



Exploring adoption of humanoid robots in education: UTAUT-2 and TOE models for science teachers

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Abstract

This study examines the factors influencing science teachers' intentions to adopt humanoid robots in educational settings. It employs the Unified Theory of Acceptance and Use of Technology 2 (UTAUT-2) and the Technology-Organization-Environment (TOE) framework as guiding theoretical models. By integrating UTAUT-2, which emphasizes individual factors, and TOE, which addresses organizational and environmental influences, the study constructs a comprehensive model that explores both personal and contextual drivers of adoption. Utilizing structural equation modeling on a sample of 1,150 pre-service and in-service science teachers, the study reveals that the integrated model demonstrates superior predictive power compared to each framework individually. Results highlight the moderating role of professional experience in the adoption process, with significant differences identified between pre-service and in-service teachers. The findings reveal significant differences between pre-service and in-service teachers, illustrating the moderating role of professional experience in the adoption process. This study provides a deeper understanding of how motivational, organizational, and environmental factors interact to influence adoption intentions. These insights provide practical guidance for developing targeted training programs, promoting institutional readiness through well-crafted policy initiatives, and implementing pilot projects to support schools in the effective integration of humanoid robots into educational curricula. These findings provide actionable insights for educational policymakers and practitioners aiming to enhance teaching quality and student engagement through innovative technologies.

Keywords Educational robotics · Humanoid robots · Science teachers · Technology adoption · UTAUT-2 model · TOE framework · Structural equation modeling

1 Introduction

Advances in educational technologies have prompted teachers and institutions to explore new tools that can enhance teaching effectiveness and student engagement. Among these, humanoid intelligent robots (see Fig. 1) designed to resemble humans in appearance or movement and are equipped with advanced artificial intelligence capabilities (Chen et al., 2023) represent a novel approach with the potential to transform science education (Asghar et al., 2022). These robots, equipped with capabilities such as natural language processing, interactive feedback, and real-time problem-solving, offer new opportunities for teaching complex concepts (Chalmers et al., 2022; Fung et al., 2024; Mishra et al., 2021). By providing personalized assistance, interactive demonstrations, and collaborative learning experiences, humanoid robots have the potential to enrich science education by fostering deeper understanding and enhancing students' motivation (Asghar et al., 2022; Ekström & Pareto, 2022a, b). However, the adoption of humanoid robots in educational settings presents both opportunities and challenges, which require a thorough understanding of the factors influencing teachers' intentions to use them.

Given the pivotal role teachers play in integrating new technologies into classrooms, understanding their intention to adopt humanoid robots is crucial for successful implementation. The intention to use such technologies powered by generative artificial intelligence is influenced not only by personal motivations but also by organizational support and environmental factors (wael AL-khatib, 2023). However, research on the use of humanoid robots in science education is still limited,

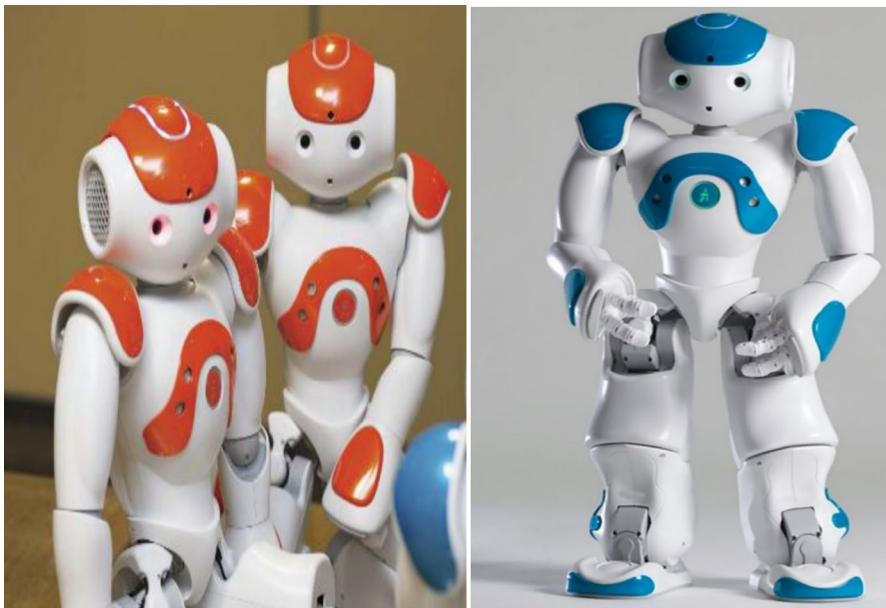


Fig. 1 Examples of humanoid robots, adapted from the studies of Chalmers et al. (2022) and Asghar et al. (2022)

particularly in understanding how teachers' intentions are influenced by multiple interrelated factors. Addressing this gap, this study adopts an integrated framework combining the Unified Theory of Acceptance and Use of Technology 2 (UTAUT-2) (Venkatesh et al., 2012) and the Technology-Organization-Environment (TOE) (Tornatzky & Fleischer, 1990) framework to provide a comprehensive view of the determinants of adoption.

The UTAUT-2 model explains behavioral intention by focusing on individual-level factors, including performance expectancy, effort expectancy, social influence, hedonic motivation, facilitating conditions, and habit (Ateş & Garzón, 2023; Chang, 2012). In the context of science education, performance expectancy refers to teachers' beliefs that humanoid robots will improve teaching quality and student engagement. Effort expectancy reflects the ease of use and perceived simplicity of operating such technologies (Acosta-Enriquez et al., 2024). Social influence captures the impact of colleagues, administrators, and students on teachers' intentions to adopt humanoid robots (Ekström & Pareto, 2022a, b), while facilitating conditions encompass the availability of resources and technical support. Additionally, hedonic motivation highlights the importance of teachers finding the use of humanoid robots enjoyable, which can motivate them to incorporate such technologies into their teaching practices.

While UTAUT-2 focuses on the individual factors influencing adoption (Tamilmani et al., 2021), the TOE framework expands the analysis to encompass organizational and environmental factors (Tornatzky & Fleischer, 1990). The TOE model assesses how technological attributes, organizational readiness, and environmental conditions shape technology adoption (Abdurrahman et al., 2024; Das & Bala, 2024). The technology dimension includes factors such as relative advantage, complexity, and compatibility with existing teaching practices. The organizational dimension examines the role of management support, teacher training, and resource availability in fostering or hindering adoption. Lastly, the environmental dimension considers external influences, such as government policies, competitive pressure, and vendor support, that can impact teachers' decisions.

By integrating UTAUT-2 and TOE frameworks, this study aims to provide a comprehensive understanding of the multi-dimensional factors that shape science teachers' intentions to adopt humanoid robots. This dual-framework approach offers a holistic lens by capturing the dynamic interplay between individual motivations, organizational readiness, and environmental conditions. While UTAUT-2 focuses on personal drivers such as performance expectancy, effort expectancy, social influence, and facilitating conditions (Taneja & Bharti, 2022), the TOE framework extends the analysis to encompass broader structural factors such as resource availability, institutional support, and policy environments (Baker, 2012). Together, these frameworks allow for a nuanced examination of both internal and external influences, identifying the barriers and enablers that affect the adoption of humanoid robots in educational settings. This integrated model acknowledges that teachers' positive perceptions of usefulness and ease of use (UTAUT-2 factors) are necessary but not sufficient for adoption. For example, even if a teacher believes that humanoid robots can improve student engagement and make teaching more efficient, external constraints—such as limited infrastructure, inadequate technical support, or lack of administrative

encouragement (TOE factors)—can significantly impede adoption efforts. The TOE framework highlights how factors beyond teachers' control, such as budget constraints, regulatory policies, or competitive pressures from other schools, may limit their ability to implement these technologies, even when individual motivation is high. Conversely, a supportive organizational culture with strong management backing, appropriate teacher training, and reliable technological infrastructure can serve as critical enablers, encouraging teachers to embrace these innovations.

This research contributes to the growing body of literature on educational technology adoption by providing insights into the specific factors that drive or deter science teachers from embracing humanoid robots. The findings will offer practical recommendations for teacher training programs, policy development, and school management strategies aimed at promoting the effective integration of humanoid robots in science classrooms. Understanding these factors is essential for developing targeted interventions that support teachers in overcoming adoption barriers and leveraging the potential of advanced robotics technologies in their teaching practices.

2 Literature review and hypothesis development

2.1 The role of humanoid robots in education: opportunities and challenges

The integration of humanoid robots in education presents a broad range of opportunities to enhance teaching practices and improve student learning (Chalmers et al., 2022). Equipped with capabilities such as speech recognition, gesture interaction, and mobility, these robots create interactive learning environments that engage students effectively (Alotaibi & Manimurugan, 2022; Stiefelhagen et al., 2007; Tong et al., 2024). Their ability to engage in two-way communication and provide real-time feedback facilitates dynamic lessons, promoting student motivation and participation (Al Hakim et al., 2022; Fung et al., 2024). These robots are particularly useful in subjects where conceptual learning benefits from interactive demonstrations, making lessons more tangible through hands-on activities (Baltes et al., 2023).

Beyond engagement, humanoid robots offer personalized instruction by analyzing students' performance data and tailoring learning strategies to meet individual needs (Asghar et al., 2022). This adaptability ensures that students receive differentiated support according to their learning pace and style, making the learning experience more effective than traditional methods (Mishra et al., 2021). Furthermore, humanoid robots can simulate abstract concepts through visual models and real-world scenarios, enhancing students' understanding (Tong et al., 2024) across subjects such as mathematics (Tilden et al., 2021), language learning (Fung et al., 2024), and science education (Asghar et al., 2022; Mertzani & Drigas, 2023).

Humanoid robots also foster collaborative learning by acting as facilitators in group activities (Chalmers et al., 2022). They can moderate discussions, assign tasks, and ensure equal participation among students, encouraging the development of teamwork and problem-solving skills. Additionally, the use of robots reduces teachers' workload by automating routine tasks such as grading, attendance tracking, and delivering standardized instructions (Pau et al., 2021). This allows educators to

focus more on creative teaching strategies, curriculum development, and individualized learning plans.

The presence of humanoid robots in classrooms can also inspire interest in STEM fields (Science, Technology, Engineering, and Mathematics). By interacting with these robots, students gain exposure to robotics, programming, and engineering, encouraging them to explore career opportunities in these fields (Mertzani & Drigas, 2023). As a result, the adoption of humanoid robots not only improves educational outcomes but also cultivates future talent, preparing students for an increasingly technology-driven world.

Despite the many benefits, the integration of humanoid robots in education presents several challenges and barriers. A significant obstacle is the high cost of acquisition and maintenance (Bogue, 2020). Schools must make substantial investments not only for the initial purchase of robots but also for ongoing software updates, repairs, and technical support. For schools with limited budgets, allocating resources for these technologies can be difficult, which restricts their accessibility and scalability.

Another challenge lies in the technical complexity and learning curve associated with using humanoid robots (Tong et al., 2024). Teachers may need specialized knowledge and training to operate these technologies effectively (Ramírez-Montoya et al., 2023). Acquiring the necessary skills can be time-consuming and demanding, particularly for educators unfamiliar with advanced technologies. Without access to adequate professional development opportunities, teachers may feel overwhelmed and reluctant to integrate robots into their teaching practices.

Classroom management issues also arise with the introduction of humanoid robots. While these robots can enhance student engagement, they may also become a source of distraction if students focus more on interacting with the robots than on learning (So & Lee, 2023). Teachers need to maintain a balance between leveraging robots for educational purposes and managing classroom discipline (Okagbue et al., 2024). Moreover, it is essential to align robot-assisted activities with curriculum standards. If these activities do not support national education frameworks or assessment criteria, teachers may hesitate to use them extensively, fearing that they may not contribute to expected learning outcomes.

Resistance to change is another barrier to adopting humanoid robots (Modliński et al., 2024). Some teachers may prefer traditional teaching methods and be skeptical about the effectiveness of robots in education. Concerns about job security or the fear of being replaced by technology may also hinder adoption (Nyholm et al., 2021). Overcoming this resistance requires behavioral and cultural change within educational institutions, along with supportive policies and incentives that foster positive attitudes toward technology adoption.

Additionally, infrastructure limitations pose challenges. Many schools may lack the necessary technological infrastructure, such as reliable internet connectivity or access to technical support, both of which are essential for the effective operation of humanoid robots. Technical disruptions during lessons can frustrate teachers and students, potentially discouraging further use. Furthermore, the use of humanoid robots raises ethical and privacy concerns (Friedman, 2023), particularly regarding data collection and student interactions. Schools must establish clear guidelines and policies to address these concerns, ensuring that the use of robots adheres to ethical standards and safeguards student privacy.

2.2 Ethical implications and long-term impacts of humanoid robot adoption in education

The integration of humanoid robots in educational settings raises significant ethical implications and long-term impacts that must be carefully considered. One of the primary ethical concerns is related to data privacy and security. Humanoid robots often collect and analyze sensitive information about students, which necessitates robust policies and compliance with data protection laws to ensure the safeguarding of this data (Alcorn et al., 2019; Cuberos, 2019). The need for stringent data protection measures is echoed in various studies that highlight the importance of ethical considerations in the deployment of technology in educational environments (Choudhury et al., 2018; Fedock et al., 2018).

Moreover, the reliance on humanoid robots in education poses a risk of diminishing the emotional connections between teachers and students. These connections are crucial for holistic learning, as they foster an environment conducive to emotional and social development (Ekström & Pareto, 2022a, b; Smakman et al., 2022). The balance between human and robotic instruction is essential to maintain these relationships, as studies suggest that while robots can serve as effective educational tools, they cannot replace the nuanced emotional support provided by human educators (Desideri et al., 2017; Mavridis et al., 2011). The potential for robots to foster psychological attachments in students also raises concerns about their long-term social and emotional development, necessitating a careful approach to their integration into learning environments (Mertzani, 2023; Smakman et al., 2022).

Bias in robot algorithms presents another ethical challenge, as pre-programmed systems may inadvertently perpetuate existing inequalities in educational settings (Andtfolk et al., 2021; Papadopoulos et al., 2020). Continuous evaluation and an inclusivity-focused design approach are critical to mitigate these risks and ensure that robotic technologies serve all students equitably (Huijnen et al., 2017). Furthermore, the financial implications of acquiring and maintaining humanoid robots could exacerbate disparities between resource-rich and underfunded schools, highlighting the need for policies that promote equitable access to these technologies (Choudhury et al., 2018; Mertzani, 2023).

The long-term impacts of humanoid robots on students' social skills and emotional well-being are also a significant concern. Prolonged interaction with robots may alter interpersonal skills and emotional development, necessitating a balanced integration of robotic technologies in educational contexts (Smakman et al., 2022; Desideri et al., 2017). Additionally, sustainability issues arise from the maintenance and eventual replacement of these technologies, which involve both financial and environmental considerations (Duğășescu, 2024; Anzalone et al., 2015).

Despite these challenges, humanoid robots have the potential to enrich educational experiences if integrated thoughtfully. Collaboration among policymakers, educators, and technologists is essential to establish ethical guidelines, ensure equitable access, and evaluate the broader implications of these technologies in classrooms (Alcorn et al., 2019; Choudhury et al., 2018; Cuberos, 2019). By addressing these ethical implications and long-term impacts, the educational sector can harness the benefits of humanoid robots while safeguarding the interests of students and educators alike.

2.3 The combination of UTAUT 2 and TOE and study hypotheses

The combination of UTAUT-2 and TOE frameworks, as illustrated in Fig. 2, offers a comprehensive understanding of the factors influencing science teachers’ intentions to adopt humanoid robots in education. This integrated approach allows for a more nuanced exploration of the interplay between personal, institutional, and contextual factors shaping teachers’ behavioral intentions.

UTAUT-2 is useful in capturing the rational decision-making processes of teachers regarding the adoption of new technologies, focusing on how individual perceptions of usefulness, ease of use, and social expectations influence their behavioral intentions (Ateş, & Garzón, 2023). However, on its own, UTAUT-2 may overlook external constraints and facilitators that are often critical in the educational setting,

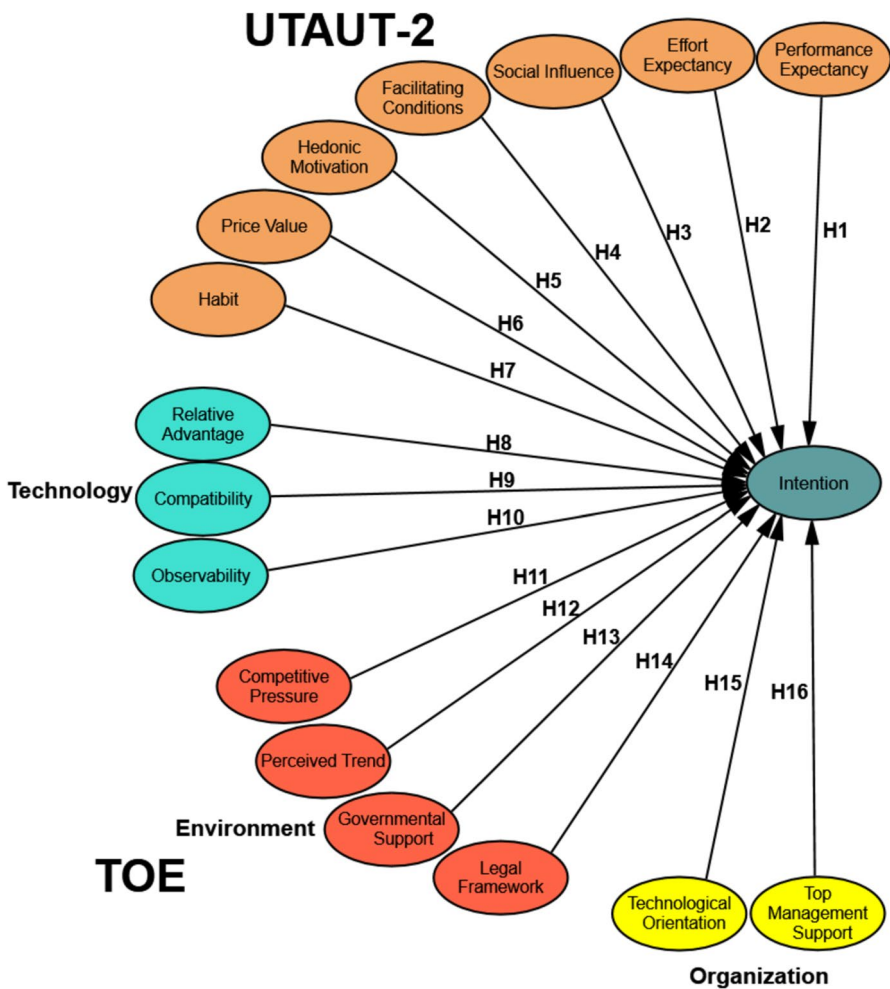


Fig. 2 Proposed UTAUT-2 and TOE integrated model for science teachers’ adoption of humanoid robot

such as the availability of resources, technical infrastructure, and institutional policies. These elements are effectively addressed by the TOE framework, which expands the analysis to include organizational readiness and environmental conditions that either enable or hinder adoption (wael AL-khatib, 2023).

Merging UTAUT-2 and TOE frameworks can enhance the understanding of teachers' decisions regarding humanoid robots. UTAUT-2 captures internal drivers (e.g., motivation and ease of use), while TOE addresses external enablers or barriers (e.g., school infrastructure, government policies). Relying exclusively on UTAUT-2 might be insufficient, as individual willingness may not translate into actual adoption if organizational or environmental support is lacking. Similarly, the TOE framework alone does not account for personal motivation and perceptions, which are crucial for behavioral intention.

This combined framework ensures a holistic perspective, acknowledging that even if teachers perceive humanoid robots as beneficial and easy to use (UTAUT-2 factors), adoption may still be inhibited by limited infrastructure or lack of administrative support (TOE factors). Conversely, strong institutional support and alignment with policies (TOE factors) can amplify the effects of individual motivations, facilitating adoption.

2.3.1 Unified theory of acceptance and use of technology 2 (UTAUT-2)

The UTAUT-2 is an extension of the original UTAUT model developed by Venkatesh et al. (2012). It incorporates new constructs relevant to consumer contexts—such as hedonic motivation, price value, and habit—which enrich the understanding of individual adoption behavior. The model retains core constructs, including performance expectancy, effort expectancy, social influence, and facilitating conditions, all of which play pivotal roles in predicting behavioral intention and actual technology use (Camillieri, 2024; Taneja & Bharti, 2022). UTAUT-2 has been widely applied across various domains, including education (e.g., García de Blanes Sebastián et al., 2024), health (e.g., Walle et al., 2023), and consumer technologies (e.g., Chopdar et al., 2023), demonstrating robust explanatory power in contexts where individual preferences and external influences coexist. In science education, the model helps assess how teachers' perceptions, motivation, and external support affect their willingness to adopt emerging technologies like humanoid robots (Ateş, & Garzón, 2023).

Performance expectancy reflects the belief that the technology will enhance both teaching efficiency and student outcomes (Duong et al., 2023). For instance, in science classes, robots can demonstrate complex concepts and facilitate interactive lessons, motivating teachers to adopt them (Ateş & Gündüzalp, 2024). Effort expectancy focuses on how easy teachers perceive the technology to be; technologies that require less effort increase the likelihood of adoption, emphasizing the need for simple interfaces and training (Sang et al., 2023). Social influence refers to the impact of expectations from peers, administrators, or students, which can encourage teachers to integrate humanoid robots. Facilitating conditions—such as the availability of technical support, infrastructure, and school policies—play a significant role in enabling adoption (Cabellos et al., 2024). In addition, hedonic motivation highlights the role of enjoyment; teachers who find satisfaction in using robots are more inclined to incorporate them into their classrooms. Another important consideration is price

value, especially in resource-constrained schools, where teachers must weigh the benefits of the robots against their cost. Finally, habit captures the importance of familiarity with the technology. Teachers who have prior experience with similar technologies are more likely to continue using robots regularly.

Although the UTAUT-2 model has recently been applied to educational technologies in the context of science education (Ateş & Garzón, 2023; Ogegbo et al., 2024), there remains a significant research gap concerning the adoption of humanoid robots in this domain. Most existing studies focus on general robotics (Suhail et al., 2024), the use of robotics in STEM education (Ateş & Gündüzalp, 2024), or artificial intelligence integration in science education (Al Darayseh, 2023; Ateş, 2024). However, the unique challenges and opportunities presented by humanoid robots—particularly their potential role in enhancing student engagement and interaction—remain underexplored. Humanoid robots provide advanced interactivity and facilitate social engagement, making them uniquely suited for educational environments (Chevalier et al., 2020; Morgante et al., 2024). Despite this potential, limited research has addressed how teachers perceive barriers such as effort expectancy, costs, or the availability of institutional support in adopting humanoid robots in classrooms. Further, studies specific to science education involving humanoid robots are sparse, leaving critical gaps in understanding how these robots can improve science learning outcomes and address practical barriers related to infrastructure and professional development. Based on the discussions above, we propose the following hypotheses:

H1 Higher performance expectancy increases science teachers' intention to adopt humanoid robots.

H2 Greater perceived effort expectancy enhances science teachers' intention to adopt humanoid robots.

H3 Positive social influence boosts science teachers' intention to adopt humanoid robots.

H4 Perceived facilitating conditions support science teachers' intention to adopt humanoid robots.

H5 Higher hedonic motivation increases science teachers' intention to adopt humanoid robots.

H6 Positive perceived price value influences science teachers' intention to adopt humanoid robots.

H7 Stronger habitual tendencies increase science teachers' intention to use humanoid robots.

Despite the strength of UTAUT-2 in education (e.g., Bessadok & Hersi, 2023; Du & Liang, 2024), existing studies often lack a focus on contextual barriers specific

to educational settings, such as curriculum alignment, limited professional development opportunities, and variability in administrative support across institutions. These deficiencies highlight the importance of integrating organizational and environmental dimensions—as captured by the TOE framework—to address the practical realities of adoption (Mahlangu & Makwasha, 2023). Without these contextual considerations, even motivated teachers may struggle to implement humanoid robots effectively due to insufficient infrastructure, resource limitations, and unclear institutional policies. Thus, a comprehensive approach that addresses both individual drivers and external constraints is essential to foster successful adoption in education.

2.3.2 Technology-organization-environment (TOE) framework

The TOE framework, introduced by Tornatzky and Fleischer (1990), offers a comprehensive model for understanding the factors influencing the adoption of innovations. It explores three key dimensions—technological, organizational, and environmental—that shape the decision-making process related to adopting technologies.

The technological context refers to the characteristics of technologies available to the organization, whether they are already in use or accessible in the broader market (Baker, 2012). Factors such as relative advantage, compatibility, and observability influence the adoption process. Relative advantage describes the extent to which the new technology is perceived as superior to current methods, while complexity refers to how difficult the technology is to understand and implement (Chittipaka et al., 2023). Compatibility reflects how well the technology aligns with existing systems, processes, and practices within the organization (Malik et al., 2021). Observability in the TOE framework refers to the extent to which the benefits of adopting a particular technology are visible to others within the organization (Awa et al., 2017a). Together, these elements help organizations assess the value and practicality of adopting a particular technology (Chittipaka et al., 2023; Nguyen et al., 2022). This is particularly relevant to the adoption of humanoid robots in educational settings, as these technological characteristics determine how easily such innovations can be integrated into existing classroom practices. In this study we suppose that science teachers are more likely to adopt humanoid robots if they perceive them as providing significant benefits over traditional teaching methods, aligning with existing practices, and being easy to use. The opportunity to test the humanoid robots before full implementation and clearly observe their benefits further supports adoption. However, prior studies often overlook practical challenges specific to science education, such as how well the technology aligns with curriculum objectives.

The organizational context focuses on internal factors that shape the adoption and implementation process. Top management support plays a critical role, as leadership commitment ensures adequate resources are allocated and motivates employees to embrace the change (Al Hadwer et al., 2021). Organizational size and the availability of resources can either facilitate or hinder adoption, with larger organizations often finding it easier to implement new technologies (Racherla & Hu, 2008). Additionally, the structure and culture of the organization are significant; decentralized structures and cultures that encourage innovation tend to be more conducive to adopting new

technologies (Ng et al., 2022). An organization's readiness, including its existing infrastructure, technical competence, and prior experience with similar technologies, also affects its capacity to integrate new systems successfully (Awa et al., 2017b). In the scope of this study, we propose that schools with sufficient infrastructure and training opportunities create an environment where science teachers can effectively integrate humanoid robots into their practices. However, studies reveal variability in institutional support across schools, with limited infrastructure or inconsistent professional development programs acting as significant barriers to adoption (Neumeyer et al., 2020). Decentralized school structures that foster innovation are more likely to succeed in implementing new technologies (Chi et al., 2021).

The environmental context emphasizes the importance of external factors that impact technology adoption. Competitive pressures and market trends often push organizations to innovate to maintain their competitive edge, while regulatory environments—including laws, standards, and policies—can either encourage or mandate the use of certain technologies (Baker, 2012). Additionally, external pressures from customers, competitors, and suppliers can further drive adoption (Chittipaka et al., 2023). The availability of external support, such as consultants, vendors, and training services, can significantly influence how smoothly new technologies are implemented (Ng et al., 2022). In the context of this study, government policies encouraging innovation, alongside technical support from vendors, are proposed as key enablers for the adoption of humanoid robots. Furthermore, competition among schools also motivates administrators to adopt advanced technologies to enhance institutional reputation. However, previous research has largely focused on these external factors within business and healthcare settings (Ghaleb et al., 2021; Racherla & Hu, 2008), with limited attention to their impact on educational technology, particularly in science education. This gap in understanding highlights the need for further research in this area to effectively address the challenges and opportunities related to adopting humanoid robots in science classrooms. Following the discussions presented above, we put forward the following hypotheses:

H8 Greater perceived advantages of humanoid robots over traditional teaching methods will increase science teachers' intention to adopt them.

H9 A higher degree of perceived alignment between humanoid robots and existing teaching practices will enhance science teachers' intention to use them.

H10 Greater visibility of the perceived benefits of humanoid robots in education will increase science teachers' intention to adopt them.

H11 Higher perceived competitive pressure from other schools will increase the likelihood of humanoid robot adoption.

H12 The perception that adopting humanoid robots is becoming an educational trend will enhance teachers' intention to integrate them into classrooms.

H13 Perceptions of greater government support through training, funding, and advisory services will increase the adoption of humanoid robots in classrooms.

H14 Perceived stronger legal frameworks ensuring privacy and incentives will positively influence science teachers' adoption of humanoid robots.

H15 Perceived technological orientation of schools will positively influence science teachers' adoption of humanoid robots.

H16 Perceptions of stronger support from school management will positively influence science teachers' adoption of humanoid robots.

3 Method

3.1 Data collection process

The data collection process for this study was systematically developed to gather reliable quantitative data from pre-service and in-service science teachers about their perceptions and intentions to adopt humanoid robots in educational settings. The process was structured to ensure participants were thoroughly informed and engaged at each stage, thereby enhancing the accuracy and relevance of the data collected.

The initial phase involved introducing participants to humanoid robots through a comprehensive educational module developed in the Turkish national language to ensure accessibility and comprehension for all participants. This module was designed to provide participants with a conceptual understanding of humanoid robots, focusing on their potential capabilities, educational benefits, and alignment with science education goals. It included multimedia presentations and interactive videos that showcased hypothetical use cases, such as enhancing student engagement, facilitating interactive learning experiences, and illustrating abstract science concepts. The module emphasized the possibilities of humanoid robot integration, rather than actual usage, as most institutions currently lack direct access to these technologies.

Following the overview, participants were provided with a technical guide, also prepared in the Turkish language, that described key aspects of humanoid robots, including their hypothetical hardware and software requirements, compatibility with existing classroom technologies, and a step-by-step guide to potential setup and usage. This guide aimed to equip teachers with a theoretical understanding of how humanoid robots could be integrated into classrooms, allowing them to provide more informed responses about their perceptions and intentions.

Once the context had been set, a structured survey was employed as the main tool for data collection. This survey was developed based on the UTAUT-2 and TOE frameworks and translated into the Turkish language to ensure clarity and ease of use for participants. To maximize participation and ensure teachers were comfortable

with the survey content, user instructions were provided alongside the survey. These instructions clarified the purpose of each section and provided practical examples to guide responses. Participants were also encouraged to attend an optional online orientation session. This session, specifically aimed at in-service teachers, covered conceptual use cases of humanoid robots in the classroom and addressed common questions about their hypothetical integration. The orientation included a brief demonstration of how humanoid robots could be used to conduct science experiments or explain difficult concepts interactively, presented as potential applications.

A pilot test of the survey was conducted with a small group of 125 pre-service and 116 in-service science teachers to identify and rectify any issues related to question clarity or technical difficulties in accessing the survey. Feedback from the pilot participants was used to revise and refine the survey questions, ensuring that the final data collection tool was effective and easy to navigate.

During the data collection phase, follow-up reminders were sent bi-weekly to participants who had not yet completed the survey to improve response rates. To further support participants, a dedicated helpline was established, allowing them to contact the research team directly via email for assistance with any technical issues or clarifications regarding the survey content.

3.2 Sample

The sample for this study comprised a total of 1,150 participants in Turkey, including both pre-service and in-service science teachers, surveyed between May and October 2024. This diverse group was selected to provide a comprehensive understanding of perspectives on the adoption of humanoid robots in science education. This extensive sample size provided both breadth and depth in exploring how different demographics and teaching contexts impact technology adoption.

The pre-service group included 600 science teacher candidates currently enrolled in teacher education programs at universities. Participants were drawn from several higher education institutions across diverse geographical areas to ensure variation in educational exposure and instructional settings. The majority of these pre-service teachers were pursuing undergraduate degrees in science education, and while they possessed limited practical teaching experience, they were well-versed in educational theories and new pedagogical tools. The insights from this group provided valuable information on the perceived benefits and barriers associated with adopting humanoid robots before entering the profession. Demographic information indicated that the pre-service group had a relatively balanced gender representation, with approximately 26% male and 74% female participants, and were primarily between 18 and 24 years old. Their prior exposure to educational technology was notably high, with around 74% indicating familiarity through coursework and practicum sessions.

The in-service group included 550 science teachers who were actively teaching at middle school levels. Participants were selected from schools in urban and rural areas, ensuring diversity in terms of access to resources, exposure to technology, and regional differences in educational practices. This group represented a broad range of teaching experiences, with participants having anywhere from 2 years to over 20 years

of teaching experience. Of the in-service teachers, 64% had more than five years of experience, which provided insights into the practical aspects of integrating humanoid robots into real classrooms, reflecting on challenges such as infrastructure limitations and classroom management. The in-service group also had a varied educational background, with 75% holding only a Bachelor's degree, 20% holding a Master's degree, and 5% having a Doctorate. There was a nearly even split between teachers from urban schools (68%) and those from rural schools (32%), providing insights into how differing access to resources impacts the feasibility of adopting humanoid robots.

The inclusion of both pre-service and in-service teachers ensured that the study accounted for theoretical expectations from teachers-in-training as well as the practical realities faced by those already in the profession. The gender distribution among in-service teachers was 47% male and 53% female, and their age distribution ranged from 25 to over 45 years, ensuring diversity in terms of life stage and professional experience. Importantly, a significant proportion of in-service teachers (70%) had previous experience with educational technology, which provided a strong basis for evaluating their perceptions of the relative advantage, compatibility, and complexity of humanoid robots compared to technologies they were already familiar with.

3.3 Data collection tools

The data collection tools used in this study comprised comprehensive scales adapted from previously validated studies for both the UTAUT-2 framework (Ateş & Garzón, 2023; Venkatesh et al., 2012) and the TOE framework (Nguyen et al., 2022; Shahadat et al., 2023). These adaptations aimed to evaluate factors influencing the adoption of humanoid robots among science teachers effectively.

The study used a total of 40 items, distributed across various constructs, to thoroughly assess both individual and contextual factors affecting the adoption of humanoid robots by science teachers. For the UTAUT-2 constructs, these included eight categories: Performance Expectancy (3 items), Effort Expectancy (4 items), Social Influence (3 items), Facilitating Conditions (4 items), Hedonic Motivation (3 items), Price Value (3 items), and Habit (3 items). Each of these constructs was measured by multiple items, reflecting dimensions such as perceived usefulness, ease of use, social influence, availability of resources, motivation, cost considerations, and habit formation. For the TOE framework, the constructs included Relative Advantage (4 items), Compatibility (3 items), Observability (3 items), Top Management Support (4 items), Competitive Pressure (3 items), Perceived Trend (3 items), Government Support (4 items), Legal Framework (3 items), and Technological Orientation (3 items). These constructs helped evaluate the perceived technological benefits, compatibility with existing practices, external support, and institutional readiness for adopting new technologies like humanoid robots. Lastly, the construct Intention to Use was measured using three items.

All constructs were measured using a 5-point Likert scale ranging from “strongly disagree” (1) to “strongly agree” (5), allowing for nuanced assessments of attitudes and perceptions. The constructs presented in Table 1 were subjected to psychometric evaluations to ensure both validity and reliability of the measurements.

3.4 Data analysis

Data analysis for this study was performed using SPSS 27 and AMOS 24. Given that the items and constructs for UTAUT-2 and TOE models were adapted from existing literature, it was necessary to evaluate their validity and reliability within the context of science teachers adopting humanoid robots. To address concerns about reproducibility and contextual appropriateness, a preliminary study was conducted with 229 pre-service and in-service science teachers to refine the measurement instruments.

Initially, Confirmatory Factor Analysis (CFA) was performed as part of a two-stage Structural Equation Modeling (SEM) approach, following the guidelines of Anderson and Gerbing (1988). The CFA, conducted with maximum likelihood estimation, indicated an acceptable fit of the measurement model to the data: $\chi^2 = 1056.42$, $df=380$, $p < 0.05$; $\chi^2/df=2.78$; Goodness of Fit Index (GFI)=0.90, Tucker-Lewis Index (TLI)=0.91, Incremental Fit Index (IFI)=0.92, Comparative Fit Index (CFI)=0.92, Root Mean Square Error of Approximation (RMSEA)=0.06, and Standardized Root Mean Residual (SRMR)=0.06. These fit indices met the acceptable standards, indicating that the data fit the hypothesized model well.

The Composite Reliability (CR) values for all constructs were above 0.70, ranging from 0.85 to 0.91, confirming the internal consistency of the constructs (Hair et al., 2019). The Average Variance Extracted (AVE) values ranged from 0.65 to 0.74, exceeding the suggested threshold of 0.50, thus supporting the convergent validity of the constructs (Anderson & Gerbing, 1988). Additionally, Cronbach's Alpha (α) values were found to be between 0.80 and 0.92, indicating strong reliability of the measurement tools.

In the final stage of data analysis, discriminant validity was assessed by ensuring that the square root of the AVE for each construct was greater than the correlations with any other construct. This confirmed that each construct was distinct and not excessively correlated with others, supporting the measurement model's discriminant validity. The findings, including factor loadings, Average Variance Extracted (AVE), Composite Reliability (CR), and Cronbach's Alpha values, are presented in Table 1. Additionally, the results related to Discriminant Validity are detailed in Table 2.

By conducting both EFA and CFA, the study ensured robust validity and reliability of the constructs used to evaluate the adoption of humanoid robots by science teachers, thereby enabling a deeper understanding of the personal, organizational, and environmental factors affecting adoption decisions.

4 Findings

4.1 Comparative evaluation of model fit and explanatory power for TOE, UTAUT-2, and the combined model

In the second phase of the analysis, the structural model fit was evaluated using SEM for the TOE model, UTAUT-2 model, and the proposed combined model. According to the findings in Table 3, all three models demonstrated an acceptable fit

Table 1 UTAUT-2 and TOE constructs, items, and Measurement Metrics

Construct	Item Statement	Factor Loading	Mean	SD	AVE	CR	α
UTAUT-2 Constructs							
Performance Expectancy (PE)	I find humanoid robots useful for my teaching tasks.	0.81	4.21	0.82	0.68	0.87	0.85
	Using humanoid robots would allow me to complete teaching tasks more efficiently.	0.82	4.18	0.85			
Effort Expectancy (EE)	Incorporating humanoid robots would increase my productivity in teaching.	0.85	4.09	0.91			
	I would find humanoid robots easy to use in my classes.	0.77	3.94	0.95	0.66	0.89	0.81
	Learning to use humanoid robots in teaching would be easy for me.	0.81	4.00	0.89			
	My interaction with humanoid robots would be clear and understandable.	0.84	4.07	0.87			
Social Influence (SI)	It would be easy for me to become skillful at using humanoid robots.	0.83	4.05	0.86			
	My colleagues encourage me to use humanoid robots in my teaching.	0.79	4.10	0.89	0.66	0.85	0.90
	School administrators support the adoption of humanoid robots in classrooms.	0.81	4.12	0.92			
Facilitating Conditions (FC)	Students expect me to use innovative tools like humanoid robots.	0.83	4.15	0.88			
	I have the tools and materials needed to use humanoid robots in my science classes.	0.82	3.78	0.98	0.66	0.88	0.89
	I have sufficient knowledge to integrate humanoid robots effectively.	0.83	3.81	0.92			
Hedonic Motivation (HM)	The robots are compatible with other teaching technologies I use.	0.80	3.90	0.88			
	I can receive help from colleagues when I encounter difficulties with humanoid robots.	0.79	3.95	0.93			
	Using humanoid robots in science classes is fun.	0.85	4.15	0.84	0.69	0.87	0.89
Price Value (PV)	Teaching with humanoid robots is enjoyable.	0.83	4.22	0.87			
	Incorporating humanoid robots makes teaching more engaging.	0.82	4.05	0.90			
	The cost of humanoid robots is reasonable for my classroom needs.	0.79	3.60	1.02	0.66	0.85	0.80
	The robots offer good value for the money invested in them.	0.84	3.71	0.94			
Habit (HT)	The benefits of using humanoid robots outweigh their cost.	0.81	3.65	1.00			
	Using humanoid robots will become a habit for me in teaching.	0.83	4.01	0.92	0.67	0.86	0.86
	I will feel the need to incorporate humanoid robots regularly.	0.82	3.95	0.89			

Table 1 (continued)

Construct	Item Statement	Factor Loading	Mean	SD	AVE	CR	α
TOE Constructs Relative Advantage (RA)	Using humanoid robots will be a routine part of my teaching practices.	0.80	3.90	0.91			
	Using humanoid robots makes teaching more effective.	0.84	4.05	0.92	0.72	0.91	0.86
	Humanoid robots help reduce the time and effort needed for teaching tasks.	0.85	4.10	0.88			
	Humanoid robots enhance the quality of interaction with students.	0.87	4.18	0.83			
Compatibility (CPT)	Adopting humanoid robots attracts student interest and participation.	0.83	4.15	0.87			
	The use of humanoid robots aligns with my teaching practices.	0.82	4.08	0.88	0.67	0.86	0.81
	Integrating humanoid robots fits the educational culture at my school.	0.81	4.00	0.91			
Observability (OBS)	It is easy to incorporate humanoid robots into my teaching routine.	0.83	3.95	0.92			
	The benefits of using humanoid robots in teaching are easy to observe.	0.79	3.85	0.90	0.66	0.85	0.80
	It is easy to see how other teachers benefit from humanoid robots.	0.81	3.90	0.88			
	I have seen many schools successfully using humanoid robots.	0.84	3.95	0.89			
Top Management Support (TMS)	School leadership considers the use of humanoid robots essential for modern teaching.	0.80	3.75	0.95	0.65	0.88	0.92
	Administrators actively communicate their support for using humanoid robots.	0.79	3.80	0.97			
	School management is willing to invest in humanoid robot-related technologies.	0.82	3.85	0.93			
	Clear goals are set by administrators to monitor the use of humanoid robots.	0.81	3.82	0.92			
Competitive Pressure (CP)	There is pressure to adopt humanoid robots to remain competitive with other schools.	0.85	3.92	0.94	0.72	0.88	0.90
	Not adopting humanoid robots could put my school at a disadvantage.	0.87	4.02	0.91			
Perceived Trend (PTR)	Schools that adopt humanoid robots are viewed more favorably.	0.82	4.05	0.89			
	The government encourages schools to adopt humanoid robots.	0.79	3.85	0.93	0.67	0.86	0.80
	The use of humanoid robots is becoming a trend in education.	0.82	3.90	0.90			
	More schools are expected to adopt humanoid robots soon.	0.84	3.95	0.91			

Table 1 (continued)

Construct	Item Statement	Factor Loading	Mean	SD	AVE	CR	α
Government Support (GOV)	The government provides training programs on using humanoid robots in education.	0.88	3.70	0.96	0.71	0.91	0.81
	Educational seminars and conferences on humanoid robots are supported by government agencies.	0.85	3.75	0.94			
	Schools receive advisory support for adopting humanoid robots.	0.82	3.78	0.92			
	Government programs assist schools with the integration of humanoid robots.	0.81	3.80	0.91			
Legal Framework (LEF)	Policies encourage the use of humanoid robots in education.	0.82	3.75	0.92	0.70	0.88	0.88
	Incentives are provided to schools that adopt humanoid robots.	0.85	3.82	0.89			
	Privacy and security laws are in place to address concerns with robotic technologies.	0.84	3.78	0.90			
Technological Orientation (TOR)	My school uses innovative technologies to enhance teaching practices.	0.83	3.95	0.91	0.71	0.88	0.92
	State-of-the-art technologies, including humanoid robots, are embraced.	0.85	4.00	0.90			
Intention to Use (INT)	My school is committed to building capacity for advanced teaching tools.	0.84	3.98	0.88			
	I plan to use humanoid robots in my science teaching frequently.	0.86	4.18	0.83	0.74	0.89	0.80
	I will try to use humanoid robots in my future classes.	0.85	4.22	0.85			
	I am committed to continuing the use of humanoid robots in my teaching.	0.87	4.12	0.88			

Table 2 Correlations between constructs and Discriminant Validity

Constructs	PE	EE	SI	FC	HM	PV	HT	RA	CPT	OBS	TMS	CP	PTR	GOV	LEF	TOR	INT	
UTAUT-2	0.82																	
PE		0.46																
EE			0.81															
SI				0.42														
FC					0.39													
HM						0.41												
PV							0.38											
HT								0.35										
RA									0.48									
CPT										0.39								
OBS											0.43							
TMS												0.45						
CP													0.47					
PTR														0.43				
GOV															0.45			
LEF																0.43		
TOR																	0.43	
INT																		0.86

Diagonal values represent the square root of the Average Variance Extracted (AVE) for each construct, indicating the level of discriminant validity

to the data, but the proposed combined model outperformed the individual models in terms of overall fit and explanatory power.

Specifically, the proposed combined model achieved a chi-square to degrees of freedom ratio (χ^2/df) of 2.55, which indicated a superior model fit compared to the TOE model ($\chi^2/df=2.62$) and the UTAUT-2 model ($\chi^2/df=2.70$). Other model fit indices, including GFI (Goodness of Fit Index), AGFI (Adjusted Goodness of Fit Index), CFI (Comparative Fit Index), TLI (Tucker-Lewis Index), IFI (Incremental Fit Index), RMSEA (Root Mean Square Error of Approximation), and SRMR (Standardized Root Mean Square Residual), all provided evidence of better fit for the proposed combined model compared to the individual frameworks. Notably, the combined model achieved a GFI of 0.93, CFI of 0.95, and RMSEA of 0.057, indicating a well-fitted model in comparison to TOE and UTAUT-2 models.

Furthermore, the explanatory power, indicated by R^2 for “Intention to Use,” was highest for the proposed combined model at 0.68. This was considerably stronger than the R^2 values for the individual models, with UTAUT-2 at 0.56 and TOE at 0.42. These results suggest that the integrated model combining both UTAUT-2 and TOE constructs provides a more comprehensive and accurate framework for understanding the adoption intentions of science teachers regarding humanoid robots, by capturing both individual and contextual factors effectively.

4.2 Structural equation modeling for evaluating adoption drivers of humanoid robots

4.2.1 Results of UTAUT 2 model

The findings from the path analysis provided key insights into the factors that influence science teachers’ intentions to adopt humanoid robots in their classrooms. The results revealed significant relationships among various UTAUT-2 constructs and teachers’ intentions to use this emerging technology, as summarized below.

Performance Expectancy showed a strong positive effect on science teachers’ intention to adopt humanoid robots ($\beta=0.41$, $p<0.01$). This suggests that teachers are more inclined to adopt humanoid robots when they perceive these technologies as beneficial for enhancing their teaching efficiency and student learning outcomes. Effort Expectancy also emerged as a significant predictor of intention ($\beta=0.36$, $p<0.01$), indicating that the perceived ease of use plays a substantial role in the decision to integrate humanoid robots into teaching practices. Teachers who find the technology intuitive and easy to use are more likely to consider it for educational purposes. Social Influence had a positive and significant relationship with teachers’ adoption intention ($\beta=0.29$, $p<0.05$), suggesting that the encouragement and support from colleagues, school administrators, and students positively impact their intention to adopt humanoid robots. Facilitating Conditions were found to significantly support the adoption intentions ($\beta=0.33$, $p<0.01$). Access to the required infrastructure, technical support, and resources was an important factor that enabled teachers to consider adopting humanoid robots. Hedonic Motivation showed a significant influence on teachers’ intentions ($\beta=0.31$, $p<0.05$). The enjoyment and

Table 3 Model Fit Indices and Explanatory Powers for TOE, UTAUT-2, and the proposed model

Model	χ^2	df	χ^2/df	GFI	AGFI	CFI	TLI	IFI	RMSEA	SRMR	R^2
TOE Model	1102.31	420	2.62	0.89	0.85	0.91	0.89	0.91	0.065	0.050	0.42
UTAUT-2 Model	962.92	356	2.70	0.91	0.87	0.93	0.92	0.92	0.060	0.045	0.56
Proposed Combined Model	855.67	335	2.55	0.93	0.90	0.95	0.94	0.94	0.057	0.042	0.68

entertainment value of using humanoid robots in the teaching process contributed to a positive attitude toward adoption. Price Value was also found to be a significant determinant ($\beta=0.28$, $p<0.05$). The cost-effectiveness of humanoid robots, as perceived by teachers, was a critical factor in shaping their intention to adopt this technology. Finally, Habit was positively related to adoption intention ($\beta=0.37$, $p<0.01$). This implies that teachers who are already familiar or comfortable with similar technologies are more inclined to make humanoid robots a routine part of their teaching practices. The detailed path coefficients that clarify these relationships within the UTAUT-2 framework are visually represented in Fig. 3.

4.2.2 Results of TOE framework

The path analysis highlighted the roles of various TOE constructs in shaping science teachers' intentions to adopt humanoid robots. The findings showed several significant relationships between these constructs and the teachers' intentions, as outlined below.

Relative Advantage was found to have a substantial positive effect on the intention to adopt humanoid robots ($\beta=0.40$, $p<0.01$), indicating that teachers are more likely to adopt humanoid robots if they believe these technologies provide clear advantages over traditional teaching methods, such as improved teaching effectiveness and efficiency. Compatibility, which measures the alignment of humanoid robots with existing teaching practices, also emerged as a significant predictor of adoption intention ($\beta=0.34$, $p<0.01$). Teachers who perceived humanoid robots as compatible with their current methods were more inclined to integrate them into their classrooms. Observability was positively related to teachers' intention to adopt humanoid robots ($\beta=0.32$, $p<0.05$), suggesting that the visibility of the successful use of humanoid robots in other schools positively influences teachers' decisions to adopt this technology. Competitive Pressure also had a significant influence on adoption intention ($\beta=0.31$, $p<0.05$), implying that the desire to keep up with or outperform other schools motivates teachers and administrators to adopt humanoid robots in their curriculum. Perceived Trend had a positive effect on adoption intention ($\beta=0.29$, $p<0.05$), indicating that teachers are influenced by the general trend towards adopting innovative teaching technologies. The perception that humanoid robots are becoming increasingly common in the educational field drives teachers to consider their use in classrooms. Government Support showed a significant influence on the adoption of humanoid robots ($\beta=0.36$, $p<0.01$), emphasizing that training, funding, and advisory services provided by government bodies play a crucial role in facilitating the adoption process. Legal Framework also emerged as an important factor ($\beta=0.35$, $p<0.01$), highlighting the role of policies, regulations, and incentives in encouraging teachers to adopt humanoid robots. Support from school leadership, measured through the Top Management Support construct, was positively associated with the intention to adopt humanoid robots ($\beta=0.38$, $p<0.01$). The commitment of school administrators, both in terms of communication and investment in the technology, was critical for teachers considering the use of humanoid robots. Lastly, Technological Orientation was found to have a significant effect ($\beta=0.37$, $p<0.01$). Schools

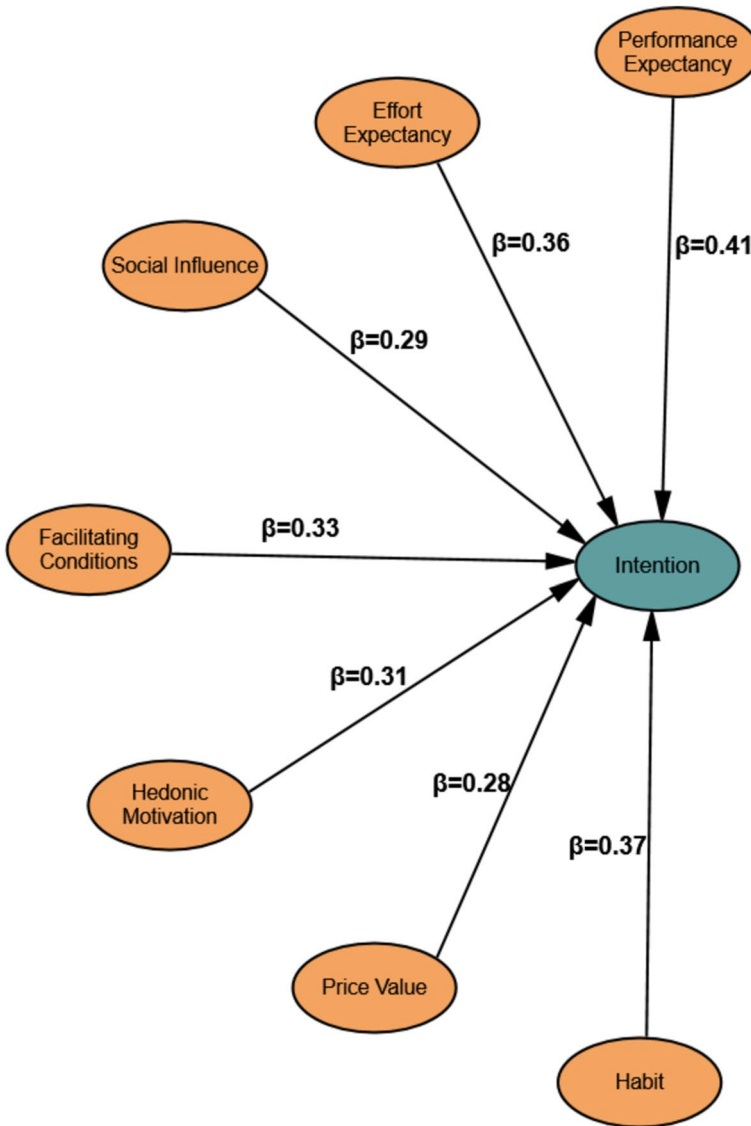


Fig. 3 Path Coefficients for Relationships among UTAUT-2 Constructs and Science Teachers' Intention to Adopt Humanoid Robots

that exhibited a proactive attitude towards the adoption of innovative technologies, including humanoid robots, created an environment conducive to the integration of such tools into teaching practices. The detailed path coefficients elucidating these relationships are visually depicted in Fig. 4.

4.2.3 Results of combined model

The results of the path analysis for the combined UTAUT-2 and TOE model, visually represented in Fig. 5, confirmed all hypotheses from H1 to H16, highlighting the influence of both individual and contextual factors on science teachers' intentions to adopt humanoid robots in educational settings.

Among UTAUT-2 constructs, Performance Expectancy had a notably significant impact ($\beta=0.50$, $p<0.01$), confirming H1, indicating that teachers were significantly more inclined to adopt humanoid robots when they perceived these technologies as enhancing their teaching efficacy and student engagement. Effort Expectancy also showed an elevated positive influence ($\beta=0.48$, $p<0.01$), confirming H2, underscoring that ease of use is crucial in promoting adoption intentions. Social Influence ($\beta=0.42$, $p<0.05$) confirmed H3, suggesting that peer support, administrative encouragement, and expectations from students have a profound effect on motivating adoption. Facilitating Conditions ($\beta=0.45$, $p<0.01$) supported H4, indicating that the presence of infrastructure, resources, and technical support is pivotal in enabling adoption. Hedonic Motivation ($\beta=0.43$, $p<0.05$) confirmed H5, suggesting that teachers are more motivated to integrate humanoid robots if they find them enjoyable to use. Price Value ($\beta=0.41$, $p<0.05$) confirmed H6, emphasizing that the perceived cost-effectiveness plays a critical role in shaping teachers' intentions. Habit ($\beta=0.47$, $p<0.01$) confirmed H7, indicating that routine familiarity with similar technologies positively impacts their adoption of humanoid robots.

For the TOE constructs, Relative Advantage was a significant driver ($\beta=0.49$, $p<0.01$), supporting H8, suggesting that teachers perceive humanoid robots as providing substantial educational advantages over traditional methods. Compatibility ($\beta=0.45$, $p<0.01$) confirmed H9, highlighting that alignment with existing teaching practices positively influences adoption. Observability ($\beta=0.44$, $p<0.05$) confirmed H10, suggesting that visible evidence of successful robot use in other schools encourages adoption. Competitive Pressure ($\beta=0.42$, $p<0.05$) confirmed H11, reflecting that external competition among schools fosters a push towards adopting advanced technologies like humanoid robots. Perceived Trend ($\beta=0.41$, $p<0.05$) confirmed H12, indicating that educational trends and the widespread adoption of similar technologies encourage teachers to adopt humanoid robots. Government Support ($\beta=0.46$, $p<0.01$) supported H13, demonstrating the importance of training, funding, and advisory services in facilitating the adoption process. Legal Framework ($\beta=0.48$, $p<0.05$) confirmed H14, emphasizing that regulatory assurances, including privacy and security laws, contribute positively to teachers' adoption intentions. Technological Orientation ($\beta=0.48$, $p<0.01$) confirmed H15, suggesting that schools with a proactive approach toward technological advancement are more inclined to adopt humanoid robots. Finally, Top Management Support ($\beta=0.50$, $p<0.01$) confirmed H16, underscoring that backing from school leadership is critical for the successful implementation of humanoid robots in classrooms. These findings highlight the comprehensive explanatory power of the combined model in predicting science teachers' adoption of humanoid robots. By incorporating individual, social, technological, and organizational factors, the model offers a robust framework for understanding how various elements interact to influence

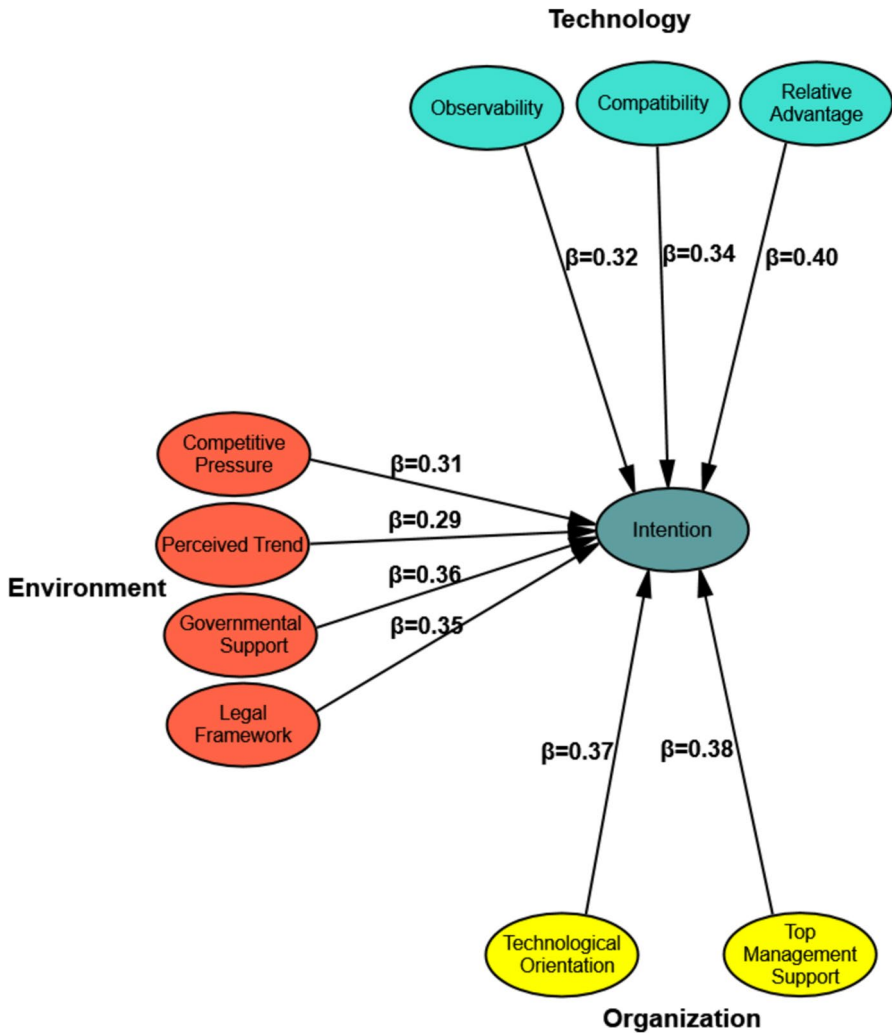


Fig. 4 Path Coefficients for TOE Constructs Influencing Science Teachers' Intention to Adopt Humanoid Robots

adoption intentions in educational environments. The detailed analysis of the relationships within the combined model validated all hypotheses from H1 to H16.

4.3 Moderating effects of sample type on humanoid robot adoption

This study investigated the moderating effect of sample type—comparing pre-service and in-service science teachers—on the adoption of humanoid robots in science education. The sample consisted of 600 pre-service science teachers and 550

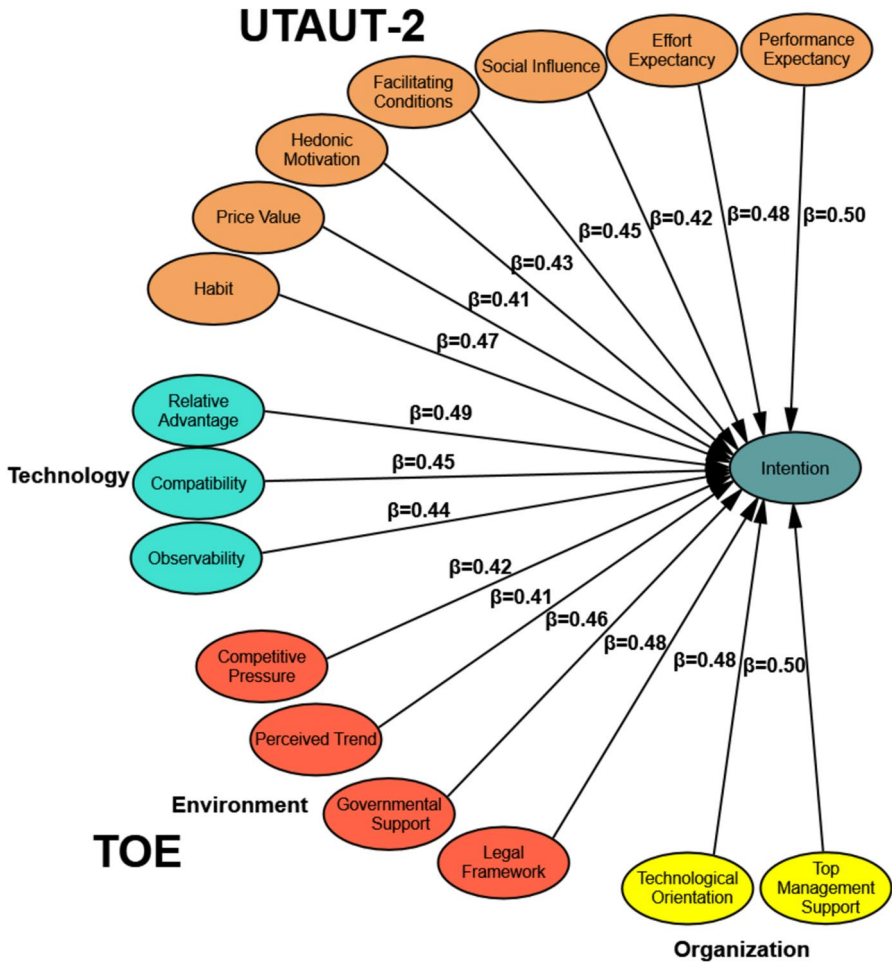


Fig. 5 Path Analysis for Combined UTAUT-2 and TOE Model on Science Teachers' Intention to Adopt Humanoid Robots

in-service science teachers, allowing for an analysis that explored how professional experience influenced attitudes towards humanoid robot adoption.

The moderating effect was assessed using multi-group analysis through SEM (see Table 4). The invariance testing approach was employed to explore differences in the relationships between the constructs within the proposed model for pre-service and in-service teachers. First, an unrestricted model was developed for both pre-service and in-service groups, yielding satisfactory model fit indices ($\chi^2 = 1955.30$, $df=785$, $p < 0.001$, $\chi^2/df=2.49$, $RMSEA=0.041$, $CFI=0.94$, $IFI=0.94$, $TLI=0.92$).

Subsequent steps involved conducting a full-metric invariance test to evaluate the measurement equivalence across groups, which also yielded acceptable fit indices (χ^2

= 2010.48, $df = 810$, $p < 0.001$, $\chi^2/df = 2.48$, $RMSEA = 0.040$, $CFI = 0.92$, $IFI = 0.92$, $TLI = 0.92$). The chi-square difference test comparing the unconstrained and constrained models indicated no significant differences ($\Delta\chi^2(25) = 55.18$, $p > 0.05$), supporting the hypothesis of measurement invariance across pre-service and in-service science teachers.

The baseline structural model was further tested by integrating the proposed relationships into the metric invariance model, resulting in satisfactory fit indices for both pre-service and in-service science teacher groups ($\chi^2 = 2187.96$, $df = 830$, $p < 0.001$, $RMSEA = 0.045$, $CFI = 0.92$, $IFI = 0.92$, $TLI = 0.92$). The subsequent nested model comparison demonstrated significant moderating effects of sample type on key paths in the model. Specifically, relationships between performance expectancy and intention ($\Delta\chi^2(1) = 6.35$, $p < 0.05$), facilitating conditions and intention ($\Delta\chi^2(1) = 5.98$, $p < 0.05$), and hedonic motivation and intention ($\Delta\chi^2(1) = 6.21$, $p < 0.05$) were influenced by whether teachers were pre-service or in-service. Furthermore, the results indicated that two constructs from the TOE framework—Relative Advantage and Top Management Support—also exhibited significant moderating effects. The relationship between Relative Advantage and adoption intention ($\Delta\chi^2(1) = 8.04$, $p < 0.05$) highlighted the varying perceived benefits between pre-service and in-service teachers, with in-service teachers placing greater emphasis on perceived improvements in teaching effectiveness when considering humanoid robots. Similarly, the relationship between Top Management Support and intention ($\Delta\chi^2(1) = 10.34$, $p < 0.05$) showed significant differences, suggesting that in-service teachers may be more responsive to institutional support and administrative commitment compared to pre-service teachers. These findings collectively emphasize that both individual (UTAUT-2) and organizational (TOE) factors are moderated by professional experience, underscoring the need for targeted approaches in promoting humanoid robot adoption across different teacher groups.

5 Discussion

5.1 Summary of results

This study proposed a comprehensive model that integrates the UTAUT-2 and TOE frameworks to evaluate the adoption of humanoid robots by science teachers in educational settings. The combined model demonstrated superior predictive power compared to each framework individually, effectively capturing the multidimensional factors influencing teachers' intentions. The findings confirmed all hypothesized relationships across the constructs of UTAUT-2 and TOE, revealing how both individual and organizational factors shape the likelihood of adoption.

The analysis revealed significant relationships among various constructs of UTAUT-2 such as performance expectancy, effort expectancy, social influence, facilitating conditions, and hedonic motivation—all of which were found to positively influence the intention to adopt humanoid robots. Specifically, the strong impact of performance expectancy suggests that teachers are more willing to adopt humanoid robots when they believe these technologies can enhance both teaching

Table 4 Moderation results by sample type for Humanoid Robot Adoption

Groups	Models	χ^2	df	RMSEA	CFI	IFI	TLI	$\Delta\chi^2$	Full-metric invariance
Pre-service and In-service Teachers	Non-restricted model	1955.30	785	0.041	0.94	0.94	0.92	$\Delta\chi^2(25) = 55.18, p > 0.05$ (ns)	supported
	Full-metric invariance	2010.48	810	0.040	0.92	0.92	0.92		Nested model
Paths	Pre-service Teachers ($n = 600$)		In-service Teachers ($n = 550$)						Baseline model
	β and t-values		β and t-values						
	PE \rightarrow INT	$\beta = 0.50, t = 11.25$	$\beta = 0.54, t = 10.85$			$\chi^2(830) = 2187.96$			$\chi^2(831) = 2193.75$ (a)
	EE \rightarrow INT	$\beta = 0.48, t = 9.87$	$\beta = 0.50, t = 10.10$			$\chi^2(830) = 2187.96$			$\chi^2(831) = 2188.91$ (b)
	SI \rightarrow INT	$\beta = 0.43, t = 8.10$	$\beta = 0.44, t = 8.65$			$\chi^2(830) = 2187.96$			$\chi^2(831) = 2190.52$ (c)
	FC \rightarrow INT	$\beta = 0.45, t = 8.95$	$\beta = 0.49, t = 9.75$			$\chi^2(830) = 2187.96$			$\chi^2(831) = 2194.05$ (d)
	HM \rightarrow INT	$\beta = 0.41, t = 7.65$	$\beta = 0.47, t = 8.45$			$\chi^2(830) = 2187.96$			$\chi^2(831) = 2193.87$ (e)
	PV \rightarrow INT	$\beta = 0.42, t = 7.20$	$\beta = 0.45, t = 8.00$			$\chi^2(830) = 2187.96$			$\chi^2(831) = 2189.34$ (f)
	HT \rightarrow INT	$\beta = 0.46, t = 8.80$	$\beta = 0.49, t = 9.30$			$\chi^2(830) = 2187.96$			$\chi^2(831) = 2190.77$ (g)
	RA \rightarrow INT	$\beta = 0.49, t = 9.35$	$\beta = 0.53, t = 10.40$			$\chi^2(830) = 2187.96$			$\chi^2(831) = 2193.00$ (h)
	CPT \rightarrow INT	$\beta = 0.45, t = 9.10$	$\beta = 0.47, t = 9.60$			$\chi^2(830) = 2187.96$			$\chi^2(831) = 2190.91$ (i)
	OBS \rightarrow INT	$\beta = 0.44, t = 8.70$	$\beta = 0.46, t = 9.20$			$\chi^2(830) = 2187.96$			$\chi^2(831) = 2189.56$ (j)
	CP \rightarrow INT	$\beta = 0.42, t = 8.25$	$\beta = 0.48, t = 8.95$			$\chi^2(830) = 2187.96$			$\chi^2(831) = 2189.15$ (k)
PTR \rightarrow INT	$\beta = 0.41, t = 8.10$	$\beta = 0.45, t = 8.80$			$\chi^2(830) = 2187.96$			$\chi^2(831) = 2189.35$ (l)	

Table 4 (continued)

Groups	Models	χ^2	df	RMSEA	CFI	IFI	TLI	$\Delta\chi^2$	Full-metric invariance
GOV → INT	$\beta=0.46, t=8.95$		$\beta=0.50, t=9.25$			$\chi^2(830)=2187.96$			$\chi^2(831)=2189.67$ (m)
LEF → INT	$\beta=0.48, t=9.00$		$\beta=0.51, t=9.55$			$\chi^2(830)=2187.96$			$\chi^2(831)=2189.48$ (n)
TOR → INT	$\beta=0.50, t=11.50$		$\beta=0.52, t=10.00$			$\chi^2(830)=2187.96$			$\chi^2(831)=2190.10$ (o)
TMS → INT	$\beta=0.50, t=11.75$		$\beta=0.55, t=11.90$			$\chi^2(830)=2187.96$			$\chi^2(831)=2194.30$ (p)

Results of chi-square difference test:

- ^a $\Delta\chi^2(1)=5.79, p<0.05$ (significant)
- ^b $\Delta\chi^2(1)=0.95, p>0.05$ (insignificant)
- ^c $\Delta\chi^2(1)=2.56, p>0.05$ (insignificant)
- ^d $\Delta\chi^2(1)=6.09, p<0.05$ (significant)
- ^e $\Delta\chi^2(1)=5.91, p<0.05$ (significant)
- ^f $\Delta\chi^2(1)=1.38, p<0.05$ (insignificant)
- ^g $\Delta\chi^2(1)=2.81, p>0.05$ (insignificant)
- ^h $\Delta\chi^2(1)=5.04, p<0.05$ (significant)
- ⁱ $\Delta\chi^2(1)=2.95, p>0.05$ (insignificant)
- ^j $\Delta\chi^2(1)=1.60, p>0.05$ (insignificant)
- ^k $\Delta\chi^2(1)=1.19, p>0.05$ (insignificant)
- ^l $\Delta\chi^2(1)=1.39, p>0.05$ (insignificant)
- ^m $\Delta\chi^2(1)=1.71, p>0.05$ (insignificant)
- ⁿ $\Delta\chi^2(1)=1.52, p>0.05$ (insignificant)
- ^o $\Delta\chi^2(1)=2.14, p>0.05$ (insignificant)
- ^p $\Delta\chi^2(1)=6.34, p<0.05$ (significant)

effectiveness and student engagement. Similarly, effort expectancy was a significant predictor, highlighting the importance of perceived ease of use in influencing adoption decisions.

The TOE constructs further highlighted the importance of contextual and organizational factors. Notably, relative advantage emerged as a crucial predictor, indicating that perceived benefits over traditional teaching methods significantly influence teachers' adoption intentions. Top management support also had a notable impact, suggesting that school leadership plays an important role in facilitating the adoption process by providing essential resources, administrative backing, and motivation.

The study also identified significant moderating effects between pre-service and in-service teachers. Differences in relationships such as performance expectancy, facilitating conditions, and relative advantage demonstrated that in-service teachers, who have greater practical experience, place more emphasis on perceived benefits and infrastructure compared to pre-service teachers. This indicates that professional experience moderates the effects of both individual and organizational factors on technology adoption.

Overall, the findings provide comprehensive insights into the individual motivations and organizational support required to successfully adopt humanoid robots in educational contexts. The combined framework not only underscores the interplay between personal and contextual factors but also highlights the importance of tailoring interventions to different teacher groups to facilitate the integration of advanced technologies into classrooms.

5.2 Theoretical implications

This study provides significant theoretical contributions by advancing our understanding of the determinants of science teachers' intentions to adopt humanoid robots in educational settings, integrating constructs from both the UTAUT-2 and TOE frameworks. To our knowledge, this research is among the first to combine UTAUT-2, which emphasizes individual-level factors such as motivation and social influences, with the TOE framework that incorporates broader organizational and environmental variables. Previous recent studies have successfully applied UTAUT-2 to predict behavioral intentions regarding technology adoption across a range of educational contexts (e.g., Ateş & Garzón, 2023; Liu et al., 2024; Warsono, 2024), while the TOE framework has been extensively used to assess the role of environmental and organizational factors in technology uptake (e.g., Nguyen et al., 2022; Shahadat et al., 2023). However, a comprehensive synthesis of these two models to specifically explore humanoid robots' adoption in science education has not been fully explored. In this research, we devised a conceptual model that integrates UTAUT-2 and TOE constructs, offering a holistic approach to understanding science teachers' technology adoption. The empirical findings provide strong support for the combined framework, demonstrating that it significantly enhances our ability to explain the adoption intentions of both pre-service and in-service science teachers. This combined approach captures a broad range of determinants—individual motivations, organizational readiness, and external pressures—highlighting

the value of integrating behavioral theories with organizational perspectives. The findings suggest that a multi-dimensional model provides a better explanatory power for adoption intentions compared to individual models alone, as it accounted for a greater proportion of variance in teachers' intentions to use humanoid robots in their classrooms. Furthermore, this research highlights the importance of including both motivational and contextual factors when attempting to understand technology adoption in educational settings. By integrating constructs related to ease of use, performance expectancy, social influence, organizational readiness, and government support, our model emphasizes the complex interplay between personal attitudes and environmental support systems. The inclusion of both UTAUT-2 and TOE constructs not only contributes to the robustness of the model but also offers adaptability for use across different educational contexts and with various emerging technologies. The insights gained from this study align with previous research that argues for the synergistic benefits of combining individual and contextual models to understand technology adoption in education (e.g., Alyoussef, 2023; Badghish & Soomro, 2024; Narayan & Naidu, 2024). The findings provide a theoretical basis for further research into the factors that drive the adoption of humanoid robots and other advanced educational technologies, contributing to the existing body of literature by presenting an innovative, comprehensive model that can be used to develop targeted interventions and strategies to support teachers. This integrated approach can help in formulating policies that promote the effective integration of humanoid robots into science education, ultimately enriching the educational experience and improving student outcomes.

The findings of this study affirm the validity of hypotheses H1 to H7, establishing that key constructs from the UTAUT-2 model—namely, Performance Expectancy, Effort Expectancy, Social Influence, Facilitating Conditions, Hedonic Motivation, Price Value, and Habit—significantly influence the intention of both pre-service and in-service science teachers to adopt humanoid robots in classrooms. These constructs collectively explained a substantial portion of the variance in adoption intention, underlining the importance of perceived usefulness, ease of use, social support, motivational aspects, and habitual behavior as pivotal factors in the technology adoption process. The theoretical foundation for these findings lies in the well-established technology acceptance theories, particularly UTAUT-2, which has been validated across a wide range of educational and organizational contexts (Venkatesh et al., 2012). Performance Expectancy, often referred to as perceived usefulness in the Technology Acceptance Model (TAM) (Davis, 1989), has consistently been shown to be a dominant factor in determining individuals' intention to use new technology (Li et al., 2024). For educators, particularly science teachers, technologies that promise improved pedagogical outcomes and efficiency are more likely to be adopted, as they directly align with professional objectives of enhancing teaching quality and improving student engagement (Ateş & Garzón, 2022). Similarly, Effort Expectancy, which parallels perceived ease of use in TAM, has been recognized as a fundamental driver in adoption, especially in educational settings where teachers face substantial time constraints and varying levels of technological proficiency (Ateş & Yilmaz, 2024; Ogegbo et al., 2024). The simplicity of technology implementation minimizes barriers to adoption and is crucial for encouraging educators to experiment with new tools

without apprehension. Social Influence, which emphasizes the impact of peers, administrators, and societal expectations, was also significant, suggesting that support and encouragement from colleagues and stakeholders positively influence teachers' decisions to adopt new technologies (Chávez Herting et al., 2023). Facilitating Conditions, encompassing the availability of resources and infrastructure, play a key role in promoting the adoption of humanoid robots by ensuring that teachers have the necessary support for effective technology use. Hedonic Motivation, reflecting the enjoyment associated with technology use, further indicates that when teachers find technology enjoyable, they are more likely to integrate it into their practices, reinforcing the motivational aspect of adoption (Wei et al., 2023). Price Value and Habit were also found to significantly influence adoption intentions. Price Value relates to the cost-benefit analysis, emphasizing that teachers are more likely to adopt technologies that they perceive as affordable and valuable for enhancing classroom outcomes (Nguyen et al., 2024). Habit represents the extent to which teachers have already integrated similar technologies into their daily practices, which facilitates easier adoption of humanoid robots, as familiarity reduces resistance to change. These findings suggest that policies or training initiatives aimed at enhancing the perceived usefulness, ease of use, affordability, and enjoyment of humanoid robots could be instrumental in promoting their widespread adoption in educational settings.

The findings from this study affirm hypotheses H8 through H15, demonstrating that several constructs from the TOE framework—namely, Relative Advantage, Compatibility, Observability, Competitive Pressure, Perceived Trend, Government Support, Legal Framework, and Technological Orientation—are significant predictors of science teachers' intentions to adopt humanoid robots in their classrooms. Together, these constructs explained a considerable percentage of the variance in adoption intentions, offering deeper insights into how both individual and organizational factors influence decision-making regarding technology adoption in educational contexts. Relative Advantage emerged as a crucial factor, suggesting that teachers are more likely to adopt humanoid robots if they perceive these technologies to provide a significant improvement over traditional teaching methods in terms of instructional effectiveness and student engagement. Compatibility also significantly influenced adoption intentions, underscoring the importance of teachers perceiving humanoid robots as a natural fit with their current teaching practices and the existing school culture. These results align with previous findings that the perceived fit between new technologies and existing pedagogical strategies can substantially impact adoption (Hiran & Henten, 2020). Observability was another significant predictor, indicating that teachers' ability to observe the benefits of humanoid robots, either through their own experiences or by observing other educators, strongly influences their willingness to adopt the technology. Competitive Pressure also played an important role, implying that schools that experience external pressure to innovate—such as those striving to maintain a competitive edge—are more likely to consider humanoid robots as a viable tool for improving educational quality. Perceived Trend reflected teachers' awareness of humanoid robots becoming increasingly popular in education. This construct suggests that when teachers perceive that other institutions are adopting such technologies, they feel an implicit push to follow suit to stay up to date and relevant. Similarly, Government Support, which includes training programs,

funding, and advisory services, was found to be a significant predictor, emphasizing the role of external support in lowering adoption barriers and promoting the uptake of innovative technologies. The presence of a supportive Legal Framework also positively influenced teachers' intentions. This factor highlights the importance of regulations, policies, and incentives that ensure the ethical use of technology and provide schools with a secure environment for adopting humanoid robots. Lastly, Technological Orientation, or the readiness of schools to embrace advanced teaching tools, was identified as a significant predictor of adoption intention. Schools with a proactive attitude towards new technologies were more likely to encourage teachers to incorporate humanoid robots in their classrooms. By validating these constructs within the TOE framework, this study provides valuable theoretical contributions by confirming the relevance of both individual and organizational-level determinants in understanding the adoption of advanced educational technologies, such as humanoid robots. These findings are consistent with prior research that emphasizes the multifaceted nature of technology adoption, suggesting that successful integration requires a comprehensive approach that addresses perceived benefits, alignment with existing practices, and external pressures or supports (Hmoud et al., 2023).

The findings regarding the moderating effects of sample type—comparing pre-service and in-service science teachers—provide significant theoretical implications for understanding technology adoption processes in education. The study reveals that professional experience influences the relationships between key UTAUT-2 and TOE constructs and adoption intentions. Specifically, pre-service teachers showed stronger relationships between performance expectancy, effort expectancy, and facilitating conditions with their adoption intentions compared to in-service teachers, who were more influenced by barriers like complexity (Ateş & Garzón, 2023). These insights extend the UTAUT-2 and TOE models by highlighting that technology adoption is not solely influenced by individual or contextual factors but also depends significantly on teachers' career stages. This finding aligns with Rogers' Diffusion of Innovations theory, which emphasizes that adopter categories—such as early adopters and the late majority—are critical in shaping technology uptake (Rogers, 2003).

5.3 Practical implications

The findings from this study provide actionable insights to support the effective adoption of humanoid robots in science education among pre-service and in-service teachers. Raising awareness of the educational benefits of humanoid robots is crucial for their successful integration. Educational stakeholders should organize workshops, interactive demonstrations, and seminars to illustrate how humanoid robots can improve teaching quality and student engagement, particularly by facilitating interactive learning and visualizing complex scientific concepts. These initiatives are instrumental in addressing misconceptions, reducing resistance, and fostering positive perceptions of the instructional value of humanoid robots.

Compatibility with existing technologies and teaching practices is another key factor in ensuring successful adoption. School administrators and policymakers must prioritize aligning humanoid robots with national curricula to enable seamless

integration into instructional frameworks. Standardized lesson plans, instructional guides, and adaptable teaching resources tailored to science education can further support this process. Additionally, professional development programs should target specific subject areas, providing teachers with the strategies and skills required to effectively incorporate humanoid robots into their teaching practices.

Institutional and governmental support is pivotal for fostering readiness and facilitating adoption. Policymakers should allocate resources for the acquisition, maintenance, and enhancement of humanoid robots and the necessary supporting infrastructure. Clear communication from school leadership regarding the strategic importance of adopting these technologies, combined with supportive institutional policies, can motivate educators. Providing financial incentives, grants for teacher training, and ongoing technical support will also help address resource-related barriers and encourage widespread adoption.

For institutions that currently lack access to humanoid robots, preparatory strategies are vital for fostering readiness. Simulated or virtual training environments can equip teachers with a conceptual understanding of humanoid robots' operational and pedagogical applications, offering practical insights into their potential use in classrooms. Developing robot-ready curricula and instructional resources aligned with national standards can ensure that schools are prepared for future implementation. Pilot programs in resource-ready schools can provide valuable insights into effective strategies for integrating humanoid robots, which can then serve as scalable models for broader adoption across schools with varying technological capabilities.

Comprehensive training and technical support are essential to minimize barriers and build teachers' confidence in using humanoid robots. Training programs should extend beyond operational instructions to include pedagogical applications, demonstrating how humanoid robots can enhance learning outcomes. Highlighting ease of use and enjoyment during training sessions can further increase teachers' willingness to adopt these innovations. Continuous professional development opportunities, tailored to meet the evolving needs of educators, will help ensure the long-term integration of humanoid robots into educational settings. Establishing collaborative networks where educators can share experiences and best practices—through teacher communities, online platforms, and follow-up workshops—will further enhance engagement and support sustained use of these technologies.

These findings underscore the importance of a holistic, multi-faceted approach that integrates awareness-building, infrastructure development, preparatory strategies, institutional and governmental backing, and tailored professional development. By adopting these strategies, stakeholders can accelerate the adoption of humanoid robots, improve the quality of science education, and enhance students' learning experiences, paving the way for a technology-driven future in education.

5.4 Limitations and suggestions for future studies

While this study provides valuable insights into the factors influencing the adoption of humanoid robots in science education through the combined UTAUT-2 and TOE

frameworks, several limitations must be acknowledged to contextualize the findings and guide future research.

First, the geographical focus on Turkey poses a limitation regarding the generalizability of the results. The educational policies, cultural factors, and technological infrastructure unique to Turkey may have influenced the findings and may limit their applicability to other regions with different educational systems and cultural contexts. Future studies should include samples from diverse geographical and cultural settings to test the robustness and universality of the proposed model across varied educational landscapes.

Second, the study relied on self-reported data collected via surveys, which are inherently subject to response biases such as social desirability or overestimation of capabilities. These biases may affect the accuracy of the results and limit their ability to reflect actual behaviors. To address this limitation, future research could employ mixed-methods approaches, incorporating observational data, experimental designs, or log data from real-world interactions with humanoid robots to validate self-reported intentions with actual behavioral outcomes. However, such methodologies may depend on the availability of humanoid robots in educational institutions.

The cross-sectional nature of the study represents another limitation, as it restricts the ability to draw causal inferences about the relationships between the examined constructs. Longitudinal studies would enable researchers to observe how science teachers' intentions and attitudes toward adopting humanoid robots evolve over time. Such research could provide valuable insights into how ongoing exposure, institutional support, and professional development influence adoption behaviors.

Additionally, while the study focused exclusively on science teachers, this sample limits the generalizability of the findings to other subject areas or educational roles. Future research should expand to include teachers from various disciplines and educational levels to explore how adoption factors differ across contexts. Moreover, including teachers from multiple countries or regions could further enhance the external validity of the findings by accounting for diverse educational environments.

The lack of widespread access to humanoid robots in most educational institutions presents another significant limitation, potentially affecting the applicability of the study's findings in real-world contexts. This study primarily explored teachers' perceptions and intentions to adopt humanoid robots, even in scenarios where these technologies are not currently available for direct use. As such, the findings serve as foundational insights to guide preparatory strategies for institutions lacking immediate access to humanoid robots. Future research could investigate scalable solutions, such as simulated environments for teacher training, the development of robot-ready curricula, and fostering institutional readiness. Pilot programs in resource-ready schools could also provide practical insights into bridging the gap between intention and implementation, offering valuable lessons for broader adoption.

Moreover, while this study focused on individual and institutional factors influencing adoption, external factors such as student attitudes toward humanoid robots and their learning outcomes were not fully explored. Future studies should include the perspectives of students to provide a more comprehensive understanding of the teaching-learning dynamics with humanoid robots. Examining their direct impact on

academic performance, engagement, and motivation would further enrich the field and strengthen the evidence base for adopting these technologies.

Lastly, this study did not extensively address specific barriers to adoption, such as ethical considerations, privacy concerns, or technical challenges associated with humanoid robot integration. Future research should delve into these critical issues, offering practical recommendations for overcoming challenges and ensuring the responsible and effective use of humanoid robots in educational environments. Addressing these barriers is essential to fostering a sustainable and equitable adoption of this technology.

By addressing these limitations and pursuing the outlined suggestions, future studies can deepen our understanding of humanoid robot adoption and pave the way for inclusive, scalable, and contextually relevant educational strategies that benefit teachers, students, and institutions alike.

6 Conclusion

This study provides valuable insights into the factors influencing the adoption of humanoid robots among science teachers in educational settings by utilizing the combined UTAUT-2 and TOE theoretical frameworks. This integrated model offers a robust understanding of both individual and organizational elements that affect teachers' decisions to incorporate humanoid robots into their teaching practices. The findings emphasize the significant roles of performance expectancy, effort expectancy, social influence, and various contextual factors, such as relative advantage, compatibility, and top management support, in shaping the adoption intentions of both pre-service and in-service science teachers. The results highlight that teachers are more likely to embrace humanoid robots when they perceive the technology as beneficial to teaching outcomes, easy to use, and well-supported by their institutions. Furthermore, the study confirms that external factors like government support, competitive pressures, and institutional backing play pivotal roles in influencing adoption decisions, underscoring the importance of creating an enabling environment for technology adoption. Discussion suggest that successful integration of humanoid robots into classrooms requires attention not only to individual beliefs and motivations but also to supportive organizational structures and incentives. Practically, these insights inform educational leaders, policymakers, and school administrators about key areas to focus on to facilitate and enhance the integration of advanced technologies in education. Providing adequate resources, training programs that build confidence in the use of new technologies, and establishing supportive leadership and institutional cultures are essential measures for ensuring successful adoption. Future research should actively investigate how adoption factors identified in this study function across diverse cultural contexts and educational disciplines. Researchers are encouraged to conduct comparative studies involving international samples and interdisciplinary teacher groups to evaluate the broader applicability and adaptability of the proposed model. Overall, the study contributes to the evolving literature on technology adoption in education by elucidating the interplay between individual perceptions, motivational drivers, and contextual influences.

This understanding can serve as a foundation for developing more effective strategies for integrating emerging technologies into educational environments, ultimately enhancing teaching practices and student learning experiences. As the educational landscape continues to evolve alongside technological advancements, educational stakeholders should actively use the findings of this research to address challenges and leverage opportunities associated with adopting humanoid robots in science education. This includes developing targeted training programs, creating supportive policies, and fostering collaborative environments to ensure successful integration.

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Data availability The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate This study was approved by a governmental institution in Turkey. All participants provided informed consent before participation.

Consent for publication Consent for publication was obtained from all participants involved in the study.

Competing interests The authors declare that they have no competing interests.

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References

- Abdurrahman, A., Gustomo, A., & Prasetyo, E. A. (2024). Impact of dynamic capabilities on digital transformation and innovation to improve banking performance: A TOE framework study. *Journal of Open Innovation: Technology Market and Complexity*, 10(1), 100215.
- Acosta-Enriquez, B. G., Farroñan, E. V. R., Zapata, L. I. V., Garcia, F. S. M., Rabanal-León, H. C., Angaspilco, J. E. M., & Bocanegra, J. C. S. (2024). Acceptance of artificial intelligence in university contexts: A conceptual analysis based on UTAUT2 theory. *Heliyon*.
- Al Darayseh, A. (2023). Acceptance of artificial intelligence in teaching science: Science teachers' perspective. *Computers and Education: Artificial Intelligence*, 4, 100132.
- Al Hadwer, A., Tavana, M., Gillis, D., & Rezanian, D. (2021). A systematic review of organizational factors impacting cloud-based technology adoption using technology-organization-environment framework. *Internet of Things*, 15, 100407.

- Al Hakim, V. G., Yang, S. H., Liyanawatta, M., Wang, J. H., & Chen, G. D. (2022). Robots in situated learning classrooms with immediate feedback mechanisms to improve students' learning performance. *Computers & Education*, *182*, 104483.
- Alcorn, A., Ainger, E., Charisi, V., Mantinioti, S., Petrovic, S., Schadenberg, B., & Pellicano, L. (2019). Educators' views on using humanoid robots with autistic learners in special education settings in England. *Frontiers in Robotics and AI*, *6*(107). <https://doi.org/10.3389/frobt.2019.00107>
- Alotaibi, S. B., & Manimurugan, S. (2022). Humanoid robotic system for social interaction using deep imitation learning in a smart city environment. *Frontiers in Sustainable Cities*, *4*, 1076101.
- Alyoussef, I. Y. (2023). The impact of massive open online courses (MOOCs) on knowledge management using integrated innovation diffusion theory and the technology acceptance model. *Education Sciences*, *13*(6), 531.
- Andtfolk, M., Nyholm, L., Eide, H., Rauhala, A., & Fagerström, L. (2021). Attitudes toward the use of humanoid robots in healthcare—a cross-sectional study. *AI & Society*, *37*(4), 1739–1748. <https://doi.org/10.1007/s00146-021-01271-4>
- Anzalone, S., Boucenna, S., Ivaldi, S., & Chétouani, M. (2015). Evaluating engagement with social robots. *International Journal of Social Robotics*, *7*(4), 465–478. <https://doi.org/10.1007/s12369-015-0298-7>
- Asghar, A., Patra, A., & Ravi, K. S. (2022). The potential scope of a humanoid robot in anatomy education: A review of a unique proposal. *Surgical and Radiologic Anatomy*, *44*(10), 1309–1317.
- Ateş, H. (2024). Integrating augmented reality into intelligent tutoring systems to enhance science education outcomes. *Education and Information Technologies*, 1–36.
- Ateş, H., & Garzón, J. (2022). Drivers of teachers' intentions to use mobile applications to teach science. *Education and Information Technologies*, *27*(2), 2521–2542.
- Ateş, H., & Garzón, J. (2023). An integrated model for examining teachers' intentions to use augmented reality in science courses. *Education and Information Technologies*, *28*(2), 1299–1321.
- Ateş, H., & Gündüzalp, C. (2024). A unified framework for understanding teachers' adoption of robotics in STEM education. *Education and Information Technologies*, *29*(11), 1–27.
- Ateş, H., & Yilmaz, R. M. (2024). A comprehensive model explaining teachers' intentions to use mobile-based assessment. *Interactive Learning Environments*, *32*(8), 4063–4087.
- Awa, H. O., Ojiabo, O. U., & Orokor, L. E. (2017a). Integrated technology-organization-environment (TOE) taxonomies for technology adoption. *Journal of Enterprise Information Management*, *30*(6), 893–921.
- Awa, H. O., Ukoha, O., & Igwe, S. R. (2017b). Revisiting technology-organization-environment (TOE) theory for enriched applicability. *The Bottom Line*, *30*(01), 2–22.
- Badghish, S., & Soomro, Y. A. (2024). Artificial intelligence adoption by SMEs to achieve sustainable business performance: Application of technology–organization–environment framework. *Sustainability*, *16*(5), 1864.
- Baker, J. (2012). The technology–organization–environment framework. *Information Systems Theory: Explaining and Predicting Our Digital Society*, *1*, 231–245.
- Baltes, J., Gerndt, R., Sadeghnejad, S., Saeedvand, S., Sun, Y. H., & Tu, K. Y. (2023, August). A Hands-On Approach to Humanoid Robots Education. In *2023 International Conference on Advanced Robotics and Intelligent Systems (ARIS)* (pp. 1–6). IEEE.
- Bessadok, A., & Hersi, M. (2023). A structural equation model analysis of English for specific purposes students' attitudes regarding computer-assisted language learning: UTAUT2 model. *Library Hi Tech*.
- Bogue, R. (2020). Humanoid robots from the past to the present. *Industrial Robot: The International Journal of Robotics Research and Application*, *47*(4), 465–472.
- Cabellos, B., Siddiq, F., & Scherer, R. (2024). The moderating role of school facilitating conditions and attitudes towards ICT on teachers' ICT use and emphasis on developing students' digital skills. *Computers in Human Behavior*, *150*, 107994.
- Camilleri, M. A. (2024). Factors affecting performance expectancy and intentions to use ChatGPT: Using SmartPLS to advance an information technology acceptance framework. *Technological Forecasting and Social Change*, *201*, 123247.
- Chalmers, C., Keane, T., Boden, M., & Williams, M. (2022). Humanoid robots go to school. *Education and Information Technologies*, *27*(6), 7563–7581.
- Chang, A. (2012). UTAUT and UTAUT 2: A review and agenda for future research. *The Winners*, *13*(2), 10–114.

- Chávez Herting, D., Pros, C., R., & Castelló Tarrida, A. (2023). Habit and social influence as determinants of PowerPoint use in higher education: A study from a technology acceptance approach. *Interactive Learning Environments*, 31(1), 497–513.
- Chen, X., Cheng, G., Zou, D., Zhong, B., & Xie, H. (2023). Artificial intelligent robots for precision education. *Educational Technology & Society*, 26(1), 171–186.
- Chevalier, P., Kompatsiari, K., Ciardo, F., & Wykowska, A. (2020). Examining joint attention with the use of humanoid robots-A new approach to study fundamental mechanisms of social cognition. *Psychonomic Bulletin & Review*, 27, 217–236.
- Chi, M., Muhammad, S., Khan, Z., Ali, S., & Li, R. Y. M. (2021). Is centralization killing innovation? The success story of technological innovation in fiscally decentralized countries. *Technological Forecasting and Social Change*, 168, 120731.
- Chittipaka, V., Kumar, S., Sivarajah, U., Bowden, J. L. H., & Baral, M. M. (2023). Blockchain Technology for Supply Chains operating in emerging markets: An empirical examination of technology-organization-environment (TOE) framework. *Annals of Operations Research*, 327(1), 465–492.
- Chopdar, P. K., Lytras, M. D., & Visvizi, A. (2023). Exploring factors influencing bicycle-sharing adoption in India: A UTAUT 2 based mixed-method approach. *International Journal of Emerging Markets*, 18(11), 5109–5134.
- Choudhury, A., Li, H., Greene, C., & Perumalla, S. (2018). Humanoid robot—application and influence. *Archives of Clinical and Biomedical Research*, 2(6):198-226. <https://doi.org/10.26502/acbr.50170059>
- Cuberos, E. (2019). Ethical implications of emotional and psychological ties in human-robot interaction (HRI)-mediated learning. *International Robotics & Automation Journal*, 5(4), 144–145. <https://doi.org/10.15406/iratj.2019.05.00187>
- Das, S. D., & Bala, P. K. (2024). What drives MLOps adoption? An analysis using the TOE framework. *Journal of Decision Systems*, 33(3), 376–412.
- Davis, F. D. (1989). Perceived usefulness, perceived ease of use and user acceptance of information technology. *MIS Quarterly*, 13, 319–340.
- Desideri, L., Negrini, M., Cutrone, M., Rouame, A., Malavasi, M., Hoogerwerf, E., & Sarro, R. (2017). Exploring the use of a humanoid robot to engage children with autism spectrum disorder (ASD). *Preprint*. <https://doi.org/10.31234/osf.io/3fvr6>
- Du, W., & Liang, R. Y. (2024). Teachers' continued VR Technology usage intention: An application of the UTAUT2 model. *SAGE Open*, 14(1), 21582440231220112.
- Dugășescu, I. (2024). Research regarding the design and development of an optimal concept for a humanoid robot. *Macromolecular Symposia*, 413(3):2300193. <https://doi.org/10.1002/masy.202300193>
- Duong, C. D., Bui, D. T., Pham, H. T., & Vu, A. T. (2023). How effort expectancy and performance expectancy interact to trigger higher education students' uses of ChatGPT for learning. *Interactive Technology and Smart Education*, (ahead-of-print).
- Ekström, S., & Pareto, L. (2022a). The dual role of humanoid robots in education: As didactic tools and social actors. *Education and Information Technologies*, 27(9), 12609–12644.
- Ekström, S., & Pareto, L. (2022b). The dual role of humanoid robots in education: As didactic tools and social actors. *Education and Information Technologies*, 27(9), 12609–12644. <https://doi.org/10.1007/s10639-022-11132-2>
- Fedock, B., Paladino, A., Bailey, L., & Moses, B. (2018). Perceptions of robotics emulation of human ethics in educational settings: A content analysis. *Journal of Research in Innovative Teaching & Learning*, 11(2), 126–138. <https://doi.org/10.1108/jrit-02-2018-0004>
- Fridin, M., & Belokopytov, M. (2014). Acceptance of socially assistive humanoid robot by preschool and elementary school teachers. *Computers in Human Behavior*, 33, 23–31.
- Friedman, C. (2023). Ethical concerns with replacing human relations with humanoid robots: An ubuntu perspective. *AI and Ethics*, 3(2), 527–538.
- Fung, K. Y., Lee, L. H., Sin, K. F., Song, S., & Qu, H. (2024). Humanoid robot-empowered language learning based on self-determination theory. *Education and Information Technologies*, 29, 18927–18957.
- García de Blanes Sebastián, M., Guede, S., Grande, J. R. A., A., & Filipe, A. F. (2024). UTAUT-2 predictors and satisfaction: Implications for mobile-learning adoption among university students. *Education and Information Technologies*, 1–37.

- Ghaleb, E. A., Dominic, P. D. D., Fati, S. M., Muneer, A., & Ali, R. F. (2021). The assessment of big data adoption readiness with a technology–organization–environment framework: A perspective towards healthcare employees. *Sustainability*, *13*(15), 8379.
- Hair, J. F., Hult, G. T. M., Ringle, C. M., & Sarstedt, M. (2019). *A Primer on Partial Least Squares Structural Equation Modeling (PLS-SEM)* (2nd ed.). Sage Publications.
- Hiran, K. K., & Henten, A. (2020). An integrated TOE–DoI framework for cloud computing adoption in the higher education sector: Case study of Sub-saharan Africa, Ethiopia. *International Journal of System Assurance Engineering and Management*, *11*, 441–449.
- Hmoud, H., Al-Adwan, A. S., Horani, O., Yaseen, H., & Al Zoubi, J. Z. (2023). Factors influencing business intelligence adoption by higher education institutions. *Journal of Open Innovation: Technology Market and Complexity*, *9*(3), 100111.
- Huijnen, C., Lexis, M., Jansens, R., & Witte, L. (2017). How to implement robots in interventions for children with autism? A co-creation study involving people with autism, parents, and professionals. *Journal of Autism and Developmental Disorders*, *47*(10), 3079–3096. <https://doi.org/10.1007/s10803-017-3235-9>
- Li, F., Zhu, D., Lin, M. T., & Kim, P. B. (2024). The technology acceptance model and hospitality and tourism consumers' intention to use mobile technologies: Meta-analysis and structural equation modeling. *Cornell Hospitality Quarterly*, *65*(4):461–477. 19389655241226558.
- Liu, J., Dai, Q., & Chen, J. (2024). Factors affecting teachers' use of digital resources for teaching mathematical cultures: An extended UTAUT-2 model. *Education and Information Technologies*, 1–30.
- Mahlangu, G., & Makwasha, L. (2023). Factors affecting the adoption and use of online assessment for learning at Polytechnics in Zimbabwe. *Cogent Education*, *10*(1), 2177475.
- Malik, S., Chadhar, M., Vatanasakdakul, S., & Chetty, M. (2021). Factors affecting the organizational adoption of blockchain technology: Extending the technology–organization–environment (TOE) framework in the Australian context. *Sustainability*, *13*(16), 9404.
- Mavridis, N., Katsaiti, M., Naef, S., Falasi, A., Nuaimi, A., Araifi, H., & Kitbi, A. (2011). Opinions and attitudes toward humanoid robots in the Middle East. *AI & Society*, *27*(4), 517–534. <https://doi.org/10.1007/s00146-011-0370-2>
- Mertzani, V. (2023). Exploring the learning gains of implementing teacher humanoid robots in STEM education: A systematic review. *International Journal of Online and Biomedical Engineering (iJOE)*, *19*(18), 18–30. <https://doi.org/10.3991/ijoe.v19i18.43893>
- Mertzani, V., & Drigas, A. (2023). Exploring the Learning gains of implementing teacher Humanoid Robots in STEM Education: A systematic review. *International Journal of Online & Biomedical Engineering*, *19*(18):18–30.
- Mishra, D., Parish, K., Lugo, R. G., & Wang, H. (2021). A framework for using humanoid robots in the school learning environment. *Electronics*, *10*(6), 756.
- Modliński, A., Fortuna, P., & Roźnowski, B. (2024). Robots onboard? Investigating what individual predispositions and attitudes influence the reactions of museums' employees towards the adoption of social robots. *Museum Management and Curatorship*, *39*(4), 457–481.
- Morgante, E., Susinna, C., Culicetto, L., Quartarone, A., & Lo Buono, V. (2024). Is it possible for people to develop a sense of empathy toward humanoid robots and establish meaningful relationships with them? *Frontiers in Psychology*, *15*, 1391832.
- Narayan, J., & Naidu, S. (2024). A new contextual and comprehensive application of the UTAUT2 model post-Covid-19 pandemic in higher education. *Higher Education Quarterly*, *78*(1), 47–77.
- Neumeyer, X., Santos, S. C., & Morris, M. H. (2020). Overcoming barriers to technology adoption when fostering entrepreneurship among the poor: The role of technology and digital literacy. *IEEE Transactions on Engineering Management*, *68*(6), 1605–1618.
- Ng, P. M., Lit, K. K., & Cheung, C. T. (2022). Remote work as a new normal? The technology-organization-environment (TOE) context. *Technology in Society*, *70*, 102022.
- Nguyen, T. H., Le, X. C., & Vu, T. H. L. (2022). An extended technology-organization-environment (TOE) framework for online retailing utilization in digital transformation: Empirical evidence from Vietnam. *Journal of Open Innovation: Technology Market and Complexity*, *8*(4), 200.
- Nguyen, A. H. D., Le, T. T., Dang, T. Q., & Nguyen, L. T. (2024). Understanding metaverse adoption in education: The extended UTAUMT model. *Heliyon*, *10*(19):e38741.
- Nyholm, L., Santamäki-Fischer, R., & Fagerström, L. (2021). Users' ambivalent sense of security with humanoid robots in healthcare. *Informatics for Health and Social Care*, *46*(2), 218–226.

- Ogegbo, A. A., Penn, M., Ramnarain, U., Pila, O., Van Der Westhuizen, C., Mdlalose, N., & Bergamin, P. (2024). Exploring pre-service teachers' intentions of adopting and using virtual reality classrooms in science education. *Education and Information Technologies*, 1–18.
- Okagbue, E. F., Muhideen, S., Anulika, A. G., Nchekwubemchukwu, I. S., Chinemerem, O. G., Tsakuwa, M. B., & Mwase, C. (2024). An in-depth analysis of humanoid robotics in higher education system. *Education and Information Technologies*, 29(1), 185–217.
- Papadopoulos, I., Koulouglioti, C., Lazzarino, R., & Ali, S. (2020). Enablers and barriers to the implementation of socially assistive humanoid robots in health and social care: A systematic review. *British Medical Journal Open*, 10(1):e033096. <https://doi.org/10.1136/bmjopen-2019-033096>. Article e033096.
- Paul, N., Ramesh, S., Bhattacharya, C., Ramesh, J., & Vijayan, P. (2021, May). Can Non-Humanoid Social Robots Reduce Workload of Special Educators: An Online and In-Premises Field Study. In *2021 IEEE International Conference on Robotics and Automation (ICRA)* (pp. 11386–11392). IEEE.
- Racherla, P., & Hu, C. (2008). eCRM system adoption by hospitality organizations: A technology-organization-environment (TOE) framework. *Journal of Hospitality & Leisure Marketing*, 17(1–2), 30–58.
- Ramírez-Montoya, M. S., Baena-Rojas, J. J., & Patiño, A. (2023, April). Educational robotics and complex thinking: instructors views' on using humanoid robots in higher education. In *International Conference on Robotics in Education (RiE)* (pp. 117–128). Cham: Springer Nature Switzerland.
- Rogers, E. M. (2003). *Diffusion of innovations* (5th ed.). Free.
- Sang, G., Wang, K., Li, S., Xi, J., & Yang, D. (2023). Effort expectancy mediate the relationship between instructors' digital competence and their work engagement: Evidence from universities in China. *Educational Technology Research and Development*, 71(1), 99–115.
- Shahadat, M. H., Nekmahmud, M., Ebrahimi, P., & Fekete-Farkas, M. (2023). Digital technology adoption in SMEs: What technological, environmental and organizational factors influence in emerging countries? *Global Business Review*, 09721509221137199.
- Smakman, M., Konijn, E., & Vogt, P. (2022). Do robotic tutors compromise the social-emotional development of children? *Frontiers in Robotics and AI*, 9, 734955. <https://doi.org/10.3389/frobt.2022.734955>
- So, S., & Lee, N. (2023). Pedagogical exploration and technological development of a humanoid robotic system for teaching to and learning in young children. *Cogent Education*, 10(1), 2179181.
- Stiefelhagen, R., Ekenel, H. K., Fugen, C., Gieslmann, P., Holzapfel, H., Kraft, F., & Waibel, A. (2007). Enabling multimodal human-robot interaction for the karlsruhe humanoid robot. *IEEE Transactions on Robotics*, 23(5), 840–851.
- Suhail, F., Adel, M., Al-Emran, M., & AlQudah, A. A. (2024). Are students ready for robots in higher education? Examining the adoption of robots by integrating UTAUT2 and TTF using a hybrid SEM-ANN approach. *Technology in Society*, 77, 102524.
- Tamilmani, K., Rana, N. P., Wamba, S. F., & Dwivedi, R. (2021). The extended Unified Theory of Acceptance and Use of Technology (UTAUT2): A systematic literature review and theory evaluation. *International Journal of Information Management*, 57, 102269.
- Taneja, B., & Bharti, K. (2022). Mapping unified theory of acceptance and use of technology (UTAUT) 2: A taxonomical study using bibliometric visualisation. *Foresight*, 24(2), 210–247.
- Tilden, S., Lugo, R. G., Parish, K., Mishra, D., & Knox, B. J. (2021). Gender differences in psychosocial experiences with humanoid robots, programming, and mathematics course. In *HCI International 2021-Late Breaking Papers: Cognition, Inclusion, Learning, and Culture: 23rd HCI International Conference, HCII 2021, Virtual Event, July 24–29, 2021, Proceedings 23* (pp. 480–490). Springer International Publishing.
- Tong, Y., Liu, H., & Zhang, Z. (2024). Advancements in humanoid robots: A comprehensive review and future prospects. *IEEE/CAA Journal of Automatica Sinica*, 11(2), 301–328.
- Tornatzky, L., & Fleischer, M. (1990). *The process of Technology Innovation*. Lexington Books.
- Venkatesh, V., Thong, J. Y., & Xu, X. (2012). Consumer acceptance and use of information technology: Extending the unified theory of acceptance and use of technology. *MIS Quarterly*, 36(1), 157–178.
- wael AL-khatib, A. (2023). Drivers of generative artificial intelligence to fostering exploitative and exploratory innovation: A TOE framework. *Technology in Society*, 75, 102403.
- Walle, A. D., Jemere, A. T., Tilahun, B., Endeabtu, B. F., Wubante, S. M., Melaku, M. S., & Gashu, K. D. (2023). Intention to use wearable health devices and its predictors among diabetes mellitus patients in Amhara region referral hospitals, Ethiopia: Using modified UTAUT-2 model. *Informatix in Medicine Unlocked*, 36, 101157.

- Warsono, S. (2024). Analysis of the acceptance of E-learning platform (SIDEK-Edu) among high school students with UTAUT2-TOE approach: Implications for digital learning. *The International Journal of Information and Learning Technology*41(5), 585-600.
- Wei, N., Peng, W., Sindakis, S., Chang, F., & Su, J. (2023). The role of intrinsic motivation in Online Teaching systems: From the collision of Knowledge Management and Information Technology. *Journal of the Knowledge Economy*, 1–27.
- Xu, S., Chen, P., & Zhang, G. (2024). Exploring Chinese University Educators' Acceptance and Intention to use AI tools: An application of the UTAUT2 model. *SAGE Open*, 14(4), 21582440241290013.

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