and both product

Table 3 The results of the path model

Hypothesis	Relationship	Model 1	Model 2	Model 3	Results
H1	Technological turbulence → Technological learning		0.43^{***}	0.42^{***}	Supported
H2(a)	Technological learning → Product innovation			0.38^{***}	Supported
H2(b)	Technological learning → Process innovation			0.38^{***}	Supported
	Technological turbulence → Product innovation	0.25^{***}		0.14	Supported
	Technological turbulence → Process innovation	0.24^{**}		0.10	Supported
Control variables	Firm size → Product innovation	0.24^{**}		0.11	
	Firm size → Process innovation	0.17		0.05	
	Firm age → Product innovation	−0.05		−0.06	
	Firm age → Process innovation	0.04		0.04	
Fit measures	Endogenous construct	R^2	R^2	R^2	Q^2
	Technological learning	-	0.19	0.17	0.07
	Product innovation	0.14	-	0.24	0.12
	Process innovation	0.13	-	0.23	0.10

$^{*}p < .1$, $^{**}p < .05$, $^{***}p < .01$

(β = 0.38, $p < .01$) and process (β = 0.38, $p < .01$) innovation. By introducing technological learning into the model, the R^2 values increased to 0.24 for product innovation and 0.23 for process innovation. These findings supported the conclusion that technological learning entirely mediated the relationship between technological turbulence and firm product and process innovation, thereby confirming H3.

A model fit assessment was conducted to evaluate the suitability of our structural equation model. The goodness-of-fit (GoF) value was calculated at 0.34, suggesting a moderate fit of the model. GoF index combines measurement model quality and structural model performance (Tenenhaus et al. 2005). Additionally, our findings from the Stone-Geisser test (Q^2) exceeded 0, affirming good predictive relevance (Chin 1998). Furthermore, the composite-based standardized root mean square residual (SRMR) was found to be 0.09, just below the threshold of 0.10, which confirms the overall fit of the PLS path model (Henseler and Sarstedt 2013).

A two-stage approach that incorporated standardized product terms, as recommended by Henseler and Fassott (2010), was employed to investigate the moderating effect of market turbulence on the relationships among technological turbulence, technological learning, and product and process innovation.

As depicted in Table 4, our analysis revealed that market turbulence does indeed moderate the relationship between technological turbulence and technological learning (β = 0.15, $p < .05$), offering support for H4. However, no significant moderating effects of market turbulence were observed on the relationship between technological turbulence and both product (β = 0.002, $p > .1$) and process (β=-0.04, $p > .1$) innovation, thus not supporting H5.

To further assess the substantive impact of the observed significant moderating effects, we employed moderator effect size analysis (Chin et al., 2003). By comparing the R^2 change with and without the moderator, we found that the inclusion of market turbulence as a moderator increased the R^2 of technological learning by 29%, indicating a small effect size (f^2=0.04).

5 Discussion and implications

5.1 Theoretical implications

This research significantly contributes to the field of technology management by introducing a comprehensive conceptual framework that illuminates the interconnected relationships among technology and market turbulence, technological learning, and firm-level product and process innovation within the context of manufacturing.

Firstly, our study empirically establishes a positive association between technological turbulence and technological learning in manufacturing firms. This finding enhances our understanding of the factors contributing to technological learning within the manufacturing sector. While prior research mainly focused on the moderating effect of technological turbulence on the relationship between technological learning and firm performance (Chen and Lien 2013), our study clearly highlights that technological turbulence acts as a precursor to a firm's technological learning. Rapid technological changes and opportunities appear to shape a firm's ability to acquire research and production/operation skills from external

Table 4 The result of the moderating analysis

Relationship	Model A (Base model)	Model B (Interaction model)
Technological turbulence → Technological learning	0.42***	0.42***
Technological learning → Product innovation	0.38***	0.38***
Technological learning → Process innovation	0.38***	0.37***
Technological turbulence → Product innovation	0.14	−0.02
Technological turbulence → Process innovation	0.10	0.04
Moderating variable		
Market turbulence → Technological turbulence		0.06
Market turbulence → Product innovation		0.27**
Market turbulence → Process innovation		0.10
Interactions		
Technological turbulence * Market turbulence → Technological learning		0.15**
Technological turbulence * Market turbulence → Product innovation		0.002
Technological turbulence * Market turbulence → Process innovation		−0.04
Control variables		
Firm size → Product innovation	0.11	0.07
Firm size → Process innovation	0.05	0.05
Firm age → Product innovation	−0.06	−0.03
Firm age → Process innovation	0.04	0.05
$R^2_{\text{tech. learn, product, process}}$	0.17; 24; 0.23	0.20; 0.29; 0.23
$R^2_{adj-\text{tech. learn, product, process}}$	0.17; 0.22; 0.20	0.18; 0.26; 0.20
$\Delta R^2_{\text{tech. learn, product, process}}$		

$^{*}p<.1$, $^{**}p<.05$, $^{***}p<.01$

sources, recognize the significance of new technology-related knowledge in their research processes, and apply assimilated technical knowledge.

Secondly, our research demonstrates the empirical impact of technological learning on both product and process innovation, expanding on previous studies (Pan et al. 2019). Whereas previous research emphasized the relationship between organizational learning and product as well as process innovation (Farzaneh et al. 2021), our study explicitly underlines the key role of technological learning, a form of absorptive capacity, in driving innovation within manufacturing firms in emerging countries (Ghazinoory et al. 2017).

Moreover, our research enriches our current comprehension of absorptive capacity within the context of technological learning and innovation. Past studies extensively demonstrated that a firm's absorptive capacity significantly influences its efforts in product and process innovation (Akgün et al. 2019). However, absorptive capacity is a multifaceted concept encompassing various domains of specific knowledge (e.g., marketing absorptive capacity, cultural absorptive capacity, IT absorptive capacity, and technological absorptive capacity) (Chang et al. 2019). Our study emphasizes that absorptive capacity serves as a foundational concept that triggers technological learning, subsequently influencing a firm's endeavors in product and process innovation. In essence, our research establishes a critical link between technological learning and absorptive capacity, consolidating their combined influence on product and process innovations.

Furthermore, our study empirically demonstrates that a firm's technological learning can transform rapidly changing technological conditions, referred to as technological turbulence, into enhanced practices for product and process innovation. This discovery advances our existing knowledge of technological learning. Team learning emerges as an organizing mechanism that conveys adapted insights into technological turbulence to individuals within the organization, effectively disseminating evolving technology-related information and diffusing messages related to turbulence into product development and process implementation efforts. Our research validates that technological learning has the potential to reframe turbulent scenarios, fostering a positive organizational environment conducive to improved product and process innovations.

Thirdly, our study unveils the moderating role of market turbulence in the relationship between technological turbulence and technological learning. Previous research has explored the moderating role of market turbulence in various relationships: knowledge recombination and innovation quality (Luo et al. 2024), marketing agility and financial performance (Zhou et al. 2019), CEO passion and exploratory and exploitative innovation (Cai et al. 2020), firm capabilities and external collaboration effectiveness (Wang et al. 2015). This finding highlights the role of market turbulence in raising awareness. When a higher level of market turbulence exists, technological turbulence heightens awareness, facilitating a firm's technological learning. This awareness prompts the exploration of novel patterns of action and the adoption of innovative thought processes and behaviors. Essentially, our research identifies that market turbulence empowers individuals to discern hidden or unforeseen technology-related challenges by triggering context-specific interpretations and judgments. This serves as a starting point for forward-looking processes that extend beyond an organization's standard repertoire, ultimately enhancing technological learning. This insight emphasizes the synergy between marketing and technology management through the role of market turbulence, empowering firms to effectively acquire external technology-related knowledge.

On the contrary, our research does not provide evidence of moderated mediation effects of market turbulence on the relationship between technological turbulence, technological learning, and product and process innovation. This result suggests that the combined influence of the interaction between technological and market turbulence on technological learning does not necessarily extend to product and process innovation. This discrepancy arises because the activities of product and process innovation are more distal outcomes stemming from interactions with environmental turbulence-related factors. Technological learning serves as a more proximal variable in the innovation process. Additionally, the interaction between technology and market turbulence demands swift action from firms to address new product and process development. Given that environmental turbulence introduces significant disruptions to organizations, firms prioritize technological learning and focus on short-term strategies and immediate actions to yield swift results amidst turbulent conditions rather than directly embarking on the time-consuming process of developing products and processes.

5.2 Managerial implications

Based on our findings, we offer actionable insights for managers to enhance the technological learning capabilities, including technology acquisition, digestion, and exploitation, of their firms. To achieve this, managers should establish mechanisms for technology acquisition within the organization, enabling the acquisition of skills related to new markets, R&D, and operations. A strategic approach involves cultivating relationships with universities and technoparks. An especially viable option for managers is to foster university-industry collaboration, thereby integrating it into their technology strategies. Managers and scholars can engage in discussions regarding novel technology strategies and advanced technological approaches. Collaborating with scholars can help managers adapt scientific advancements to their workplace and incorporate them into their strategies for new product or process development.

Furthermore, managers can devise organizational structures that leverage advanced information and communication technologies. Implementing boundary-spanning activities and forming cross-functional teams can help capture new technological knowledge from external sources. This proactive approach ensures that the organization remains at the forefront of technological innovation.

Additionally, managers should prioritize technology digestion within the organization. To achieve this, managers can schedule regular employee training sessions to familiarize them with new technological developments. Expanding the human resources pool and augmenting human resource capabilities should also be a managerial focus. Managers can boost employees' sense-making capability to facilitate an effective technology digestion process. In this context, managers should encourage employees to think freely, interpret new information without constraints, and foster greater interpersonal proximity.

Moreover, managers should reconsider functional and team boundaries, working to establish a knowledge ecosystem that promotes technology digestion. Such an inter-organizational knowledge ecosystem mitigates the impact of high-risk perceptions and facilitates a multilevel value information exchange system.

Subsequently, managers should establish the conditions for optimizing the exploitation of technological knowledge. To facilitate an effective technology exploitation process, managers need to overhaul organizational dynamics, including routines, procedures, and interpersonal relationships. The creation of new funds and the allocation of resources are vital steps in this regard. Furthermore, managers should harmonize employee-level interpretation of technological knowledge with overarching corporate strategy and culture.

Additionally, managers should consider technological turbulence as an opportunity for achieving product and process innovation through technological learning. In this context, managers should employ ambidextrous decision-making to transform technological turbulence into avenues for product and process innovations. For instance, managers can simultaneously utilize both a consequential perspective, demonstrating decision-making by considering outcomes for each option, and the non-consequential approach, highlighting the effect of emotions in the decision-making process.

Moreover, managers need to recognize that technological learning involves a continuous adaptation of organizational processes, procedures, and capabilities driven by technological turbulence and responses to market turbulence. In line with this understanding, managers should foster technological learning strategies in specific domains, aligning them with different trajectories of technological advancements. This approach encompasses ensuring the sustainability of existing markets, diversifying options for customers, and creating niche marketplaces.

5.3 Limitations and future research

While this study contributes to our understanding of technological learning and innovation within the context of manufacturing, it is essential to acknowledge certain limitations.

One significant limitation relates to the cross-sectional research design employed in this study, which presents challenges in terms of drawing causal inferences and ascertaining the effects among technology and market turbulence, technological learning, and product and process innovation. To address this limitation, future studies could employ longitudinal data to gain deeper insights into the reciprocal relationships among these variables, offering a more nuanced perspective.

Another limitation pertains to the sample used in this research, as the data were collected from manufacturing firms in Turkey, an emerging country. Consequently, it is crucial to exercise caution when interpreting the findings of this study. Future research should consider the potential variances that may exist in different contexts, including developed economies, to provide a more comprehensive understanding of the phenomena studied.

This study also points toward several promising avenues for future research. While we explored environmental turbulence as an antecedent and moderating variable within the context of technological learning and innovation, future research could delve into extreme events within the scope of technological learning. For example, studies could investigate how extreme circumstances, such as financial crises, operational breakdowns, and climate crises, impact the different dimensions of technological learning. Furthermore, examining how extreme events moderate the association between technological learning and product and process innovation could offer valuable insights into managing disruptions.

Researchers can expand their focus on the consequences of technological learning that subsequently influence firm-level product and process innovation. For instance, there is potential to investigate how technological learning contributes to organizational resilience and digital transformation. Additionally, the antecedents of technological learning could be enriched. Factors such as future corporate memory, digital strategies, and capacity readiness (encompassing organizational willingness, congruence, capability to build, and sustainability) warrant further exploration in future studies.

6 Conclusion

In this research, we have extended our understanding of technological learning from the perspective of emerging countries, assessing its influence on product and process innovations within the context of manufacturing firms operating under turbulent conditions. This study has demonstrated a direct connection between technological turbulence and a firm's technological learning, which, in turn, significantly impacts the firm's endeavors in product and process innovation.

Moreover, our research has unveiled a novel perspective on the moderating role of market turbulence in the complex interplay between technological turbulence and technological learning. This finding emphasizes that the interplay of environmental turbulence-related variables can serve as opportunities for firms to enhance their technological learning capabilities, thereby potentially shaping the trajectory of their innovation endeavors.

We firmly believe that further exploration of technological learning under a spectrum of environmental conditions, including turbulence and extreme events, holds the potential for uncovering valuable insights in future research endeavors. This is particularly pertinent in the face of ongoing global transformations in the business landscape, characterized by emerging business models, the integration of artificial intelligence, and profound societal changes.

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Declarations

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Authors and Affiliations

Ali Ekber Akgün[1] · Halit Keskin[1] · Ekrem Tatoglu[2,3] · Büşra Müceldili[1] · Ayşenur Mavuş[1]

✉ Ekrem Tatoglu
tatoglu.e@gust.edu.kw; ekrem.tatoglu@ihu.edu.tr

Ali Ekber Akgün
aakgun@yildiz.edu.tr

Halit Keskin
hkeskin@yildiz.edu.tr

Büşra Müceldili
busramu@yildiz.edu.tr

Ayşenur Mavuş
aysenur.mavus@std.yildiz.edu.tr

[1] Department of Management, Faculty of Economics and Administrative Sciences, Yildiz Technical University, Istanbul, Turkey

[2] College of Business Administration, GUST Center for Sustainable Development (CSD), Gulf University for Science & Technology, West Mishref 32093, Kuwait

[3] Department of Management, School of Business, Ibn Haldun University, Basaksehir, Istanbul 34480, Turkey

Construct	Items	Source(s)
Technological learning		Pan et al. (2019)
Technology acquisition	1. Enterprises can easily obtain production operation skills from the outside. 2. Enterprises can easily obtain market development skills from the outside. 3. Enterprises can easily obtain research skills from the outside. 4. Enterprises can easily obtain a new patent from the outside.	
Technology digestion	1. Enterprises can quickly understand the newly acquired technical knowledge. 2. Enterprises can quickly identify the difference between newly acquired technical knowledge and existing technology. 3. Enterprises can quickly identify the role of new technology knowledge in research practice.	
Technology exploitation	1. Enterprises can quickly apply digested technical knowledge to improve quality control operations. 2. Enterprises can quickly integrate digested technical knowledge with existing technology. 3. Enterprises can quickly introduce digested technical knowledge into technological innovation. 4. Enterprises can quickly apply digested technical knowledge to new product development.	
Firm innovation		Wang and Ahmed (2004)
Product innovation	1. In terms of new product and service introductions, our firm is often first-to-market. 2. Our new products and services are often perceived as very novel by customers. 3. New products and services in our company often put us up against new competitors. 4. Our recent new products and services are major changes from our previous products and services. 5. In comparison with competitors, our company has introduced more innovative products and services during the past five years. 6. In comparison with our competitors, our company is faster in bringing new products or services into the market.	
Process innovation	1. The nature of the manufacturing process in our company is new compared with that of our main competitors. 2. We are constantly improving our business process. 3. Our company changes production methods at a great speed in comparison with our competitors. 4. Our future investments in new methods of production are significant compared with our annual turnover.	

Construct	Items	Source(s)
Environmental turbulence		Jaworski and Kohli (1993), Moorman and Miner (1997)
Technological turbulence	1. Technology in the industry was changing rapidly. 2. A large number of new product ideas have been made possible through technological breakthroughs in the industry. 3. Technological changes provided big opportunities in the industry. 4. A large number of new product ideas in this area have been made possible through technological breakthrough* 5. Technology in this product area was changing rapidly*	
Market turbulence	1. Customers' preferences changed quite a bit over time. 2. Customers tended to look for new products all the time. 3. New customers tended to have product-related needs that are different from those of our existing customers* 4. We are witnessing demand for our products from customers who never bought them before*	

Note: The marked (*) items are deleted and removed from further analysis