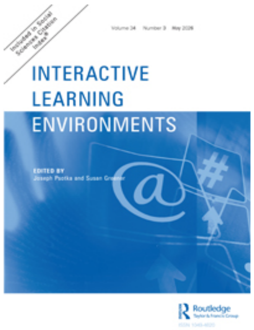

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Harnessing holographic technology in science education: an integrated GETAMEL-TOE model analysis

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ABSTRACT

This study develops and validates an integrated framework combining the General Extended Technology Acceptance Model for E-Learning (GETAMEL) with the Technology-Organization-Environment (TOE) framework to explore science teachers' adoption of holographic technology in middle schools. Survey data from 750 in-service teachers across Turkey were analyzed using structural equation modeling. The integrated model demonstrated stronger explanatory power (R^2 = 0.59) than either framework alone. Key findings highlight the influence of subjective norms, perceived usefulness, perceived ease of use, perceived enjoyment, and self-efficacy in shaping positive attitudes and adoption intentions. Mediation effects were identified: perceived usefulness partially mediated the roles of prior teaching experience and subjective norms, while perceived ease of use mediated the effect of self-efficacy on attitude. Organizational and environmental factors, including relative advantage, compatibility, competitive pressure, government support, and managerial endorsement, were also significant predictors. However, teacher anxiety emerged as a substantial barrier, underscoring the need for targeted interventions to reduce psychological resistance. The study's implications emphasize professional development, institutional support, clear policies, and pilot programs to foster adoption. Theoretically, it contributes by integrating cognitive, emotional, and organizational perspectives, while practically, it provides guidance for advancing holography adoption in education. Limitations and directions for future research are also outlined.

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Holographic technology; Science education; GETAMEL; TOE framework; Technology adoption

1. Introduction

Advancements in educational technology have continually transformed science education, introducing innovative tools that enhance both student engagement and conceptual understanding (Ateş, 2025; Maričić & Lavicza, 2024). Among these advancements, holography stands out as a particularly promising technology, offering three-dimensional (3D) visualizations that can bridge the gap between abstract scientific theories and tangible learning experiences (Salloum et al., 2024). In traditional middle school science classrooms, complex topics such as molecular structures, planetary systems, and human anatomy are often presented through static images, two-dimensional diagrams, or physical models that may fail to fully capture their dynamic and spatial nature. Holographic technology (see Figure 1), however, provides an interactive, immersive, and multisensory approach, allowing students to explore scientific concepts from multiple perspectives, manipulate virtual models in real time, and engage in experiential learning that can enhance retention and deepen conceptual understanding (Kavanagh et al., 2025). Despite these advantages, the integration of holography into science education is far from straightforward, as it necessitates overcoming multiple barriers, including teachers' perceptions of its pedagogical value, their technological readiness, and the level of institutional support provided for implementation (Agustian & Setiawan, 2024).

The adoption of emerging educational technologies is fundamentally shaped by teachers, who act as primary agents of change in classroom innovation (Lee & Lee, 2024). However, research indicates that teachers' willingness to adopt new tools is influenced by a complex interplay of technological, psychological,

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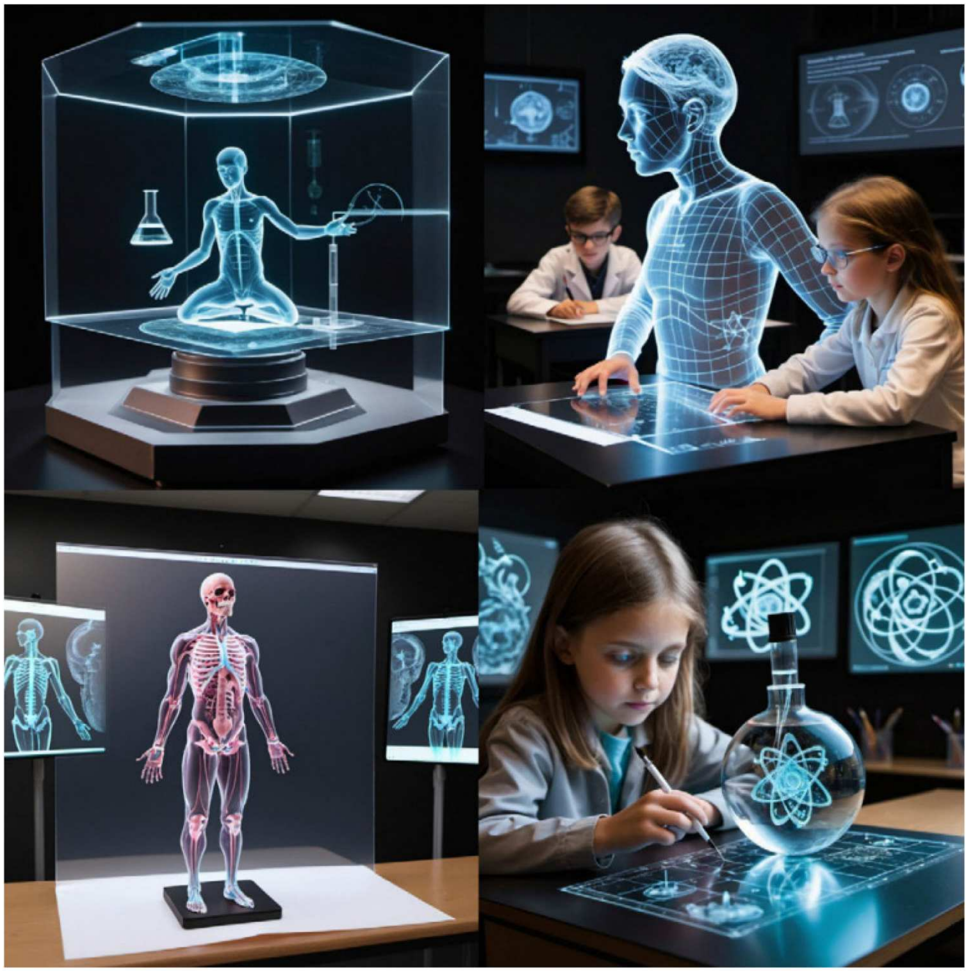

Figure 1. An example of holographic technology in science education, adapted from the study of Salloum et al. (2024).

and institutional factors (Ateş & Polat, 2025a; Stumbrienė et al., 2024). Key determinants include teachers' self-efficacy in using digital tools, their perceptions of the instructional effectiveness of new technologies, and the extent to which professional development opportunities equip them with the necessary skills (Ateş & Gündüzalp, 2025a). In the case of holography, additional practical and logistical challenges come into play, including concerns about high implementation costs, the need for specialized training, potential technical difficulties, and the extent to which holography aligns with existing curricula and assessment frameworks (Bajwa et al., 2024). Without addressing these barriers, the widespread adoption of holography in science education remains uncertain. Consequently, a deeper investigation is essential to identify the factors that influence science teachers' intentions to integrate holography into their instructional practices and to develop strategies that facilitate its seamless incorporation into contemporary science education.

The Technology-Organization-Environment (TOE) framework (Tornatzky & Fleischer, 1990) is a well-established model in technology adoption research, offering a comprehensive lens through which the technological, organizational, and environmental factors influencing the adoption of emerging tools can be examined. This framework is particularly valuable in the context of science education (Ateş & Polat, 2025a), where the successful integration of technologies like holography depends not only on the technology itself but also on the surrounding institutional and contextual conditions. The TOE model enables a structured analysis of three key dimensions: (1) technological factors, which include the perceived benefits, compatibility, and complexity of holographic applications; (2) organizational factors, such as infrastructure availability, administrative support, professional development opportunities, and school leadership's openness to innovation; and (3) environmental factors, which encompass broader influences like government policies, curriculum requirements, and peer adoption trends (Chatterjee et al., 2021; Chen et al., 2024; Kumar et al., 2022;

Sulaiman et al., 2023). By examining these dimensions, the TOE framework provides critical insights into the systemic challenges and enablers that shape the adoption of holography in science classrooms (Ateş & Polat, 2025a).

Complementing this structural perspective, the General Extended Technology Acceptance Model for E-Learning (GETAMEL) expands upon traditional technology acceptance theories by integrating psychological, cognitive, and motivational elements that influence individual adoption behavior (Abdullah & Ward, 2016). Unlike models that focus primarily on external enablers or constraints, GETAMEL may delve into teachers' intrinsic and extrinsic motivations for adopting holographic tools. It considers factors such as self-efficacy (confidence in using the technology), perceived ease of use (how effortlessly teachers believe they can integrate holography into their instruction), perceived usefulness (the extent to which they see educational value in its application), and perceived enjoyment (the degree of engagement and satisfaction derived from its use; Zhang & Yang, 2025). These constructs may be crucial in determining teachers' willingness, enthusiasm, and persistence in utilizing holography for science education. By integrating TOE's macro-level institutional perspective with GETAMEL's micro-level individual perspective, this study aims to provide a holistic understanding of the factors driving or hindering the adoption of holography in middle school science education.

While the adoption of emerging technologies in science education has been widely explored, research on holography as a pedagogical tool remains limited. Existing studies on virtual reality (VR) and augmented reality (AR) in education have demonstrated their potential to enhance student engagement and learning outcomes (Ateş & Polat, 2025b), yet these findings may not fully translate to holography due to its distinct technological requirements, implementation complexity, and collaborative affordances. In particular, holography enables hands-free, shared 3D visualization without the need for personal devices, posing both unique opportunities and specific barriers that differ from VR/AR approaches. Moreover, most prior studies have focused on student-centered outcomes, overlooking institutional and teacher-related factors – such as readiness, training needs, and support structures – that critically influence classroom adoption. Research on teacher adoption of digital tools has often applied the Technology Acceptance Model (TAM) and the Unified Theory of Acceptance and Use of Technology (UTAUT), which primarily emphasize perceived usefulness and ease of use while neglecting broader organizational and environmental constraints (Ateş & Polat, 2025a). Although the TOE framework has been used in educational technology adoption studies (Isiaku & Adalier, 2025), its integration with psychological models such as GETAMEL remains underexplored – especially for novel technologies like holography. Thus, a critical gap remains in understanding how the unique pedagogical and technical features of holography interact with institutional readiness, teacher perceptions, and external influences. Addressing this gap requires an integrated, context-sensitive theoretical approach, which this study seeks to provide.

To address this gap, this study integrates the TOE framework and GETAMEL to develop a comprehensive model for examining the adoption of holography in science education. This dual-theory approach allows for an in-depth exploration of both macro-level structural factors and micro-level psychological determinants, offering a more holistic perspective than previous studies that focus on either organizational barriers or individual acceptance in isolation. By applying TOE, this study identifies the external enablers and constraints that affect institutional adoption, while GETAMEL provides insights into the cognitive and motivational mechanisms that drive teachers' behavioral intentions. This integration not only extends the applicability of GETAMEL to emerging immersive technologies but also broadens the scope of TOE by incorporating teacher-level adoption behaviors, making a novel theoretical contribution to the field of educational technology research.

Beyond its theoretical contributions, this study provides practical recommendations for educational policymakers, school administrators, and teacher training institutions to support the integration of holography in science education. The findings will help identify key adoption barriers, such as lack of infrastructure, insufficient training opportunities, and resistance to change, while proposing targeted strategies to overcome these challenges. By examining the role of self-efficacy and instructional readiness, this study also aims to guide professional development initiatives, ensuring that teachers have the necessary skills and confidence to implement holography effectively in their classrooms. Additionally, the research offers evidence-based recommendations for policy formulation, particularly in areas related to funding allocation, curriculum alignment, and institutional support mechanisms, which are crucial for the sustainable adoption of holographic technologies. Furthermore, the study provides valuable insights for EdTech developers, helping them better understand teachers' needs, concerns, and implementation challenges, which in turn can inform the development of more user-friendly, pedagogically aligned holographic applications. By addressing both theoretical and practical gaps, this research not only advances academic discourse on educational technology adoption but also delivers actionable insights for key stakeholders, ensuring a more effective and sustainable integration of holography in middle school science education.

2. Literature review

2.1. Holography in science education: potential and challenges

Holography is increasingly recognized as a transformative tool in science education, providing interactive three-dimensional (3D) visualizations that can substantially enhance students' conceptual understanding and engagement (Kavanagh et al., 2025; Salloum et al., 2024). By enabling learners to explore dynamic, spatial representations of complex scientific phenomena – such as molecular structures, anatomical systems, or astronomical models – holography supports experiential learning and caters to diverse learning styles (Huang & Chen, 2019; Rahmawati et al., 2021).

While holography shares some commonalities with other extended reality (XR) technologies – such as virtual reality (VR) and augmented reality (AR) – notably the ability to visualize abstract scientific concepts (Li et al., 2024), it also presents distinct pedagogical and technological challenges. Unlike VR, which typically immerses users in fully computer-generated environments, and AR, which overlays digital information onto the physical world via screens or headsets, holography enables the projection of fully three-dimensional images that appear to occupy real space without the need for wearable devices (Czaja et al., 2023; Rehu et al., 2023). This hands-free and often collaborative nature of holographic displays facilitates group interactions and allows multiple learners to engage with the same visual content simultaneously, a feature that is less prominent in VR or AR applications (Flores-Cáceres et al., 2024).

However, holography introduces unique implementation challenges (Dong et al., 2023; Matsumoto & Takaki, 2017). The cost and technical complexity of producing true holographic displays – requiring specialized hardware such as light field projectors or holographic screens – tend to be higher than for most VR or AR solutions, which often utilize more widely available devices like smartphones or headsets (Blanche, 2021). Additionally, integrating holography into science curricula faces hurdles related to content development, as creating educationally relevant holographic models is more resource-intensive and may lack the off-the-shelf software ecosystems available for VR and AR (Qin et al., 2020). Teacher training for holography must therefore address not only general digital literacy but also the specific skills needed to operate, calibrate, and integrate holographic systems in classroom practice.

Despite the rapid expansion of VR and AR research in education – where the focus has largely been on enhancing student motivation, engagement, and achievement – empirical studies that specifically investigate the pedagogical affordances and barriers of holography remain scarce. Most available literature continues to concentrate on student learning outcomes, leaving important questions about science teachers' perceptions, readiness, and the practicalities of classroom implementation largely unexplored (Kavanagh et al., 2025; Salloum et al., 2024). There is a need for systematic comparative research to determine not only the added value of holography over VR and AR, but also the context-specific conditions under which it can be most effectively adopted. These distinctions mean that successful adoption of holography may require different institutional strategies, infrastructure investments, and teacher support mechanisms compared to VR or AR.

In summary, advancing the effective use of holography in science education requires not only recognizing its pedagogical benefits in comparison to other XR tools, but also systematically investigating the distinct institutional, technological, and psychological challenges that shape teachers' adoption decisions. These gaps form the basis for the current study's integrated theoretical approach.

2.2. Integrating TOE and GETAMEL: a comprehensive framework for holography adoption in science education

This study employs an integrated model that combines the TOE framework and the GETAMEL to comprehensively examine the determinants of science teachers' intentions to adopt holographic technology. The TOE framework contributes insights into the external and institutional factors influencing technology adoption – including technological characteristics, organizational support, and environmental context – while GETAMEL addresses the psychological and motivational factors, such as self-efficacy, perceived ease of use, perceived usefulness, perceived enjoyment, and behavioral intention.

Integrating these frameworks enables a holistic analysis of adoption dynamics by capturing both contextual and individual-level influences. However, the combination also introduces conceptual proximity between certain constructs – for example, perceived usefulness (from GETAMEL) and relative advantage (from TOE) both pertain to the perceived benefits of holography. To address this, the study retains both constructs, distinguishing perceived usefulness as the teacher's personal belief in the technology's instructional value, and relative advantage as a broader comparison to existing teaching methods at the organizational level. Their theoretical and empirical distinctiveness is critically examined in the analysis, and the issue of potential overlap is further discussed as a limitation of the model.

By drawing on the complementary strengths of both frameworks, the integrated model aims to offer a more nuanced and comprehensive understanding of the multifaceted drivers and barriers that shape holography adoption in science education.

2.2.1. The general extended technology acceptance model for e-learning (GETAMEL) in teacher adoption studies

The GETAMEL offers an advanced framework for understanding technology adoption by educators, building upon foundational models such as the Technology Acceptance Model (TAM; Davis, 1989) and the (UTAUT; Venkatesh et al., 2003). Unlike its predecessors, GETAMEL incorporates not only cognitive factors – such as perceived usefulness and perceived ease of use – but also crucial psychological, motivational, and contextual variables that are particularly relevant to educational settings (Abdullah & Ward, 2016; Ateş et al., 2024). In the context of science education, this expanded perspective allows for a more nuanced understanding of how teachers' individual beliefs and motivations interact to shape their willingness to adopt innovative technologies such as holography. This stands in contrast to frameworks like TOE, which emphasize organizational and environmental influences, thereby positioning GETAMEL as an ideal complement in an integrated approach.

Within GETAMEL, several key constructs are central to predicting technology adoption behaviors. Self-efficacy, defined as teachers' confidence in their ability to effectively use new technologies, has been shown to increase educators' willingness to experiment and integrate digital tools into their instructional practices (Tian & Wang, 2024; Zhang & Yang, 2025). Perceived ease of use – or the degree to which teachers believe that a technology can be used with minimal effort – also plays a pivotal role, as higher perceptions of ease significantly reduce resistance and foster adoption (Alarabiat et al., 2024). Perceived usefulness, reflecting the belief that technology will meaningfully enhance teaching effectiveness and student learning, has consistently emerged as a powerful predictor of adoption intentions. Additionally, perceived enjoyment, which captures the intrinsic satisfaction and motivation derived from using technology, is critical for predicting sustained and enthusiastic use (Ateş & Garzón, 2022). Conversely, anxiety surrounding technology use can act as a significant barrier, diminishing both self-efficacy and intention to adopt. Ultimately, these factors combine to influence teachers' behavioral intentions – the likelihood that they will actively integrate holography into their instructional routines.

Despite the increasing attention to technology adoption in education, research explicitly applying GETAMEL to the context of holography in science teaching remains limited. This gap is particularly significant given the unique characteristics of holographic technology, such as its immersive, hands-free interaction and real-time manipulation of three-dimensional content (Rehu et al., 2023). These features distinguish holography from more conventional e-learning tools, potentially altering the weight or nature of key determinants within adoption models. As such, there is a clear need to investigate whether and how the psychological, cognitive, and motivational factors specified by GETAMEL operate in the context of holography.

This study directly addresses this gap by empirically examining the role of GETAMEL constructs – alongside those from the TOE framework – in shaping science teachers' intentions to adopt holographic technology. By integrating these perspectives, the research aims to provide a comprehensive account of both individual and systemic drivers and barriers to holography adoption in science education. This approach not only advances theoretical understanding by extending the application of GETAMEL to a novel technological and disciplinary context, but also offers practical insights for designing targeted interventions and support mechanisms to facilitate the effective integration of holographic tools in schools. Building on these insights, the study puts forward the following hypotheses:

H1: Subjective norm positively influences science teachers' perceptions of holographic technology's usefulness.

H2: Subjective norm positively contributes to science teachers' perceptions of the ease of using holographic technology.

H3: Prior teaching experience enhances science teachers' perceptions of holographic technology's educational benefits.

H4: Prior teaching experience improves science teachers' confidence in using holographic technology effectively.

H5: Teachers' enjoyment of interactive digital tools strengthens their perception of holographic technology as a valuable educational resource.

H6: Teachers' enjoyment of using digital tools enhances their perception of holographic technology as user-friendly.

H7: Anxiety related to new technologies negatively impacts science teachers' confidence in using holographic tools.

H8: Technology-related anxiety reduces science teachers' perceptions of holographic technology's benefits in education.

H9: Higher self-efficacy among teachers leads to a greater perception of holographic technology as easy to use.

H10: Greater self-efficacy in digital skills strengthens science teachers' perception of holographic technology's educational value.

H11: The ease of use of holographic technology positively influences science teachers' beliefs about its effectiveness.

H12: Teachers who find holographic technology easy to use are more likely to develop a positive attitude toward its adoption.

H13: Teachers who perceive holographic technology as beneficial for learning are more likely to hold positive attitudes toward its integration.

H14: Perceived usefulness of holographic technology directly impacts teachers' willingness to incorporate it into their instruction.

H15: Teachers with favorable attitudes toward holographic technology are more likely to demonstrate a strong intention to adopt it in their teaching practices.

2.2.2. The technology-organization-environment (TOE) framework in educational technology adoption

The TOE framework (Tornatzky & Fleischer, 1990) offers a comprehensive lens for analyzing the adoption of emerging technologies, categorizing influences into three interrelated dimensions: technological, organizational, and environmental (Adade & de Vries, 2025; Bhuiyan, 2024; Loo et al., 2024; Salah & Ayyash, 2024). This framework enables a nuanced examination of how institutional context, resource availability, and external factors shape science teachers' decisions to adopt holographic technology in education.

The technological dimension centers on the characteristics of holography that impact its adoption, such as relative advantage, compatibility, complexity, and observability. Holography provides immersive 3D visualization of scientific concepts, which can enhance student learning compared to conventional methods (Chittipaka et al., 2023; Yu et al., 2024). However, issues such as technical complexity and the challenge of curriculum alignment may hinder adoption, particularly for teachers with limited experience in advanced digital tools (Malik et al., 2021; Morris, 2025). Pilot programs and demonstration sessions can help overcome uncertainty by making the benefits of holography observable and accessible (Awa, Ojiabo, et al., 2017; Yeganeh et al., 2025).

The organizational dimension highlights the critical roles of leadership support, infrastructure, and institutional culture. Successful adoption depends on strong administrative backing, professional development opportunities, and adequate technological resources (Al Hadwer et al., 2021; Ng et al., 2022). Conversely, schools lacking dedicated training or sufficient financial capacity may struggle to implement holography, despite recognizing its potential benefits. Institutions that foster a culture of innovation and encourage teacher collaboration are better positioned for technology integration (Awa, Ukoha, et al., 2017; Neumeyer et al., 2020).

The environmental dimension examines external drivers such as government policy, regulatory frameworks, market competition, and partnerships with technology providers (Baker, 2012; Chittipaka et al., 2023). National educational policies and funding incentives are vital for scaling adoption, as is ongoing technical support from vendors (Ng et al., 2022; Ghaleb et al., 2021). Competitive pressures may also motivate schools to lead in technological innovation (Racherla & Hu, 2008).

While TOE has been widely applied to the study of educational technology – such as learning management systems, VR, AR, and AI (Addy et al., 2024; Bayaga, 2024; Fattah et al., 2022; Karan & Angadi, 2025; Sousa et al., 2023) – its application to science teachers' adoption of holography remains rare. Most research addresses either individual acceptance or institutional readiness separately. This study addresses this gap by integrating the TOE framework with GETAMEL, allowing for a comprehensive analysis of both systemic and personal factors influencing holography adoption in science education. Based on this discussion, the following hypotheses are proposed:

H16: A greater perceived advantage of holographic technology over traditional teaching methods will increase science teachers' intention to adopt it.

H17: A higher degree of perceived alignment between holography and existing teaching practices will enhance science teachers' intention to use it.

H18: Greater visibility of the benefits of holography in education will increase science teachers' intention to adopt it.

H19: Higher perceived competitive pressure from other schools will increase the likelihood of holography adoption.

H20: The perception that holography is becoming a key trend in science education will enhance teachers' intention to integrate it into classrooms.

H21: Perceptions of greater government support through training, funding, and advisory services will increase the adoption of holography in science education.

H22: Perceived stronger legal frameworks ensuring privacy, data security, and incentives will positively influence science teachers' adoption of holographic technology.

H23: The perceived technological orientation of schools, including their focus on digital learning and innovation, will positively influence science teachers' adoption of holography.

H24: Perceptions of stronger support from school leadership and administration will positively influence science teachers' adoption of holographic technology.

Given the novelty of integrating the GETAMEL and TOE frameworks for examining holography adoption in science education, we adopted a comprehensive approach to hypothesis development. This strategy enabled us to empirically explore a wide range of theoretically plausible relationships, thereby providing a robust foundation for understanding the multifaceted determinants of adoption. We recognize that this breadth is intended to establish an initial empirical baseline for future research, where model refinement and prioritization of the most impactful pathways can be systematically pursued.

Figure 2 presents a conceptual framework integrating GETAMEL and TOE, illustrating the key factors that influence science teachers' adoption of holographic technology. The model emphasizes cognitive and motivational elements from GETAMEL, while also incorporating institutional and environmental influences as outlined in TOE.

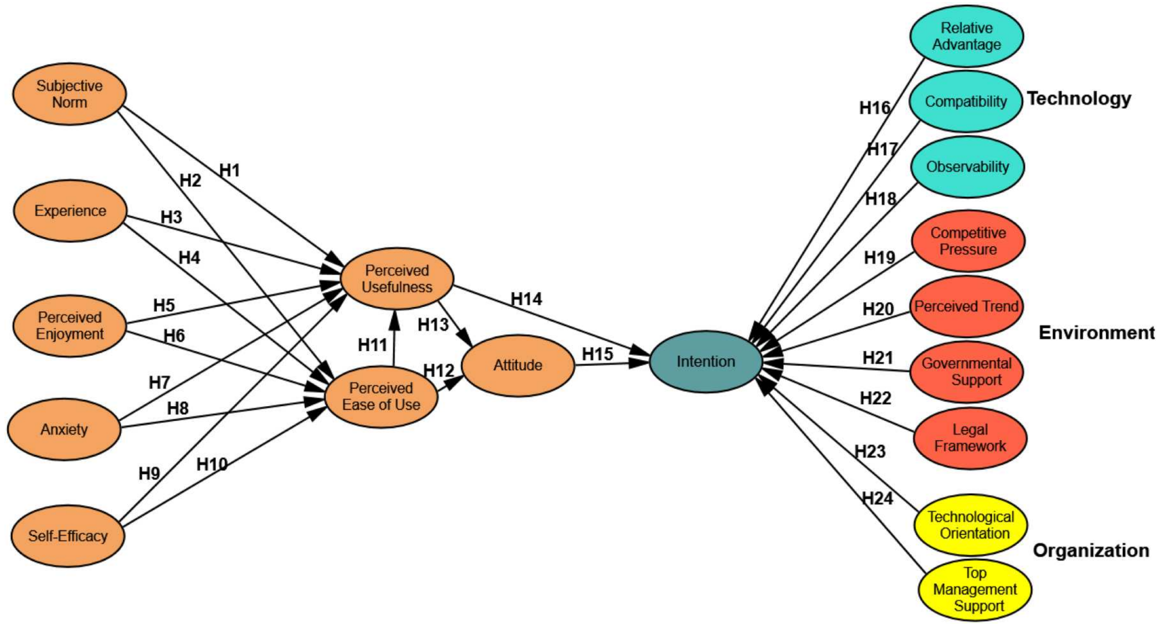

Figure 2. Proposed GETAMEL and TOE integrated model for science teachers' adoption of holographic technology.

3. Method

3.1. Research method

This study adopts a quantitative, cross-sectional survey research design to systematically examine the factors affecting science teachers' intentions to adopt holographic technology in middle school education. The quantitative approach was selected for its capacity to objectively measure relationships among multiple psychological, technological, and organizational variables within a large and diverse sample. By employing a structured questionnaire grounded in the integrated GETAMEL and TOE theoretical frameworks, this method allows for robust statistical analysis of hypothesized relationships and the generalization of findings across different educational contexts.

A cross-sectional design was chosen because it enables the collection of data from a broad population at a single point in time, providing a comprehensive snapshot of teachers' perceptions, attitudes, and intentions regarding holography adoption. This approach is particularly appropriate given the study's aim to identify key predictors and mediators influencing technology adoption within current institutional and policy environments.

The use of an online, self-administered survey was also justified by practical and ethical considerations. It ensured accessibility for participants across geographically and institutionally diverse regions of Turkey, allowed for anonymity and confidentiality, and facilitated efficient data collection and management. Collectively, this research method is well-suited to testing complex theoretical models in educational technology adoption and informing policy and practice with generalizable empirical evidence.

3.2. Sampling

This study collected data from 750 in-service science teachers across Turkey between October 2024 and February 2025, aiming to explore their perceptions and intentions toward adopting holographic technology in science education. The selection of exclusively in-service teachers allowed for a practical, experience-based perspective on how holography could be integrated into middle school classrooms, accounting for real-world challenges such as infrastructure availability, curriculum alignment, and institutional support. The sample was intentionally diverse, incorporating teachers from both urban and rural schools to ensure varied insights into access to resources, digital literacy, and regional differences in technology adoption.

Participants were drawn from a range of public and private middle schools, ensuring representation from different educational environments. Teaching experience within the sample ranged from 2 years to over 25 years, allowing for an analysis of how career stage influences the willingness to adopt holographic tools. Of the participating teachers, 60% had over five years of experience, providing valuable insights into practical classroom implementation and the challenges of integrating new technologies. The educational backgrounds of participants varied, with 78% holding a Bachelor's degree, 18% possessing a Master's degree, and 4% having a Doctorate in education or a related field. The gender distribution was 49% male and 51% female, ensuring a balanced representation of perspectives. The age range of participants spanned from 25 to over 50 years, allowing the study to capture generational differences in attitudes toward emerging digital technologies. To explore how regional disparities impact technology adoption, the sample included teachers from urban (65%) and rural (35%) schools. Urban-based teachers generally reported greater access to digital tools, stronger institutional support, and more professional development opportunities, whereas teachers in rural areas faced challenges such as limited technological infrastructure, inconsistent internet connectivity, and fewer training resources. A significant portion of the sample (72%) reported prior exposure to educational technology, including tools such as interactive whiteboards, virtual labs, and online simulations. This familiarity provided a strong foundation for assessing teachers' perceptions of the relative advantages, compatibility, and complexity of holographic technology compared to other digital resources they had used in their teaching.

By focusing exclusively on in-service teachers, this study ensures that findings reflect real-world educational environments, highlighting both the potential benefits and challenges associated with integrating holographic tools into science education. The data collected from this diverse group of participants will help identify the key institutional, technological, and motivational factors influencing the adoption of holographic technology in middle school science classrooms.

3.3. Data collection process and tools

3.3.1. Data collection procedures

The data collection process for this study was carefully structured to obtain reliable quantitative data from in-service science teachers regarding their perceptions and intentions to adopt holographic technology in science education. A systematic approach was followed to ensure that participants were well-informed about holography's educational applications, allowing for accurate and meaningful responses.

The process began with an introductory module designed to familiarize participants with holographic technology and its potential role in science education. This module, developed in the Turkish national language for accessibility, provided a theoretical foundation on the capabilities, instructional benefits, and potential alignment of holography with the science curriculum. It included multimedia presentations, virtual simulations, and expert-led discussions, illustrating how holography could enhance engagement, facilitate interactive learning, and support the visualization of complex scientific phenomena, such as molecular structures, planetary systems, and biological processes. Since most schools do not currently have direct access to holographic tools, the focus was placed on conceptual applications rather than hands-on use.

Following the introductory session, participants received a technical guide – also in Turkish – outlining hypothetical requirements for integrating holographic technology into classrooms. The guide included information on potential hardware and software specifications, compatibility with existing educational infrastructure, and a step-by-step guide on how holography could be incorporated into lesson plans. This preparatory material ensured that teachers had a solid understanding of how holography might fit into their teaching practices, enabling them to provide well-informed responses in the subsequent survey.

A structured survey was employed as the primary data collection instrument. The survey, based on the TOE and GETAMEL frameworks, was carefully designed and translated into Turkish to ensure clarity and ease of use. Detailed user instructions were included to guide participants through the survey, explaining the purpose of each section, offering examples of holography-enhanced lesson scenarios, and clarifying how to interpret and respond to the items. To further support engagement, an optional online orientation session was offered, where teachers could explore theoretical use cases of holography in science classrooms and address common concerns regarding implementation challenges. This session also featured a brief virtual demonstration, illustrating how holography could be used to conduct science experiments, simulate dynamic processes, or visualize abstract scientific principles in an interactive manner.

To ensure the validity and reliability of the survey, a pilot study was conducted with a group of in-service science teachers to identify and rectify any issues related to question clarity, technical accessibility, or comprehension. Feedback from pilot participants was analyzed and used to refine and optimize the final survey.

During the data collection phase, bi-weekly reminders were sent to participants who had not yet completed the survey, increasing response rates. Additionally, to provide technical assistance and clarification, a dedicated support channel was established, allowing teachers to contact the research team via email or a designated communication platform for any inquiries related to the survey. This structured and supportive approach ensured a smooth data collection process, maximizing participation and strengthening the reliability of the study findings.

3.3.2. Instrument development and validation

The data collection instrument was developed by integrating constructs from the GETAMEL and TOE frameworks, ensuring a comprehensive measurement approach that captured both cognitive, social, and institutional factors relevant to technology adoption.

The process of developing the instrument began with a thorough review of existing literature to identify validated measurement scales aligned with holography adoption in education (e.g. Abdullah et al., 2016; Abdullah & Ward, 2016; Ajzen, 2006; Ateş & Gündüzalp, 2025b; Ateş & Polat, 2025a; Davis, 1989; Nguyen et al., 2022; Shahadat et al., 2023). Each item was carefully adapted or modified to ensure its applicability within the context of holography integration in science classrooms.

To enhance content validity and contextual appropriateness, the preliminary questionnaire was reviewed by five subject-matter experts, specializing in science education, instructional technology, and educational psychology. Their feedback led to minor modifications in item wording to improve clarity and relevance for in-service teachers in Turkey. Additionally, a double-blind translation-back-translation method (Esfandiar et al., 2020) was employed to ensure semantic accuracy between English and Turkish versions of the survey.

A pilot study was conducted with 210 in-service science teachers to assess the instrument's reliability and internal consistency. Results indicated strong Cronbach's alpha values, demonstrating high reliability across all constructs. Items that exhibited low factor loadings or ambiguity were refined or removed to enhance the robustness of the final instrument. After completing the pilot survey, participants were invited to provide written feedback regarding item clarity, relevance, response options, and the overall survey experience. The research team systematically reviewed all feedback and categorized participant comments into key themes, such as ambiguous wording, technical terminology, and item redundancy. Items that exhibited low factor loadings, received consistent feedback regarding ambiguity or confusion, or were identified as redundant were refined or removed to enhance the robustness of the final instrument. This iterative process ensured that the revised instrument was both psychometrically sound and clearly understood by the target population.

The final questionnaire integrated constructs from both the GETAMEL and TOE frameworks, capturing cognitive, social, and institutional factors influencing holography adoption. All items were measured on a 5-point Likert scale ranging from "Strongly Disagree" (1) to "Strongly Agree" (7), allowing for a nuanced assessment of teachers' agreement levels across different constructs. In total, the final survey contained 56 items, evenly distributed among the GETAMEL and TOE dimensions. For a detailed breakdown of constructs and their corresponding items, see Table 1.

3.4. Data analysis

To analyze the collected data, SPSS and AMOS were employed to ensure a rigorous and systematic evaluation of the study's findings. The analysis process began with Confirmatory Factor Analysis (CFA) to validate the measurement model, ensuring that the observed variables accurately represented their respective latent constructs. This step was essential in confirming the construct validity and reliability of the scales measuring science teachers' perceptions and intentions regarding holography adoption in science education. Following this, Structural Equation Modeling (SEM) was applied to test the proposed theoretical framework and examine the relationships between the GETAMEL and TOE constructs. This approach allowed for a comprehensive assessment of how cognitive, technological, and organizational factors interact to influence teachers' adoption of holographic tools in science education.

Table 1. Constructs, items, and measurement metrics for GETAMEL and TOE fraeworks.

Construct	Item Statement	Factor Loading	Mean	SD	AVE	CR	α
GETAMEL Constructs							
Perceived Ease of Use	I find holographic technology easy to use for teaching science.	0.84	4.05	0.82	0.69	0.87	0.89
	It is easy for me to become skilled in using holography for science instruction.	0.85	4.22	0.85			
	My interactions with holographic tools during science teaching are clear and understandable.	0.81	4.33	0.91			
Perceived Usefulness	Using holography for science instruction is beneficial for my teaching objectives.	0.80	3.90	0.95	0.67	0.86	0.85
	Integrating holographic tools enhances my teaching effectiveness.	0.82	4.13	0.89			
	Holographic technology improves my students' engagement and learning outcomes.	0.84	4.18	0.87			
Perceived Enjoyment	I find using holography for science instruction enjoyable.	0.81	4.19	0.89	0.69	0.87	0.94
	Using holographic tools makes science teaching more engaging for me.	0.83	4.16	0.92			
	Teaching with holography makes me feel excited and fulfilled.	0.85	4.11	0.88			
Anxiety	I feel apprehensive about using holographic technology for science instruction.	0.80	3.97	0.98	0.68	0.86	0.87
	It worries me that I might make mistakes I cannot correct while using holography.	0.82	3.89	0.92			
	The idea of using holography for science instruction feels somewhat intimidating.	0.85	3.99	0.88			
Experience	I enjoy using holographic tools in my teaching activities.	0.84	4.22	0.84	0.76	0.90	0.88
	I feel comfortable incorporating holography into science lessons.	0.89	4.10	0.87			
	I am confident using technology when applying holographic tools in science education.	0.88	4.13	0.90			
Self-Efficacy	I feel confident using holography for science teaching, even without assistance.	0.80	3.88	1.02	0.72	0.89	0.89
	I have sufficient skills to integrate holographic technology into my science lessons.	0.89	3.98	0.94			
	I am confident in my ability to effectively use holography for teaching science.	0.86	3.87	1.00			
Attitude	Using holography for science teaching is a good idea.	0.87	4.12	0.92	0.77	0.91	0.89
	I like the idea of using holographic technology in science instruction.	0.88	3.99	0.89			
	Teaching with holography would be enjoyable and rewarding for me.	0.88	3.95	0.91			
Subjective Norm	People who are important to me think that I should use holographic technology for science teaching.	0.81	3.89	0.99	0.67	0.80	
	People who influence my teaching practices encourage me to use holography in my science classes.	0.83	4.02	0.96			
TOE Constructs							
Relative Advantage	Using holographic technology makes teaching more effective.	0.87	4.05	0.99	0.76	0.93	0.89
	Holography helps reduce the time and effort needed for teaching tasks.	0.88	4.10	0.94			
	Holographic tools enhance the quality of interaction with students.	0.89	4.18	0.94			
	Adopting holographic technology attracts student interest and participation.	0.85	4.15	0.97			
Compatibility	The use of holography aligns with my teaching practices.	0.89	4.08	0.98	0.76	0.90	0.88
	Integrating holographic tools fits the educational culture at my school.	0.88	4.00	0.99			
	It is easy to incorporate holography into my teaching routine.	0.84	3.95	0.99			
Observability	The benefits of using holographic technology in teaching are easy to observe.	0.88	3.85	0.95	0.75	0.90	0.88
	It is easy to see how other teachers benefit from holography.	0.85	3.90	0.89			
	I have seen many schools successfully using holographic tools.	0.87	3.95	0.88			
Top Management Support	School leadership considers the use of holographic technology essential for modern teaching.	0.85	3.75	0.96	0.74	0.92	0.90
	Administrators actively communicate their support for using holographic tools.	0.83	3.80	0.96			
	School management is willing to invest in holography-related technologies.	0.89	3.85	0.95			
	Clear goals are set by administrators to monitor the use of holography.	0.88	3.82	0.95			
Competitive Pressure	There is pressure to adopt holographic technology to remain competitive with other schools.	0.87	3.92	0.95	0.77	0.91	0.87
	Not adopting holography could put my school at a disadvantage.	0.88	4.02	0.92			
	Schools that adopt holographic tools are viewed more favorably.	0.89	4.05	0.83			
Perceived Trend	The government encourages schools to adopt holography.	0.78	3.85	0.97	0.68	0.86	0.83
	The use of holographic technology is becoming a trend in education.	0.81	3.90	0.95			
	More schools are expected to adopt holography soon.	0.88	3.95	0.96			
Government Support	The government provides training programs on using holography in education.	0.89	3.70	0.98	0.76	0.93	0.91

(*Continued*)

Table 1. Continued.

Construct	Item Statement	Factor Loading	Mean	SD	AVE	CR	α
	Educational seminars and conferences on holographic technology are supported by government agencies.	0.88	3.75	0.93			
	Schools receive advisory support for adopting holography.	0.87	3.78	0.93			
	Government programs assist schools with the integration of holographic tools.	0.85	3.80	0.94			
Legal Framework	Policies encourage the use of holographic technology in education.	0.86	3.75	0.94	0.73	0.89	0.90
	Incentives are provided to schools that adopt holography.	0.82	3.82	0.88			
	Privacy and security laws are in place to address concerns with holographic tools.	0.88	3.78	0.98			
Technological Orientation	My school uses innovative technologies to enhance teaching practices.	0.89	3.95	0.95	0.76	0.91	0.93
	State-of-the-art technologies, including holography, are embraced.	0.88	4.00	0.91			
	My school is committed to building capacity for advanced teaching tools.	0.85	3.98	0.89			
Intention to Use	I plan to use holographic technology in my science teaching frequently.	0.88	4.18	0.87	0.76	0.90	0.90
	I will try to use holography in my future classes.	0.88	4.22	0.89			
	I am committed to continuing the use of holographic tools in my teaching.	0.85	4.12	0.89			

To further investigate the mechanisms within the model, a bootstrapping method was employed, allowing for an in-depth exploration of mediating effects among study variables. This method provided critical insights into how different constructs contribute to teachers' intentions to integrate holography into their instructional practices, strengthening the overall validity of the findings.

The first stage of the data analysis focused on evaluating the measurement model using CFA with Maximum Likelihood Estimation (MLE). The results demonstrated a strong model fit, with a χ^2 value of 1382.41 and a χ^2/df ratio of 2.72, indicating a well-structured model with good parsimony. The Root Mean Square Error of Approximation (RMSEA) was found to be 0.047, with a 90% confidence interval ranging from 0.041 to 0.053, confirming the model's adequacy. Additionally, the Comparative Fit Index (CFI) was recorded at 0.95, the Incremental Fit Index (IFI) yielded a value of 0.94, and the Tucker-Lewis Index (TLI) reached 0.93, all surpassing the recommended thresholds and affirming the measurement model's reliability and validity.

To assess internal consistency, Cronbach's alpha (α) and composite reliability (CR) were calculated. The results indicated that all constructs met the recommended α threshold of 0.70 (Bagozzi & Yi, 2012), with values ranging from 0.83 to 0.94, demonstrating high internal reliability. Similarly, CR values ranged between 0.80 and 0.93, exceeding the 0.60 benchmark, ensuring strong internal consistency across constructs (Bagozzi & Yi, 2012).

To establish construct validity, both convergent validity and discriminant validity were examined, following the guidelines of Hair et al. (2018) and Kline (2023). The Average Variance Extracted (AVE) values, ranging between 0.67 and 0.77, surpassed the recommended 0.50 threshold, confirming adequate convergent validity. Additionally, discriminant validity was supported, as the squared correlations between constructs were lower than their respective AVE values, ensuring that the constructs were distinct and well-defined.

These findings confirm that the measurement model is reliable and valid, supporting the suitability of the proposed theoretical framework for investigating the factors influencing science teachers' adoption of holography in education. A detailed summary of construct reliability and validity metrics is presented in Table 2.

To address potential common method bias arising from self-report data collected at a single time point, Harman's single-factor test was conducted. All measured items were loaded into an unrotated exploratory factor analysis. The results showed that the first factor accounted for 29.4% of the total variance, which is below the 50% threshold, suggesting that common method variance is unlikely to be a serious concern. In addition, procedural remedies – such as the use of varied item wording, logical separation of constructs in the survey, and anonymity assurances – were implemented to further reduce potential bias (Podsakoff et al., 2003).

Table 2. Summary of descriptive statistics and construct validity.

Constructs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1. PEOU	0.83																	
2. PU	0.44	0.82																
3. PE	0.51	0.35	0.83															
4. ANX	0.52	0.52	0.47	0.82														
5. EXP	0.55	0.37	0.49	0.34	0.87													
6. SE	0.37	0.58	0.47	0.42	0.54	0.85												
7. ATT	0.35	0.50	0.54	0.57	0.31	0.40	0.88											
8. SN	0.33	0.50	0.43	0.35	0.37	0.52	0.58	0.82										
9. RA	0.54	0.59	0.40	0.48	0.48	0.44	0.34	0.47	0.87									
10. CPT	0.54	0.54	0.40	0.41	0.38	0.49	0.55	0.47	0.56	0.87								
11. OBS	0.55	0.47	0.54	0.48	0.50	0.58	0.30	0.55	0.37	0.54	0.87							
12. TMS	0.51	0.57	0.44	0.59	0.40	0.33	0.49	0.39	0.35	0.40	0.47	0.86						
13. CP	0.34	0.55	0.34	0.32	0.48	0.57	0.38	0.32	0.40	0.36	0.56	0.35	0.88					
14. PTR	0.52	0.54	0.53	0.45	0.39	0.35	0.54	0.38	0.54	0.51	0.45	0.59	0.48	0.82				
15. GOV	0.57	0.44	0.38	0.50	0.48	0.39	0.38	0.47	0.55	0.52	0.44	0.54	0.34	0.53	0.87			
16. LEF	0.47	0.48	0.58	0.52	0.56	0.43	0.52	0.59	0.51	0.53	0.58	0.48	0.44	0.39	0.54	0.85		
17. TOR	0.47	0.57	0.56	0.57	0.54	0.54	0.56	0.44	0.54	0.58	0.60	0.41	0.44	0.32	0.40	0.50	0.87	
18. INT	0.50	0.48	0.53	0.51	0.40	0.59	0.58	0.44	0.36	0.37	0.45	0.31	0.60	0.51	0.50	0.34	0.33	0.87

Note. The bold values indicate the square root of AVE. PEOU = Perceived Ease of Use, PU = Perceived Usefulness, PE = Perceived Enjoyment, ANX = Anxiety, EXP = Experience, SE = Self-Efficacy, ATT = Attitude, SN = Subjective Norm, RA = Relative Advantage, CPT = Compatibility, OBS = Observability, TMS = Top Management Support, CP = Competitive Pressure, PTR = Perceived Trend, GOV = Government Support, LEF = Legal Framework, TOR = Technological Orientation, INT = Intention to Use Holography.

3.5. Validity and reliability

The validity and reliability of the research process were ensured through a series of systematic procedures addressing both the measurement instrument and the analysis phase.

Content validity was established during instrument development by consulting five subject-matter experts in science education, instructional technology, and educational psychology. Their feedback led to refinements in item wording and contextual relevance. In addition, a double-blind translation – back-translation process was implemented to guarantee semantic accuracy between the English and Turkish versions of the survey.

Construct validity was assessed via Confirmatory Factor Analysis (CFA), as described in Section 3.4. The CFA results indicated strong factor loadings (all >0.80), excellent model fit (χ^2/df = 2.72; RMSEA = 0.047; CFI = 0.95; TLI = 0.93), and satisfactory convergence of items within each construct. Convergent validity was confirmed as all Average Variance Extracted (AVE) values exceeded the recommended threshold of 0.50. Discriminant validity was established as the squared correlations between constructs were lower than their respective AVE values, indicating clear distinction among measured constructs.

Reliability was addressed by calculating Cronbach's alpha (α) and Composite Reliability (CR) for each construct, with all values exceeding 0.80, indicating strong internal consistency. The instrument's robustness was further supported through pilot testing with 210 in-service teachers, leading to the refinement or removal of ambiguous or low-loading items.

Common method bias was minimized by using varied item wording, logical separation of constructs, and assurances of anonymity within the survey. Harman's single-factor test showed the first factor accounted for only 29.4% of total variance – well below the 50% threshold – suggesting common method variance was not a significant concern.

3.6. Ethical issues

This research strictly adhered to established ethical standards in social science research. Ethical approval for the study was obtained from the appropriate institutional ethics committee prior to data collection. All research procedures were conducted in accordance with relevant guidelines and ethical principles. Informed consent was obtained from all participants. Before participating, teachers received detailed information outlining the study's objectives, procedures, voluntary nature, and the confidentiality of their responses. Consent was documented electronically at the start of the survey. Data protection measures were rigorously implemented to safeguard participant privacy and the security of the collected data. All responses were anonymized, with no personally identifiable information being collected or stored. Data were encrypted and kept on secure, password-protected servers accessible only to the research team. Findings are reported in aggregate form, ensuring that no individual participants can be identified. Participation was entirely voluntary, and participants were informed of their right to withdraw from the study at any stage without penalty. Any questions or concerns raised by participants were addressed promptly by the research team. These measures ensured that the rights, privacy, and well-being of all participants were protected throughout the research process.

4. Findings

4.1. Analysis of model suitability and explanatory power of the combined framework

To evaluate model effectiveness, this study compared the explanatory power of three distinct frameworks: the integrated TOE-GETAMEL model, the standalone GETAMEL model, and the TOE-only model. SEM was applied to assess model fit, with all three models demonstrating acceptable indices according to established criteria by Bagozzi and Yi (2012) and Browne and Cudeck (1992). Nevertheless, the integrated TOE-GETAMEL model consistently showed superior performance. Specifically, the integrated model presented the most favorable χ^2/df ratio (χ^2/df = 2.58), outperforming both the GETAMEL-only model (χ^2/df = 2.84) and the TOE-only model (χ^2/df = 2.91).

Additionally, the integrated model exhibited higher predictive capability, with an R^2 value of 0.59, surpassing the GETAMEL-only model (R^2 = 0.51) and the TOE-only model (R^2 = 0.45). This highlights that the

Table 3. Comparative analysis of fit indices and model predictive capability.

Model	χ^2/df	R^2	χ^2	df	NFI	IFI	TLI	CFI	RMSEA	SRMR
Integrated Model	2.58	0.59	462.15	179	0.96	0.95	0.94	0.97	0.048	0.039
GETAMEL-only Model	2.84	0.51	495.23	174	0.93	0.92	0.92	0.94	0.053	0.052
TOE-only Model	2.91	0.45	511.68	176	0.92	0.91	0.90	0.92	0.057	0.056

integration of technological, organizational, environmental, cognitive, and motivational constructs provides a more detailed and accurate depiction of science teachers' intentions to adopt holographic technology. By incorporating factors such as perceived ease of use, perceived enjoyment, organizational support, and competitive pressure, the integrated model offers a robust framework for understanding educational technology adoption behaviors. A comprehensive comparison of model fit indices and predictive strength is summarized in Table 3.

4.2. Examination of structural relationships and hypothesis validation for holography integration

This section provides the results of the path analysis, evaluating theoretical relationships derived from the integrated GETAMEL and TOE frameworks. The primary aim was to examine factors influencing science teachers' intentions to integrate holographic technology into middle school science instruction.

4.2.1. Path analysis for GETAMEL

The results demonstrate that Subjective Norm significantly influences Perceived Usefulness ($\beta = 0.41$, $p < 0.01$) and Perceived Ease of Use ($\beta = 0.38$, $p < 0.01$). This indicates that social expectations from colleagues and school administrators significantly shape teachers' perceptions regarding holography's educational value and ease of adoption. When teachers perceive strong social support, they view holography more positively, both in terms of usability and effectiveness. Experience was found to have a meaningful positive impact on Perceived Usefulness ($\beta = 0.34$, $p < 0.01$) and Perceived Ease of Use ($\beta = 0.36$, $p < 0.01$). Teachers with prior exposure to similar digital technologies exhibit greater confidence, viewing holography as easier to integrate and beneficial for enhancing instruction. Moreover, Perceived Enjoyment had a significant positive relationship with both Perceived Usefulness ($\beta = 0.39$, $p < 0.01$) and Perceived Ease of Use ($\beta = 0.37$, $p < 0.01$). Teachers who find holographic teaching enjoyable perceive greater educational benefits and ease of use, which encourages adoption. In contrast, Anxiety negatively impacted Perceived Ease of Use ($\beta = -0.35$, $p < 0.01$) and Perceived Usefulness ($\beta = -0.31$, $p < 0.01$). Teachers experiencing anxiety about using holographic technology tend to view it as complicated and less effective, thus lowering their intention to adopt it. Self-Efficacy demonstrated a strong positive influence on Perceived Ease of Use ($\beta = 0.45$, $p < 0.01$) and Perceived Usefulness ($\beta = 0.42$, $p < 0.01$). Teachers with higher self-efficacy perceive themselves as capable of effectively using holographic tools, increasing their confidence in the technology's ease of use and educational effectiveness. Further analysis revealed that Perceived Ease of Use significantly affected both Perceived Usefulness ($\beta = 0.47$, $p < 0.01$) and Attitude ($\beta = 0.45$, $p < 0.01$). Teachers who perceive holography as user-friendly develop more favorable attitudes and recognize its instructional benefits. Additionally, Perceived Usefulness positively influenced Attitude ($\beta = 0.53$, $p < 0.01$) and Intention to Use Holography ($\beta = 0.54$, $p < 0.01$). Teachers who acknowledge the pedagogical advantages of holography show stronger intentions and positive attitudes toward its implementation. Finally, Attitude had a robust positive impact on Intention to Use Holography ($\beta = 0.56$, $p < 0.01$). Teachers with favorable attitudes toward holography are significantly more likely to integrate the technology into their teaching practices. The theoretical relationships between these constructs are illustrated in Figure 3.

4.2.2. TOE framework path analysis results for holography integration

The analysis revealed significant contributions of various TOE constructs toward science teachers' intentions to adopt holographic technology. Key relationships between these constructs and teachers' adoption intentions are detailed as follows.

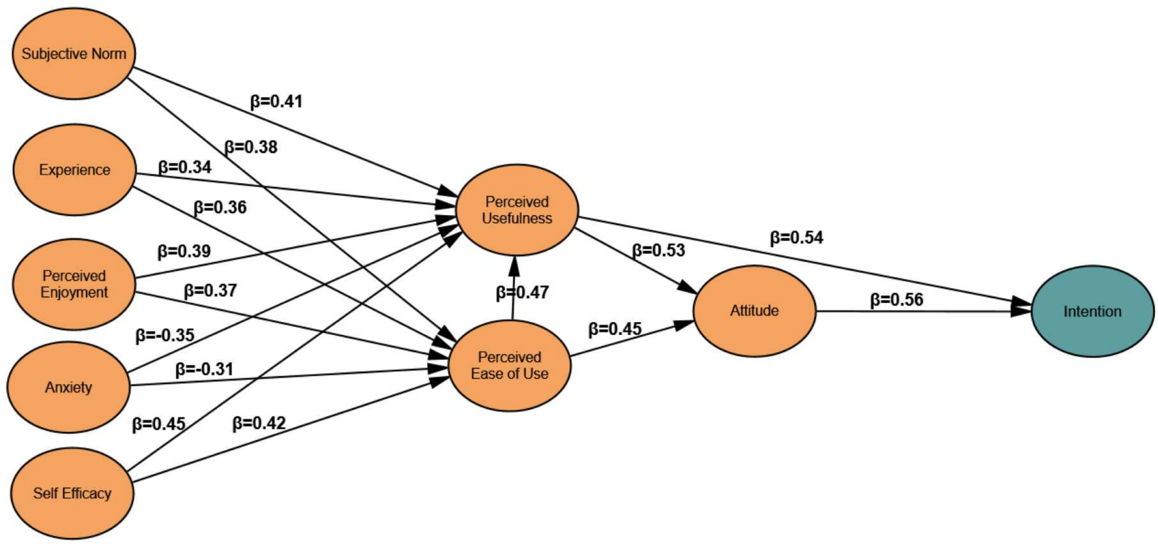

Figure 3. Structural path outcomes within the GETAMEL framework.

Relative Advantage exhibited a robust positive influence on teachers' intention to adopt holography ($\beta = 0.43$, $p < 0.01$), suggesting that educators who perceive clear pedagogical benefits, such as enhanced instructional effectiveness and increased student engagement, are more inclined to implement holographic tools in their teaching. Compatibility also emerged as a crucial determinant ($\beta = 0.37$, $p < 0.01$), indicating that teachers whose existing instructional practices align closely with the functionality of holography are more motivated to incorporate it into their classrooms.

Observability significantly predicted teachers' adoption intentions ($\beta = 0.34$, $p < 0.05$), highlighting that witnessing the effective use of holography in other educational contexts positively influences teachers' own decisions to adopt the technology. Competitive Pressure similarly played a meaningful role ($\beta = 0.32$, $p < 0.05$), implying that teachers who sense competition with other schools in adopting innovative technologies are driven to integrate holography to maintain institutional prestige or excellence.

Perceived Trend was positively associated with adoption intention ($\beta = 0.30$, $p < 0.05$), reflecting that teachers are influenced by the growing acceptance and implementation of holographic tools within the educational sector. The increasing presence of holography in science education motivates teachers to consider adopting these technologies proactively.

Government Support exhibited a strong positive impact on teachers' intentions to adopt holography ($\beta = 0.39$, $p < 0.01$), emphasizing the importance of government-provided training, financial incentives, and technical guidance in facilitating successful technology adoption. Legal Framework also demonstrated a significant effect ($\beta = 0.36$, $p < 0.01$), underscoring the crucial role that educational policies, clear regulatory guidelines, and incentives play in promoting the adoption of holographic tools.

Top Management Support emerged as an essential predictor of adoption intention ($\beta = 0.41$, $p < 0.01$). Teachers were significantly more likely to consider adopting holography when school leaders actively communicated their support, provided adequate resources, and demonstrated commitment to technological innovation. Finally, Technological Orientation had a substantial positive influence ($\beta = 0.38$, $p < 0.01$), signifying that institutions emphasizing technological innovation create favorable conditions that encourage the effective integration of holography into teaching practices.

These relationships, including detailed path coefficients, are visually summarized in Figure 4.

4.2.3. Integrated model path analysis results for holography adoption

The integrated model, synthesizing constructs from the GETAMEL and TOE frameworks, provides a comprehensive understanding of the factors influencing science teachers' intentions to adopt holographic technology. This section presents the results of the path analysis, simultaneously testing all 24 hypotheses, thereby illustrating the enhanced explanatory and predictive capability of the integrated approach compared to the individual frameworks.

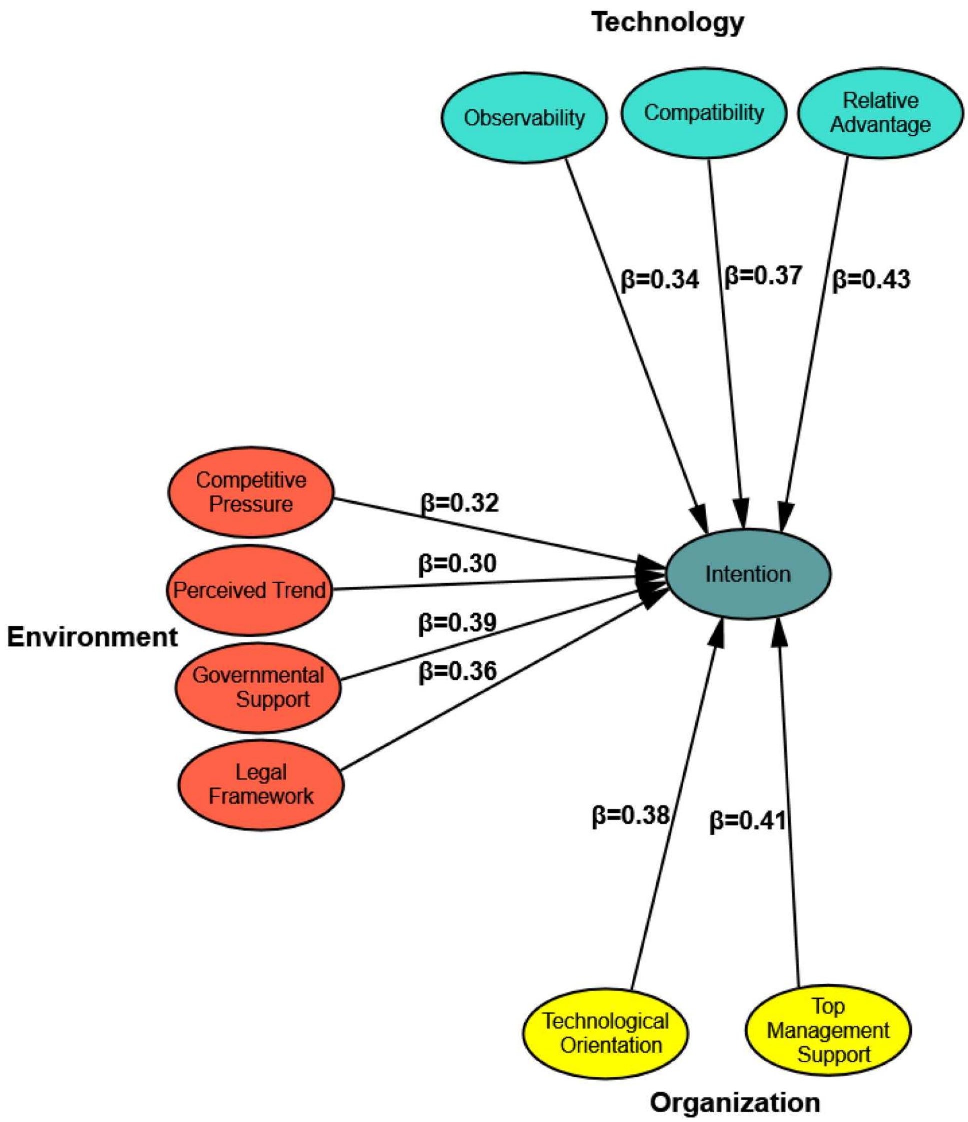

Figure 4. Path analysis results for the integrated GETAMEL-TOE framework in holography adoption.

Subjective norm significantly shaped teachers' perceptions of holography, positively affecting Perceived Usefulness (β = 0.42, $p < 0.01$) and Perceived Ease of Use (β = 0.40, $p < 0.01$), thus supporting H1 and H2. Teachers perceiving strong encouragement from colleagues and school administrators regarded holographic technology as both valuable and manageable. Prior Teaching Experience notably increased Perceived Usefulness (β = 0.36, $p < 0.01$) and Self-Efficacy (β = 0.38, $p < 0.01$), validating H3 and H4. Teachers experienced in interactive educational technologies felt more confident and identified clear educational benefits in holography. Perceived Enjoyment was positively linked to both Perceived Usefulness (β = 0.41, $p < 0.01$) and Perceived Ease of Use (β = 0.37, $p < 0.01$), supporting H5 and H6. Teachers who enjoyed engaging with digital tools perceived holographic technology as both beneficial and user-friendly. In contrast, Anxiety negatively influenced both Self-Efficacy (β = −0.34, $p < 0.01$) and Perceived Usefulness (β = −0.30, $p < 0.01$), confirming H7 and H8. Teachers experiencing higher levels of technological anxiety perceived holography as more challenging and less beneficial. Self-Efficacy showed significant positive relationships with Perceived Ease of Use (β = 0.45, $p < 0.01$) and Perceived Usefulness (β = 0.44, $p < 0.01$), supporting H9 and H10. Teachers confident in their technological skills perceived holography as accessible and educationally valuable. Perceived Ease of Use had substantial positive impacts on both Perceived Usefulness (β = 0.49, $p < 0.01$) and Attitude (β = 0.47, $p < 0.01$), supporting H11 and H12. Teachers finding holographic technology easy to operate developed positive attitudes toward its educational integration. Perceived Usefulness

Table 4. Results of hypothesis testing and structural relationships in the combined model.

Hypothesis	Hypothesized Relationship	β Value	t-value	*p*-value	Supported
H1	SN → PU	0.42	9.62	<0.01	Yes
H2	SN → PEOU	0.40	8.95	<0.01	Yes
H3	EXP → PU	0.36	8.12	<0.01	Yes
H4	EXP → SE	0.38	8.40	<0.01	Yes
H5	PE → PU	0.41	9.14	<0.01	Yes
H6	PE → PEOU	0.37	8.58	<0.01	Yes
H7	ANX → SE	−0.34	−7.45	<0.01	Yes
H8	ANX → PU	−0.30	−6.68	<0.01	Yes
H9	SE → PEOU	0.45	9.83	<0.01	Yes
H10	SE → PU	0.44	9.59	<0.01	Yes
H11	PEOU → PU	0.49	10.57	<0.01	Yes
H12	PEOU → ATT	0.47	10.22	<0.01	Yes
H13	PU → ATT	0.52	11.39	<0.01	Yes
H14	PU → INT	0.54	11.68	<0.01	Yes
H15	ATT → INT	0.56	12.01	<0.01	Yes
H16	RA → INT	0.41	9.45	<0.01	Yes
H17	CPT → INT	0.36	8.31	<0.01	Yes
H18	OBS → INT	0.34	7.84	<0.01	Yes
H19	CP → INT	0.32	7.36	<0.01	Yes
H20	PTR → INT	0.33	7.62	<0.01	Yes
H21	GOV → INT	0.38	8.71	<0.01	Yes
H22	LEF → INT	0.35	8.03	<0.01	Yes
H23	TOR → INT	0.37	8.49	<0.01	Yes
H24	TMS → INT	0.40	9.20	<0.01	Yes

strongly influenced both Attitude (β = 0.52, $p < 0.01$) and Intention to Use (β = 0.54, $p < 0.01$), confirming H13 and H14. Teachers who recognized the educational benefits of holography demonstrated stronger intentions to incorporate it. Attitude was significantly associated with Intention to Use holography (β = 0.56, $p < 0.01$), supporting H15. Favorable attitudes among teachers correlated strongly with their intention to integrate holography in science classrooms.

Within the TOE constructs, Relative Advantage notably impacted adoption intention (β = 0.41, $p < 0.01$), confirming H16. Teachers perceiving clear advantages of holography over traditional methods expressed stronger intentions for adoption. Compatibility also positively influenced adoption intentions (β = 0.36, $p < 0.01$), supporting H17, indicating teachers favor technologies aligning with existing pedagogical methods. Observability positively influenced adoption intentions (β = 0.34, $p < 0.01$), confirming H18. Teachers witnessing successful applications of holography elsewhere showed increased willingness to adopt it. Competitive Pressure significantly predicted adoption intentions (β = 0.32, $p < 0.01$), confirming H19, as schools sought competitive advantages by adopting advanced technologies. Perceived Trend positively influenced adoption intentions (β = 0.33, $p < 0.01$), validating H20, suggesting teachers perceived a rising emphasis on holography in education as motivation for adoption. Government Support strongly affected intentions (β = 0.38, $p < 0.01$), supporting H21, highlighting the critical role of governmental incentives and resources in promoting technology adoption. The Legal Framework significantly enhanced adoption intentions (β = 0.35, $p < 0.01$), supporting H22, reflecting teachers' preferences for clear regulatory support and incentives for adopting holography. Technological Orientation significantly predicted adoption (β = 0.37, $p < 0.01$), supporting H23, indicating that schools with strong digital learning orientations fostered favorable conditions for holography adoption. Finally, Top Management Support emerged as a critical determinant (β = 0.40, $p < 0.01$), supporting H24, underscoring the pivotal role of school leadership in facilitating the integration of holographic technology into instructional practices.

The integrated model demonstrated superior explanatory power, with an R^2 value of 0.59, surpassing the individual GETAMEL ($R^2 = 0.47$) and TOE ($R^2 = 0.43$) frameworks. These results highlight that teachers' intentions to adopt holographic technology are driven by complex interactions among cognitive, social, and organizational factors. Table 4 and Figure 4 visually summarize these relationships, clearly illustrating how various factors collectively shape teachers' intentions to adopt holography.

4.2.4. Mediating analysis

This section examines the mediating effects within the integrated GETAMEL-TOE model, emphasizing the roles of Perceived Usefulness, Perceived Ease of Use, and Attitude in shaping science teachers' Intention

Table 5. Mediating effects within the integrated GETAMEL-TOE model.

Mediating Path	Indirect Effect	Direct Effect Before Mediation	Direct Effect After Mediation	Mediation Type
EXP → PU → INT	0.23**	0.34**	0.12*	Partial
SN → PU → INT	0.20**	0.31**	0.13*	Partial
SE → PEOU → ATT	0.26**	0.33**	0.11*	Partial
PEOU → PU → ATT → INT	0.30**	-	-	Chain
PU → ATT → INT	0.32**	0.54**	0.22*	Partial
RA → ATT → INT	0.21**	0.28**	ns	Full

Note. ** $p < 0.01$, * $p < 0.05$, ns = not significant. EXP = Prior Teaching Experience, SN = Subjective Norm, SE = Self-Efficacy, PEOU = Perceived Ease of Use, PU = Perceived Usefulness, ATT = Attitude, RA = Relative Advantage, INT = Intention to Use holography.

to Use holography. Utilizing the bootstrapping method, the analysis identified several significant indirect pathways, revealing the nuanced dynamics underlying holographic technology adoption.

Perceived Usefulness significantly mediated the relationship between prior teaching experience and intention. Science teachers with prior experience using interactive educational technologies perceived holography as more useful, which in turn increased their intention to adopt it. The indirect effect for EXP→PU→INT was 0.23 ($p < 0.01$), while the direct effect of experience on intention decreased from 0.34 to 0.12 ($p < 0.05$), confirming partial mediation. Similarly, perceived usefulness mediated the relationship between subjective norm and intention, showing that social encouragement enhanced perceived usefulness, thereby strengthening adoption intentions (indirect effect SN→PU→INT = 0.20, $p < 0.01$).

Perceived Ease of Use also emerged as a critical mediator. Specifically, it mediated the relationship between self-efficacy and attitude, indicating that teachers with higher self-efficacy viewed holography as easier to use, fostering more positive attitudes towards its integration. The indirect effect SE→PEOU→ATT was 0.26 ($p < 0.01$), with the direct effect of self-efficacy on attitude dropping from 0.33 to 0.11 ($p < 0.05$), supporting partial mediation. This pathway aligns with Bandura's (1997) Social Cognitive Theory, which emphasizes self-efficacy as a foundational belief influencing behavioral outcomes through cognitive appraisals like perceived ease of use. Moreover, a chain mediation was identified (PEOU→PU→ATT→INT), demonstrating how perceived ease of use indirectly affects intention through enhanced usefulness perceptions and attitudes (total chain effect = 0.30, $p < 0.01$).

Attitude itself served as a significant mediator within the integrated model. Perceived usefulness influenced intention indirectly through attitude (indirect effect = 0.32, $p < 0.01$), with the direct effect dropping from 0.54 to 0.22 ($p < 0.05$), indicating partial mediation. Notably, attitude fully mediated the effect of relative advantage on intention (indirect effect RA→ATT→INT = 0.21, $p < 0.01$), rendering the direct effect non-significant, which suggests that perceptions of relative advantage influence intention primarily through their impact on teachers' attitudes toward holography.

These mediation findings enrich the theoretical understanding by elucidating the mechanisms through which cognitive, social, and emotional factors jointly influence teachers' adoption decisions. They confirm the importance of affective and cognitive pathways proposed in technology acceptance theories and social cognitive frameworks (Table 5).

5. Discussion

5.1. Summary of results

This study integrated constructs from the GETAMEL and TOE frameworks to explore the determinants of science teachers' intentions to adopt holographic technology. The integrated model offered comprehensive insights, highlighting the significance of both cognitive and organizational factors in shaping teachers' adoption intentions. The cognitive elements from GETAMEL, specifically perceived ease of use and perceived usefulness, were validated as critical determinants, suggesting that teachers who perceive holographic technology as practical and user-friendly exhibit greater willingness to adopt it.

Subjective norm also emerged as influential, with the findings confirming that peer support and encouragement from school administrators significantly strengthened teachers' positive perceptions of holography. Within the organizational perspective of the TOE framework, the study underscored the importance of relative advantage, compatibility, and observability. Teachers who identified clear educational advantages of holography over traditional methods and found it compatible with their existing teaching practices showed stronger intentions to adopt the technology. Additionally, observing successful implementations of holography in educational settings positively influenced teachers' adoption intentions.

The analysis further emphasized the critical roles of institutional support, government incentives, and effective legal frameworks. Teachers who perceived substantial support from school leadership, comprehensive training, adequate funding, and clear regulatory frameworks were more likely to embrace holographic technology. This indicates that organizational and environmental factors are pivotal enablers of successful adoption.

In addition to the direct relationships, mediation analyses revealed important indirect pathways within the integrated model. For example, perceived usefulness partially mediated the effects of prior teaching experience and subjective norm on adoption intention, while perceived ease of use mediated the impact of self-efficacy on attitude toward holography. Furthermore, attitude served as a significant mediator between constructs such as perceived usefulness and relative advantage, and teachers' intention to adopt holography. These findings underscore the complex mechanisms through which cognitive and social factors influence adoption decisions, providing a more nuanced understanding of how holographic technology is embraced by science educators.

Overall, integrating GETAMEL and TOE frameworks into a unified model effectively illustrated the complex dynamics influencing science teachers' decisions to adopt holography. The findings provide a robust theoretical foundation for understanding technology adoption in educational contexts, highlighting practical strategies to encourage wider acceptance and integration of innovative technologies like holography in science education.

5.2. Implications

5.2.1. Theoretical implications

This study significantly advances theoretical understanding by integrating the GETAMEL and TOE frameworks, offering a comprehensive perspective on science teachers' adoption of holographic technology. While previous research often examined these models independently (e.g. Karan & Angadi, 2025; Tian & Wang, 2024; Zhang & Yang, 2025), the present study enhances theoretical richness by explicitly unifying cognitive, social, emotional, technological, and organizational dimensions. This holistic integration specifically addresses critical gaps by incorporating dimensions traditionally underexplored in isolated theoretical analyses, such as anxiety, competitive pressure, government support, and legal frameworks.

The study confirms several key hypotheses foundational to the integrated model. Aligning with GETAMEL, Subjective Norms significantly influenced Perceived Usefulness and Perceived Ease of Use (H1, H2), underscoring the importance of social support. These findings align with previous research (Dehghani & Mashhadi, 2024; Kong et al., 2024), emphasizing that positive social environments substantially enhance teachers' receptivity to technology adoption. Moreover, the significant positive impacts of Prior Teaching Experience on Perceived Usefulness and Self-Efficacy (H3, H4) support earlier studies (Abdullah & Ward, 2016), indicating that familiarity and previous exposure reduce technology adoption barriers.

Perceived Enjoyment emerged as another critical factor, positively affecting both Perceived Usefulness and Perceived Ease of Use (H5, H6). These results underscore intrinsic motivation as a substantial element, reinforcing prior findings that enjoyable interactions with technology foster sustained positive attitudes and higher adoption likelihood (Ateş et al., 2024). In contrast, Anxiety negatively affected Self-Efficacy and Perceived Usefulness (H7, H8), highlighting the crucial need for strategies that address emotional barriers to facilitate successful technology integration.

Self-Efficacy was confirmed as a pivotal predictor, significantly enhancing Perceived Ease of Use and Usefulness (H9, H10). These outcomes reinforce earlier findings about the centrality of technological confidence for successful integration (Yang & Lou, 2024). Additionally, Perceived Ease of Use was found to substantially shape positive attitudes and perceived benefits (H11, H12), aligning with established TAM research (Davis, 1989).

The validation that Perceived Usefulness strongly predicts both Attitude and Intention to Use holography (H13, H14) aligns with previous assertions that recognition of educational benefits significantly strengthens adoption intentions (Al-Adwan et al., 2024). Moreover, the significant influence of Attitude on Intention (H15) aligns with the Theory of Planned Behavior (Ajzen, 1991), emphasizing attitude as a primary determinant of behavioral intentions.

In terms of the TOE constructs, Relative Advantage notably predicted adoption intention (H16), emphasizing that clearly perceived educational advantages over traditional methods significantly motivate technology adoption. The significant roles of Compatibility, Observability, Competitive Pressure, and Perceived Trend (H17–H20) further illustrate that pedagogical alignment, visibility of successful adoption, institutional competition, and perceived trends notably influence adoption decisions (Ateş & Polat, 2025a). Importantly, the substantial influence of Competitive Pressure challenges prior assumptions in literature that suggest competitive dynamics are relatively insignificant in educational technology adoption (e.g. Tian & Wang, 2024), providing a critical theoretical counterpoint.

Additionally, Government Support and Legal Framework emerged as significant predictors (H21, H22), underscoring the importance of external incentives and clear regulatory environments for successful adoption. Technological Orientation and Top Management Support (H23, H24) further highlighted the critical role institutional readiness and leadership commitment play in facilitating adoption (Galimova et al., 2024).

Notably, this study also addresses a critical gap in the educational technology literature by highlighting how the adoption dynamics of holography differ from those of other XR tools, such as virtual and augmented reality. While VR and AR have been widely studied, their implementation typically relies on individual headsets or personal devices and centers on immersive or overlay experiences. In contrast, holography offers hands-free, spatially-shared 3D visualizations that introduce unique pedagogical affordances (e.g. collaborative viewing, group manipulation of content) and distinct technological barriers, including higher costs, complex setup, and the need for new content development strategies. These differences mean that the cognitive, organizational, and environmental determinants – and their interactions within the integrated GETAMEL-TOE framework – may operate differently for holography compared to other XR technologies. Thus, by empirically validating these distinctions, this study extends theoretical understanding beyond general technology adoption to capture the unique, context-dependent mechanisms that shape the successful integration of advanced visualization tools in science education.

Furthermore, the mediation analyses conducted in this study elucidate important indirect pathways within the integrated framework, providing nuanced insights consistent with established technology adoption theories. For instance, perceived usefulness partially mediated the effects of prior teaching experience and subjective norm on teachers' intention to adopt holography, aligning with the TAM proposition that perceived usefulness is a key mediator between external variables and behavioral intention (Davis, 1989). Similarly, perceived ease of use mediated the relationship between self-efficacy and attitude toward holographic technology, supporting Bandura's (1997) social cognitive theory which posits that self-efficacy influences behavioral outcomes through cognitive appraisals such as perceived ease. Additionally, attitude served as a significant mediator between constructs such as perceived usefulness and relative advantage, and the intention to adopt holography, consistent with the Theory of Planned Behavior's emphasis on attitude as a proximal determinant of intention (Ajzen, 1991). These findings enrich the theoretical understanding by highlighting the complex mechanisms through which cognitive, social, and emotional factors jointly influence adoption decisions. They emphasize the value of integrating multiple theoretical perspectives to capture the layered and dynamic nature of educational technology adoption processes.

Overall, this integrated framework provides a robust theoretical foundation for understanding the multifaceted dynamics involved in science teachers' adoption of holographic technology. It highlights the necessity of simultaneously addressing cognitive evaluations, emotional responses, organizational contexts, and external supports. These insights offer valuable theoretical implications for future research, emphasizing the benefits of employing integrated theoretical approaches to comprehensively analyze technology adoption in diverse educational contexts.

5.2.2. Practical implications

The findings of this study offer several critical and context-sensitive implications for integrating holographic technology into science education, particularly in settings with limited resources or systemic constraints.

First, professional development initiatives must be tailored to both the unique challenges and opportunities of holography. Unlike VR or AR – where teachers may rely on more familiar devices – holography often requires hands-on calibration and group-oriented engagement. Thus, training should provide "sandbox" sessions in which teachers can safely explore, experiment, and make mistakes with holographic tools before deploying them in real classrooms. Establishing peer-mentoring systems, where early adopters support colleagues, and professional learning communities can foster collaborative troubleshooting and reduce apprehension. Crucially, training must address technology-related anxiety, integrating stress management workshops, ongoing access to counseling, and peer support groups. These approaches are essential for building the self-efficacy that, as demonstrated by our mediation analyses, has indirect positive effects on perceived ease of use, attitudes, and ultimately, intention to adopt holography.

Second, practical solutions for schools with limited funding are essential to ensure equitable adoption. Phased implementation – starting with small pilot projects, rotating "mobile holography labs," or leveraging low-cost, open-source holographic apps that operate on existing devices (such as tablets or smartphones) – can enable schools to begin adoption without prohibitive upfront costs. Partnerships with universities, technology firms, or educational consortia can facilitate resource-sharing, and joining collaborative purchasing initiatives or applying for grants can help offset expenses. Even small-scale demonstration projects can showcase the feasibility and benefits of holography, building momentum for wider adoption.

Third, fostering a supportive institutional culture is vital. School leaders should actively champion the educational value of holography, connect its use to specific curricular objectives, and establish realistic, staged implementation goals. Providing regular feedback and public recognition for teachers experimenting with or sharing best practices can help normalize and encourage broader participation.

Fourth, robust governmental and policy support is critical. Policymakers should establish targeted funding streams, provide subsidies for professional development, and offer continuous technical advisory services. Developing clear legal and regulatory frameworks to address privacy, data security, and ethical considerations will reassure teachers and administrators, thereby promoting responsible integration.

Fifth, curriculum alignment is crucial for sustainable adoption. Collaboration among policymakers, curriculum developers, and science teachers is needed to ensure that holography is embedded within learning objectives and standards. Developing ready-to-use lesson plans, assessment tools, and pilot programs can bridge the gap between technological innovation and everyday classroom practice.

Sixth, highlighting observable benefits – through demonstration classrooms or showcase events – can serve as a powerful motivator. Opportunities for teachers to see real-world applications and hear directly from peers who have successfully integrated holography can build confidence and address lingering skepticism.

Finally, successful adoption requires practical attention to both perceived and actual barriers. Simplifying system interfaces, ensuring available technical support, and providing clear resource allocation guidance can minimize implementation burdens and make it easier for teachers to adopt holography.

It is important to note that these recommendations are primarily drawn from research within the Turkish education system. While many of these strategies may be relevant to similar educational contexts, their transferability to substantially different cultural or institutional settings should be considered with care. Future research should investigate how these approaches can be adapted and optimized in diverse environments to further develop best practices for equitable and effective integration of holographic (and broader XR) technologies in science education.

5.3. Limitations and suggestions for future studies

Despite offering valuable insights into the factors influencing science teachers' adoption of holographic technology, this study has several limitations that provide important directions for future research.

First, this study employed a cross-sectional research design, which restricts the ability to make definitive causal inferences regarding the relationships among the examined constructs. Although structural equation modeling allows for the identification of statistically significant associations, it does not establish the temporal ordering or directionality necessary for determining causality. To more convincingly demonstrate causal linkages and better understand how teachers' perceptions, attitudes, and intentions toward holographic technology adoption evolve over time, future research should employ longitudinal designs that follow participants across multiple time points or intervention-based experimental studies that manipulate key variables. These approaches would enable researchers to observe changes and the direction of effects, thereby providing much stronger evidence for causal relationships.

Second, the sample was exclusively composed of in-service science teachers from Turkey, which may restrict the generalizability and applicability of the findings to other educational contexts and cultural backgrounds. The Turkish education system is characterized by a centralized administrative structure, government-driven technology initiatives, and specific cultural attitudes toward innovation and authority. These systemic and cultural features, such as hierarchical leadership, national curriculum policies, and disparities in technology access between urban and rural schools, may have influenced the observed adoption dynamics. As such, caution should be exercised in extrapolating these results to countries with more decentralized governance, different professional development models, or alternative cultural orientations toward educational technology. Future studies are encouraged to replicate and extend the integrated TOE-GETAMEL model in diverse international settings and among different subject domains, grade levels, and educational systems. Cross-cultural comparative research would be especially valuable in distinguishing universal determinants of technology adoption from those shaped by local policies, institutional cultures, and societal values, thereby enhancing the theoretical robustness and practical relevance of the model.

Third, this study relied exclusively on self-report surveys as the data collection method. While surveys are a practical means of gathering large-scale data, they are inherently susceptible to various forms of response bias, including social desirability bias and inaccuracies in self-assessment. Such biases may affect the validity of the findings by prompting participants to provide responses they perceive as more socially acceptable or by misestimating their own competencies and behaviors. To address these limitations and enhance the credibility of future research, it is recommended to employ methodological triangulation through mixed-methods approaches. Incorporating qualitative methods such as semi-structured interviews, classroom observations, and focus groups would not only mitigate single-source bias but also offer richer, more nuanced insights into instructors' authentic perspectives and the contextual factors influencing technology adoption.

Fourth, given that all data were collected via self-report questionnaires at a single time point, there is a risk of common method bias (CMB), which could inflate observed relationships among variables. To assess this, Harman's single-factor test was conducted. The results showed that the first factor accounted for only 29.4% of the variance, suggesting that CMB is unlikely to be a major concern in this study. However, this test alone does not entirely rule out the possibility of bias. More robust procedures – such as the use of marker variables or latent method factor techniques (Podsakoff et al., 2003) – were not implemented. Future studies are encouraged to incorporate procedural and statistical remedies to minimize and diagnose CMB, and to consider collecting data from multiple sources or across multiple time points to enhance methodological rigor.

Fourth, an important limitation of this study is that participants did not have direct, hands-on experience with holographic technology, but rather received conceptual overviews through virtual guides and multimedia presentations. This hypothetical exposure may limit the ecological validity of the findings, as teachers' responses could reflect aspirational attitudes rather than fully grounded behavioral intentions. Constructs such as self-efficacy and anxiety are particularly likely to be influenced by actual interaction with the technology, which was not possible in this study's design. Future research should incorporate real-world, hands-on experiences with holographic tools to better capture authentic teacher attitudes and adoption behaviors, thereby enhancing the practical relevance and validity of the findings.

Fifth, while the integrated GETAMEL-TOE model in this study encompasses cognitive, motivational, and organizational determinants of technology adoption, it may overlook other critical factors that influence technology integration in real educational contexts. Specifically, the model does not systematically account for student demographics (e.g. age, gender, prior technology experience, socioeconomic status), classroom dynamics (e.g. interaction patterns, class size, instructional style), and essential technological features (e.g. usability, accessibility, technical reliability). These dimensions can substantially impact the success, inclusiveness, and equity of holographic technology adoption. Therefore, future research should expand and refine the theoretical framework to explicitly incorporate these factors, enabling a more holistic and contextually sensitive analysis of adoption behaviors and educational outcomes in diverse learning environments.

Sixth, although this study conceptualizes holographic technology and its potential in science education, it does not provide detailed descriptions of the specific hardware, software, or classroom setup necessary for practical implementation. The absence of such technical and logistical information may limit the practical applicability of the findings, as educators and policymakers are left without clear guidance regarding infrastructure requirements, device compatibility, or potential challenges of integrating holography in real classrooms. Future research should include comprehensive accounts of the technological components involved – such as types of holographic displays, software platforms, necessary supporting devices, classroom space modifications, connectivity, and maintenance. Addressing these technical and operational aspects will bridge the gap between theoretical adoption models and real-world educational practice, supporting more effective and scalable implementation.

Seventh, while high implementation costs are widely recognized as a significant barrier to the adoption of advanced educational technologies such as holography, this study does not examine the financial implications or cost-related challenges associated with classroom integration. The absence of a cost analysis represents a limitation, as economic feasibility often plays a crucial role in the decision-making process for educational technology adoption. Future research should address cost-related hurdles by systematically evaluating both the direct and indirect expenses of holographic implementation and exploring potential solutions, such as the development of scalable or low-cost holographic systems, shared resource models, or the identification of funding mechanisms. Incorporating financial analyses will contribute to a more realistic and actionable understanding of the factors influencing the adoption and sustainability of holographic technology in diverse educational settings.

Eighth, a potential conceptual overlap exists between the constructs of Perceived Usefulness (from the GETAMEL model) and Relative Advantage (from the TOE framework), both of which were included in the present model. While each construct is theorized to capture distinct aspects of technology adoption, they both reflect the perceived benefits of using holographic technology and may introduce redundancy or multicollinearity into the model, potentially affecting explanatory power and construct clarity. Future research should provide clearer conceptual and operational distinctions between these constructs and employ statistical methods – such as variance inflation factor (VIF) analysis or confirmatory factor analysis – to detect and address multicollinearity issues. This will help to ensure robust and interpretable model outcomes.

Ninth, although this study's sample includes both urban and rural teachers, it does not examine how geographical characteristics – such as infrastructure availability, internet connectivity, or digital literacy – may influence the adoption of holographic technology. This omission is a limitation, as teachers in different geographical settings may experience distinct challenges and opportunities regarding technology integration. Future research should conduct subgroup analyses or comparative studies to investigate the impact of geographical disparities on access, readiness, and uptake of holographic tools in science education. Such analyses would provide a more nuanced and contextually grounded understanding of barriers and inform more equitable implementation strategies.

Tenth, this study primarily examines positive determinants that facilitate the adoption of holographic technology by science teachers, but does not investigate cases of instructor resistance or failure to embrace such technology. The absence of a negative case analysis is a limitation, as it may overlook additional barriers or contextual factors that hinder adoption. Future research should incorporate analyses of non-adopters or resistant cases to identify a broader range of obstacles and provide a more comprehensive understanding of factors that impede the successful integration of holographic tools in educational settings.

Furthermore, while this study highlights the initial uptake of holographic technology, it does not consider issues related to long-term sustainability, such as ongoing maintenance expenses or the risk of teacher burnout associated with continuous use of new technology in the classroom. The omission of these factors represents a limitation, as the sustainability of technology integration depends not only on initial adoption but also on the ability to support and maintain its use over time. Future studies should examine the financial, technical, and human factors – such as ongoing costs, workload, and teacher well-being – that influence the sustained use of holographic tools in educational practice.

Additionally, the present study employed a comprehensive model, testing 24 hypotheses derived from the integration of the GETAMEL and TOE frameworks. While this approach allowed for a broad exploration of potential pathways influencing holography adoption, we acknowledge that the large number of hypotheses may increase model complexity and dilute the interpretive focus of the findings. Future research should consider employing more parsimonious approaches, such as exploratory factor analysis, hierarchical model testing, or theory-driven prioritization of key pathways, to refine and streamline integrated models. Such approaches would not only enhance model clarity but also strengthen the theoretical contribution by focusing on the most impactful relationships.

This study did not examine potential moderation effects of demographic or experiential variables such as age, teaching experience, or technological proficiency on the relationships within the integrated GETAMEL-TOE model. The absence of moderation analysis limits the understanding of whether and how different subgroups of science teachers may vary in their adoption patterns and determinants of holographic technology use. Given that these factors can significantly influence technology acceptance behaviors, future research should incorporate moderation analyses to identify critical subgroup differences. Such insights would enable more targeted interventions and enhance the theoretical precision and practical applicability of adoption models in diverse educational contexts.

Finally, while the current research emphasizes teachers' intentions regarding holographic technology adoption, it does not directly assess the impact of such technology on student learning outcomes or classroom engagement. However, teacher attitudes and intentions represent only an initial step in the broader process of educational technology integration. For a more robust justification of holography's adoption in science education, future studies should integrate student-centered measures, including academic achievement, conceptual understanding, motivation, and active engagement. Employing experimental or quasi-experimental methodologies that examine both teacher and student outcomes will yield more comprehensive empirical evidence regarding the effectiveness and educational value of holographic technology. Such research is essential to inform educators, policymakers, and technology providers about best practices and the practical implications of implementing holographic tools in science classrooms.

6. Conclusion

This study provided a comprehensive analysis of the factors influencing science teachers' intentions to adopt holographic technology by integrating constructs from the GETAMEL and TOE frameworks. The findings demonstrated that teachers' adoption intentions are significantly shaped by cognitive, social, emotional, and organizational dynamics. Specifically, perceptions of usefulness, ease of use, enjoyment, and technological self-efficacy strongly facilitated positive attitudes and intentions toward holography. Mediation analyses further elucidated important indirect pathways within the integrated framework, such as perceived usefulness partially mediating the effects of prior teaching experience and subjective norm on intention, and perceived ease of use mediating the relationship between self-efficacy and attitude. Attitude also served as a significant mediator between constructs such as perceived usefulness and relative advantage, and intention to adopt holography. These insights deepen theoretical understanding by revealing the complex mechanisms through which cognitive, social, and emotional factors jointly influence adoption decisions.

Additionally, social influences from colleagues and administrators emerged as essential catalysts, underscoring the importance of a supportive institutional environment. From an organizational standpoint, the results highlighted that perceived advantages of holography, compatibility with existing teaching practices, observable benefits, and competitive pressures notably influenced teachers' willingness to integrate the technology. Furthermore, the critical roles of government support, regulatory clarity, school leadership commitment, and technological orientation emphasized the necessity of multi-level systemic support to ensure successful adoption.

Practically, these findings suggest targeted professional development programs, institutional encouragement, and supportive governmental policies as essential components for facilitating holographic technology integration in science education. Minimizing teachers' perceived barriers through accessible resources and ongoing technical support is also pivotal in promoting sustainable technology adoption.

However, given that the sample comprised exclusively Turkish in-service science teachers, caution is warranted in generalizing these results to other cultural or national contexts. The policy recommendations offered herein are primarily relevant to educational systems and institutional environments similar to Turkey's centralized and government-driven framework. Future research should aim to replicate and extend this integrated framework across more diverse and international contexts to better understand the global applicability of these findings.

Overall, this study contributes meaningfully to educational technology adoption literature by demonstrating that a nuanced combination of cognitive perceptions, motivational factors, and organizational supports must be simultaneously addressed. Future research should continue refining this integrated framework, employing longitudinal and experimental designs to clarify causal relationships and evaluate holography's concrete impact on educational outcomes. Such insights will further strengthen the foundation for effective and contextually relevant adoption of innovative technologies in education.

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