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RESEARCH ARTICLE

Adoption of 3D Holograms in Science Education: Transforming Learning Environments

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ABSTRACT This study delves into the deployment of 3D holographic technologies within the realm of science education, with the goal of evaluating their effects on both student engagement and learning achievements. It also seeks to understand the perceptions of consumers in the UAE regarding the adoption of 3D holography in educational environments. The study employs a theoretical framework that incorporates variables such as Perceived Compatibility, Observability, Trialability, Relative Advantage, Ease of Doing Business, and Technology Export. Data were collected through 828 questionnaires distributed across various educational institutions. To analyze the collected data, the study utilized a combination of Machine Learning (ML) algorithms and Partial Least Squares-Structural Equation Modeling (PLS-SEM), focusing on responses from the student surveys. Additionally, Importance-Performance Matrix Analysis (IPMA) was employed to assess the significance and performance of various factors. What distinguises this study is its theoretical framework, which integrates individual and technological characteristics, offering a novel perspective on the subject matter. Results revealed that factors derived from diffusion theory notably surpassed those concerning the Ease of Doing Business and Technology Export in their influence on technology adoption. Notably, the J48 decision tree classifier demonstrated superior accuracy over other classifiers in predicting the value of the dependent variable. The outcomes of this study highlight the revolutionary capabilities of 3D holograms to enrich science education through creating a dynamic, interactive learning space, thereby significantly boosting learners' comprehension and participation. The implications of this research are profound, providing essential insights for educators, policy makers, and technology developers on the pivotal factors driving 3D holography adoption. This facilitates the development of educational strategies that leverage cutting-edge technologies to enhance learning outcomes. Ultimately, the integration of 3D holographic technology not only aids in the visualization of intricate scientific ideas but also cultivates a more captivating and efficacious educational experience, setting the stage for the advancement of teaching methodologies.

INDEX TERMS 3D holographic technology, importance-performance matrix analysis (IPMA), machine learning algorithms, science education, technology adoption.

I. INTRODUCTION

In the rapidly evolving landscape of educational technology [1], [2], 3D holography emerges as a groundbreaking tool with the potential to transform traditional learning environments into interactive, immersive experiences [3], [4]. Holographic technology, which allows for the projection of three-dimensional images in space without the need for specialized glasses, offers a unique opportunity to engage students in a way that traditional two-dimensional tools cannot [5], [6]. In science education, where understanding complex structures and phenomena is crucial, the ability to

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visualize and interact with these concepts in three dimensions can significantly enhance learning outcomes [7].

The integration of innovative technologies like 3D holograms in educational settings is driven by the growing recognition of the importance of visual learning and engagement in the cognitive development and academic success of students [8]. With the increasing demand for more effective educational tools that cater to diverse learning needs and preferences, educators and researchers are exploring the potential of holographic technology to provide a more engaging, effective, and accessible learning experience. This exploration is supported by the constructivist learning theory, which posits that learners construct knowledge most effectively through active engagement in the learning process.

Figure 1 presents a scene set within the confines of a science education space, where two pupils are deeply engaged with a state-of-the-art holographic apparatus that vividly renders the human anatomy into a palpable format. Captured in the frame is a young scholar, donned in a pristine white laboratory garment and protective ocular gear, who is immersed in an interactive exploration with a full-scale, tri-dimensional holographic emanation of the human physique. The hologram stands as a silent tutor by her side, its luminescence casting an ethereal azure glow that underscores the young investigator's earnest expression. In the periphery, her peer, similarly outfitted in a laboratory coat, lends his gaze to the unfolding spectacle, his curiosity ignited by the avant-garde pedagogical experience. The ambient glow from the displays punctuates the obscurity of the learning environment, each screen a portal into the vastness of scientific knowledge, displaying intricate biological schematics. This tableau is a testament to the vanguard of holographic innovation in pedagogy, bridging the chasm between the abstract intricacies of human biology and the tangible reality, thereby demystifying complex concepts for the academic enrichment of the nascent minds.

Given the promising capabilities of 3D holography and its potential impact on science education, this study seeks to investigate the adoption and integration of holographic technology in science classrooms. Specifically, the research aims to examine how the use of 3D holograms affects students' understanding of scientific concepts, their engagement with the material, and the overall learning experience. The central research question guiding this study is: ''How does the integration of 3D holograms into science education influence students' conceptual understanding, engagement, and learning outcomes?''

By addressing this question, the study aims to contribute to the body of knowledge on educational technology adoption and provide insights into the effectiveness of 3D holograms as an instructional tool in science education. Furthermore, this research seeks to inform educators, policymakers, and technology developers about the benefits and challenges of integrating holographic technology into educational curricula, ultimately aiming to enhance the quality and accessibility of science education for students of all backgrounds.

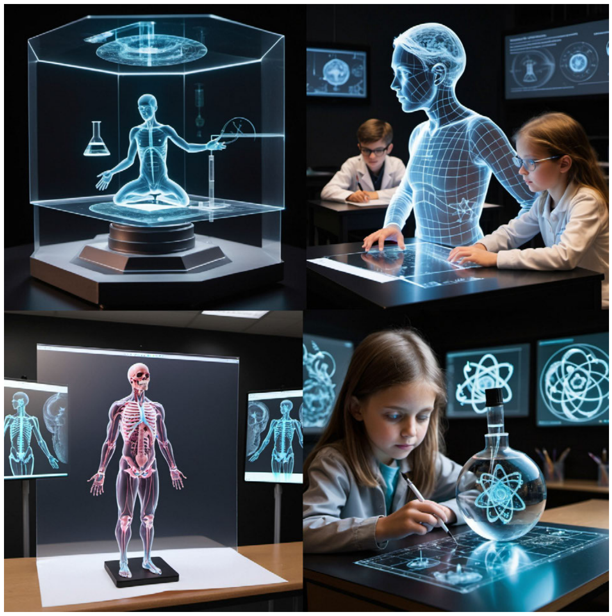

FIGURE 1. Teaching science using 3D holograms [9].

II. LITERATURE REVIEW

The integration of holographic technology in education has been an area of burgeoning interest over the past decade [7], [10], [11]. Early research focused on the technical feasibility of such integrations, with pioneers like [12] examining the foundational aspects of holographic projection and its potential applications in classroom settings. More recent studies have shifted towards empirical evaluations of these technologies in educational contexts, such as the work of [13], who demonstrated the positive impacts of holographic representations in teaching complex scientific concepts to high school students.

Visual learning, a cornerstone of educational psychology, has been revolutionized by the advent of three-dimensional (3D) visualization technologies. The meta-analysis conducted by [14] synthesized findings from multiple studies, concluding that 3D technologies generally enhance understanding and retention of visual-spatial information. Engagement, a critical factor in educational outcomes, has also been linked to the use of these technologies. For instance, [15] found that interactive 3D models significantly increased student engagement and motivation, particularly in STEM fields.

Further investigations into the efficacy of holographic technology in education have revealed nuanced insights into student cognition and learning processes. Notable studies by [16] and [17] delved into the cognitive load implications of interacting with holographic images, suggesting that while holograms can enhance engagement, they also require careful instructional design to avoid overloading the learner's working memory. On a similar note, [18] conducted a randomized controlled trial to compare traditional teaching methods with hologram-based instruction in anatomy classes, finding that students exposed to holographic images performed better in both immediate and delayed retention tests, thereby supporting the cognitive theory of multimedia learning proposed by [19].

The potential for holographic technology to foster collaborative learning environments has also been a subject of research. Al Mukhallafi, 2023 [20] implemented a series of holographically-enhanced lessons in a middle school setting and used observational data to highlight increased instances of peer-to-peer interaction and collaborative problem-solving. This finding echoes the principles outlined by social constructivist theorists, such as [21], who emphasized the importance of social interaction in the learning process. However, the literature still lacks a comprehensive understanding of how such interactions are affected by the novelty factor of holographic technology and whether the observed benefits are sustainable over time.

Despite the promise shown by 3D visualization technologies in educational settings, there remains a notable gap in the literature regarding long-term educational outcomes. While studies such as those by [22] have shown immediate improvements in engagement and comprehension, the sustainability of these outcomes over time is less clear. Moreover, there is a scarcity of research on the differential impacts of these technologies across diverse student populations, including those with varying learning preferences and abilities.

This study aims to fill these gaps by not only assessing the immediate educational benefits of 3D holographic technology but also examining the long-term retention of information and conceptual understanding. Furthermore, this research seeks to understand the inclusivity of holographic technology by evaluating its efficacy across a diverse cohort of students, providing insights into the equitable distribution of educational technology benefits. In this present study, two distinct analytical approaches were employed to assess the conceptual frameworks: Partial Least Squares Structural Equation Modeling (PLS-SEM) and Machine Learning (ML) algorithms. PLS-SEM facilitates the concurrent analysis of both measurement and structural models, a process underscored by Ringle et al. [23]. Barclay et al. [24] have recognized the significant insights gained from the simultaneous application of PLS-SEM. Additionally, this study incorporates ML techniques through the application of SPSS software [25] to explore the intricate interconnections among the variables within the research model. This exploration is furthered by the use of decision trees, Bayesian networks, and neural networks within the ML suite to forecast interactions amongst the model's attributes [26]. The evaluation of the constructed model, featuring predictive elements such as OneR, Logistic, LWL, J48, and BayesNet, was conducted using the Weka software platform.

Historically, much of the scholarly literature has focused on one-dimensional linear data analysis techniques [27], predominantly employing Structural Equation Modeling (SEM) to forecast interactions among elements. This traditional focus on linear associations has been a staple of prior research. However, Sim et al. [28] argue that these linear associations do not necessarily translate to predictive decision-making capabilities. To surmount the limitations inherent in SEM's unidimensional approach, several researchers [29], [30], [31] have advocated for the use of Artificial Neural Network (ANN) analysis as a subsequent analytical stage. In a differing perspective, Huang and Stokes [32] note that the majority of such applications tend to utilize a simple deep subtype ANN that includes only a singular hidden layer. Further research [33] has proposed the adoption of deep ANN or multi-layered ANN techniques as a means to refine the precision of non-linear models. In alignment with these recommendations, this present study utilizes a deep ANN within a novel SEM-ANN hybrid methodology to analyze the data.

III. THEORETICAL FRAMEWORK AND HYPOTHESIS DEVELOPMENT

The adoption of technology and the principles of the Diffusion of Innovation (DOI) theory critically examine key factors pivotal to both organizational and societal embracement of new technologies. The applicability of DOI posits a focus on the relative advantages of a technology when opportunities for adoption arise [34]. However, existing literature reveals a gap in understanding the role of organizational factors in the adoption of 3D holograms within organizations [35]. The impact of organizational elements and stakeholders on the incorporation of 3D holograms applications within educational settings remains an area lacking comprehensive insight. Furthermore, the interplay between variables defined by the Innovation Diffusion Theory and other macro-level factors critical to the adoption of innovative technologies has not been extensively investigated in prior research. Consequently, this study aims to explore hypotheses related to perceptions of 3D holograms application use among learners, the preparedness of educational institutions for 3D holograms integration, and the broader societal acceptance of such technologies. Through this investigation, the study seeks to shed light on the multifaceted dynamics influencing the adoption of 3D holograms in educational contexts, addressing the noted research gaps. This exploration is visually represented in Figure (2), providing a conceptual overview of the study's focus areas.

A. THE DIFFUSION OF INNOVATION THEORY (DOI THEORY)

The Diffusion of Innovation (DOI) theory offers a sophisticated lens through which the intricacies of adopting novel technologies in organizational settings are explored, distinguishing itself from frameworks like the Technology Acceptance Model (TAM) and the Unified Theory of Acceptance and Use of Technology (UTAUT) by emphasizing the situational factors dictating adoption choices. The theory probes into the integration of avant-garde technologies into societal infrastructures, pinpointing compatibility, observability, trialability, and relative advantage as pivotal elements steering technological assimilation at the institutional echelon [25]. While DOI contemplates a spectrum of situational factors, it notably accentuates the significance of specific technological attributes, particularly relative advantage [36], [37], [38]. Notwithstanding its thorough methodology, DOI faces critique for not sufficiently highlighting other critical aspects such as contextual or institutional influences. Addressing this gap, the current investigation incorporates the Technology Adoption Rate as a novel measure to capture such broad-scale influences.

Within the framework of DOI, Perceived Compatibility (PCO) is identified as a crucial factor, depicted as the extent to which individuals resonate with 3D holograms technologies based on their pre-existing convictions, encounters, and anticipations for future utility. This inquiry refines the notion of Perceived Compatibility to the perspective of organizations and consumers regarding the capability of 3D holograms to bolster their adoption processes and widen the scope of future informational system utilities [39], [40]. Observability (BSR) is the extent to which the benefits and functionalities of 3D holographic technology are noticeable and recognizable within the educational environment. This visibility suggests that 3D holograms can facilitate collaborative learning and discourse about new scientific concepts, as learners and educators engage in the shared exploration and assessment of this innovative educational tool [40]. On the flip side, Trialability (TRI) is envisaged as the facility with which individuals can explore new technologies [40]. Specifically, Trialability denotes the user-friendliness with which 3D holograms technologies can be employed and adapted to innovative scenarios [41], [42], [43]. Moreover, Relative Advantage (RA) evaluates the perceived merit of an innovation against traditional alternatives [40]. In this context, Relative Advantage is interpreted as the extent to which students perceive 3D holograms as a superior alternative to conventional educational methods, with the potential to enhance their future outcomes. Given these frameworks, the research is set to test hypotheses that scrutinize the adoption of 3D holograms, concentrating on the impact of Perceived Compatibility, Trialability, and Relative Advantage on the deployment of 3D holograms technologies in educational settings.

H1: PCO would predict the EDB.
H2: PCO would predict the TEP.
H3: BSR would predict the EDB.
H4: BSR would predict the TEP.
H5: TRI would predict the EDB.
H6: TRI would predict the TEP.
H7: RAD would predict the EDB.
H8: RAD would predict the TEP.

B. EASE OF DOING BUSINESS (EDB)

Ease of Doing Business (EDB) emerges as a pivotal factor determining a population's readiness to embrace innovative technologies. Serving as a critical indicator, EDB illuminates the conducive environment necessary for the advancement of contemporary technological solutions. It represents a unique measure that encapsulates the capacity of organizations at a macroeconomic scale to navigate significant business challenges effectively. The propensity of businesses to foster technological integration plays a significant role in driving business expansion. Furthermore, the perception that conducting business is straightforward significantly heightens consumer willingness to adopt novel technologies [44], [45]. Based on this foundational premise, it is posited that:

H9: EDB would predict the BIU.

C. TECHNOLOGY EXPORTS (TEP)

Technology exports encompass a broad spectrum of products and services that emerge from intensive research and significant investment, aimed at innovating in response to societal needs. This category includes an array of offerings from advanced instrumentation and electrical devices to support services and creative solutions [46]. In recent times, there has been a noticeable trend towards the export of high-technology products, which originate in affluent economies and are then distributed and marketed to nations with lower economic status. Consequently, the recipient countries are typically those less familiar with the rapid proliferation of technology and its integration into societal frameworks [46], [47]. Thus, the factor of technology export represents an external influence that significantly impacts the measurement of technology adoption rates. Based on these observations, the following hypothesis is proposed:

H10: TEP would predict the BIU.

IV. RESEARCH METHODOLOGY

A. DATA COLLECTION

Students from various educational institutions in the UAE participated in online surveys conducted between January 1, 2024, and February 29, 2024. The study's objective and a link to the survey were distributed via email to the selected student body. To enhance participation rates, we also posted the survey on relevant social media and messaging platforms, including Facebook, WhatsApp, and ClassDojo groups affiliated with the schools. We ensured that potential respondents were aware that their involvement in the study was entirely voluntary. The research team randomly distributed 900 questionnaires, achieving a response rate of 92%; 828 of these questionnaires were fully completed, while 72 questionnaires were discarded due to incomplete responses, resulting in a final tally of 828 valid questionnaires for analysis. According to the standards set by Krejcie & Morgan [48], the number of usable responses fell within the acceptable range for the expected sample size (calculated for 306 respondents out of a target population of 1500), despite the actual sample size of 828 exceeding the minimum requirements by a significant margin. This discrepancy underscores the robustness of the sample size for the study. Consequently, structural equation modeling [49] was deemed an appropriate method for sample size consideration and was utilized to validate the study's hypotheses. It's noteworthy that the development of these hypotheses was built upon prior research on the evolution

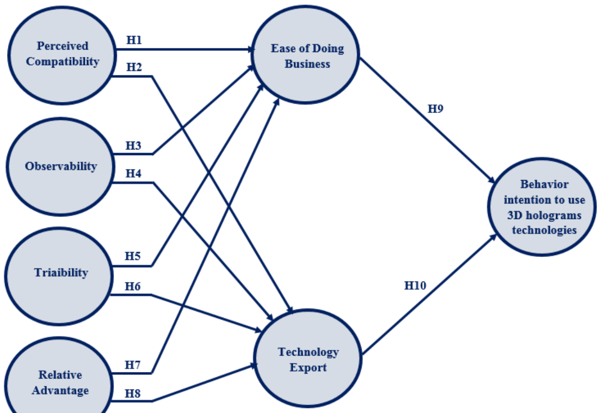

FIGURE 2. Research model.

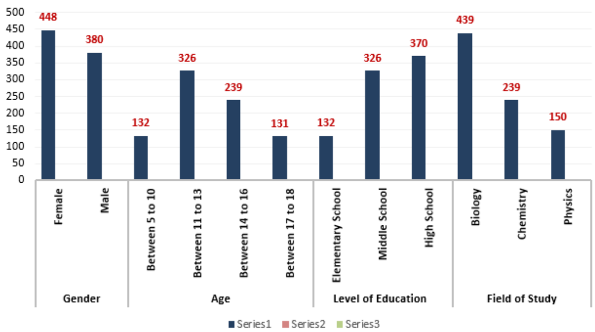

FIGURE 3. Demographic data of the respondents (n = 828).

of 3D holographic technology. The research team employed structural equation modeling (SEM) using SmartPLS Version 3.2.7 to analyze the measurement model. This approach facilitated the execution of advanced analytical techniques to interpret the data effectively.

B. PERSONAL/DEMOGRAPHIC INFORMATION

Figure 3 presents an analysis of the demographic and individual characteristics of the study population. The gender distribution within the cohort of learners indicates a slight female majority, with 54% female and 46% male participants. Regarding the age distribution, 16% of respondents fall within the 5-10 years age bracket, with the remainder surpassing this age range. The data delineates a predominance of responses from students at the high school level, surpassing those from middle and elementary school levels. The age category of 11-13 years, generally aligning with middle school attendance, is the most substantially represented group, indicating a robust participation rate from this demographic. In the context of academic disciplines, Biology emerges as the most frequently reported field of study, suggesting a potential alignment or interest in 3D holography within science education amongst participants in this subject area.

The sampling strategy, potentially aligned with Salloum & Shaalan's [50] recommendation, could employ a purposive sampling technique in scenarios where participant willingness is a determining factor. This specific sample comprised individuals from various academic institutions, encompassing a diverse range of ages and educational levels. Additionally, the demographic data were processed and analyzed using IBM SPSS Statistics version 23, facilitating a thorough statistical examination of the demographic variables in question.

C. STUDY INSTRUMENT

In this study, a questionnaire was utilized as a key instrument for hypothesis validation. Seven constructs were meticulously selected to serve as the foundation for reliable measurement, leading to the inclusion of 17 new items within the questionnaire. These constructs are detailed in Table 1, designed to enhance the utility of the study's framework and offer evidence from existing research that bolsters the current theoretical structure. To ensure relevance and accuracy, the research team adapted the survey questions from those used in previous studies, tailoring them to fit the specific context and objectives of the current investigation.

D. A PILOT STUDY OF THE QUESTIONNAIRE

To ascertain the reliability of the questionnaire items, a pilot study was conducted, drawing on a random selection of data based on the premise that 90 students, representing 10% of the total sample size, were selected from the target demographic for this preliminary investigation. This approach was deliberately chosen to reflect the study's methodological requirements and to ensure a manageable yet representative sample size of 900 students for the comprehensive evaluation. The internal consistency and reliability of the survey questions were rigorously assessed using the Cronbach's alpha coefficient through IBM SPSS Statistics version 23. This statistical method is instrumental in verifying the validity of the measurement items, ensuring that the survey produces reliable outcomes. In the context of social science research, a Cronbach's alpha coefficient of 0.70 is considered satisfactory [53], indicating an acceptable level of internal consistency among the items within each scale. The results from this pilot study, particularly the Cronbach's alpha scores, are meticulously documented in Table 2, spanning across five distinct measurement scales. This structured evaluation not only underscores the reliability of the survey instrument but also sets a foundation for the subsequent phases of the research, ensuring that the data collected are both reliable and reflective of the constructs being investigated.

E. COMMON METHOD BIAS (CMB)

To address potential concerns of Common Method Bias (CMB) within the dataset, this study implemented Harman's single-factor test, incorporating seven distinct variables to assess the integrity of the collected data [47]. Subsequent to this initial analysis, the data from ten factors were amalgamated into a singular comprehensive factor for further examination. The results of this refined analysis revealed that the newly amalgamated factor contributed to 29.36% of the total variance observed, a figure significantly below the established threshold of 50% [47]. This outcome indicates that

TABLE 1. Measurement items.

Constructs	Items	Instrument	Sources
Behavior Intention to Use 3D holographic technology	BIU1	Educational institutions are prepared to incorporate 3D holographic technology within their teaching syllabi.	[51]
	BIU2	Educational establishments are poised to implement 3D holographic technology for instructional system enhancements.	
Observability	BSR1	3D holographic technology is regarded by other institutions as an efficacious educational tool.	[41], [52]
	BSR2	Educators perceive 3D holographic technology as an advantageous method for fostering an educational environment.	
	BSR3	Adjacent countries recognize 3D holographic technology as a forefront innovation.	
Perceived Compability	COM1	The existing teaching infrastructure is compatible with the integration of 3D holographic technology.	[39]
	COM2	Teaching methods and pedagogical strategies align with the use of 3D holographic technology in scientific education.	
	COM3	3D holographic technology presents a contrast to the existing educational system.	
Trialability	TRI1	Future possibilities are enabled through the application of 3D holographic technology.	[41], [52]
	TRI2	Upcoming educational projects can be appraised through the use of 3D holographic technology.	
	TRI3	3D holographic technology is transformative, offering enriched content opportunities in science classrooms.	
Relative Advantage	RAD1	3D holographic technology boasts additional educational functionalities compared to previous technologies.	[41], [52]
	RAD2	3D holographic technology offers significant time savings over traditional methods.	
	RAD3	The implementation of 3D holographic technology in education challenges current teaching norms.	
Ease of Doing Business	EDB1	The adoption of 3D holographic technology at the organizational level is notably high in scientific education.	[44]
	EDB2	3D holographic technology enjoys widespread recognition and application in modern society.	
	EDB3	Both educational experts and students show a preference for 3D holographic technology.	
Technology Export	TEP1	Several nations have advanced 3D holographic technology to meet societal demands.	[46]
	TEP2	There is a pronounced demand within institutions for the innovative features offered by 3D holographic technology.	
	TEP3	The requirements of educators are not fully met by 3D holographic technology.	

the dataset is largely free from the influences of CMB, thus affirming the reliability of the collected data and mitigating concerns related to the presence of common method bias in this research.

V. FINDINGS AND DISCUSSION

A. DATA ANALYSIS

This study adopts the Weka software (version 3.8.3) to analyze its research models using a range of classifiers such as OneR, BayesNet, J48, and Logistic, diverging from prior

TABLE 2. Cronbach's alpha values for the pilot study (Cronbach's Alpha ≥ 0.70).

Constructs	Cronbach's Alpha.
BIU	0.840
BSR	0.887
PCO	0.783
EDB	0.822
RAD	0.853
TEP	0.781
TRI	0.799

research that predominantly utilized Machine Learning (ML) algorithms through different methodologies like Neural Networks and Bayesian networks [25]. Unlike other studies that primarily conducted a single-stage Structural Equation Modeling (SEM) analysis, this investigation employs a novel hybrid SEM-Artificial Neural Network (ANN) approach for hypothesis validation. The hybrid model integrates two distinct phases: an initial PLS-SEM [23] phase to assess the research model and a subsequent deep ANN phase to further validate the findings.

Given the nascent stage of the conceptual framework with scant prior research for guidance [54], PLS-SEM serves as an apt choice for initially applying general Information Systems (IS) principles and conducting both structural and measurement model analyses [55]. The study also incorporates Importance Performance Map Analysis (IPMA) via SmartPLS to gauge the significance and impact of various factors within the research model, enhancing the traditional PLS-SEM methodology. This is followed by an examination through deep ANN to confirm the PLS-SEM assessment, effectively addressing the model's non-linear and complex relationships between variables.

Deep ANN is recognized for its capacity to intricately analyze the efficacy of both predictor and outcome variables within the research model. ANN methodologies typically leverage three fundamental components: learning rules, transfer functions, and network architecture [55], which further include radial basis networks, recurrent networks, and multilayer perceptron (MLP) networks. Among these, the MLP network is particularly valued for its ability to connect input and output layers via hidden nodes [28], with predictors in the input layer transmitting information to the hidden layers and synaptic weights facilitating data transfer. The activation function selected determines each hidden layer's output, with the sigmoid function being a commonly employed activation mechanism. Thus, to scrutinize the theoretical framework of this study, an MLP neural network configuration is utilized, showcasing the study's comprehensive and innovative analytical approach.

B. CONVERGENT VALIDITY

In the domain of measurement model evaluation, [56] the nuanced concept of construct validity encompasses both discriminant and convergent validity, alongside construct reliability, which includes metrics such as Cronbach's alpha (CA) and composite reliability (CR). As per the data presented in Table 3, Cronbach's alpha values, serving as indicators of construct reliability, span from 0.796 to 0.881. These figures comfortably exceed the established threshold of 0.7 [57], thereby affirming the constructs' reliability within this study. Further scrutiny of Table 3 reveals that the scores for Composite Reliability (CR) range between 0.808 and 0.867, surpassing the requisite benchmark [51] and signifying a robust Construct Reliability. The assessment of Mean-Variance Extracted (AVE) alongside factor loadings is imperative for appraising Convergent Validity [56]. Excluding previously noted exceptions, the factor loading values documented in Table 3 exceed the benchmark value of 0.7. Moreover, the AVE values, delineated in the same table, range from 0.542 to 0.649, surpassing the minimum criterion of '0.5' and thus, by the logic previously established, likely fulfilling the criteria for convergent validity. This comprehensive evaluation underscores the study's adherence to rigorous standards for both construct validity and reliability, paving the way for a robust and credible assessment of the measurement model. The findings collectively affirm that the constructs under investigation are reliably measured and validly represented within the study's framework, thereby establishing a firm foundation for the subsequent analyses and interpretations.

C. DISCRIMINANT VALIDITY

The evaluation of discriminant validity within this research necessitated a reassessment using two pivotal criteria: the Heterotrait-Monotrait (HTMT) ratio and the Fornell-Larcker criterion, to ensure rigorous validation of the measurement model [56]. The application of the Fornell-Larcker criterion, which compares the square roots of the Average Variance Extracted (AVE) of each construct with its correlations with other constructs, demonstrated in Table 4, unequivocally supports the discriminant validity. This is evidenced by each construct's AVE square root surpassing its correlations with other constructs, thereby meeting the specified criteria [58].

Furthermore, the HTMT ratio outcomes, depicted in Table 5, reinforce the validity assessment by showing that all construct ratios fall below the threshold of '0.85' [59], satisfying the recommended limit and affirming discriminant validity. The employment of the HTMT ratio as a novel metric thus substantiates the discriminant validity of the constructs within this study. The synthesis of these findings conclusively indicates that the measurement model's validity and reliability stand uncontested, facilitating the use of the collected data for subsequent structural model evaluation. This comprehensive validation process not only attests to the robustness of the measurement model but also sets a solid foundation for the reliability of the study's overall findings, ensuring that the structural model's assessment is grounded on a validated and reliable measurement framework.

TABLE 3. Measuring the construct reliability and convergent validity.

Constructs	Items	Factor Loading	CA	CR	AVE
BIU	BIU1	0.887	0.835	0.867	0.629
	BIU2	0.754			
	BIU3	0.804			
BSR	BSR1	0.783	0.826	0.865	0.637
	BSR2	0.881			
	BSR3	0.820			
PCO	COM1	0.740	0.881	0.852	0.614
	COM2	0.787			
	COM3	0.754			
EDB	EDB1	0.887	0.796	0.808	0.560
	EDB2	0.885			
	EDB3	0.773			
RAD	RAD1	0.754	0.800	0.819	0.542
	RAD2	0.733			
	RAD3	0.843			
TEP	TEP1	0.707	0.819	0.826	0.649
	TEP2	0.727			
	TEP3	0.884			
TRI	TRI1	0.834	0.805	0.811	0.632
	TRI2	0.888			
	TRI3	0.753			

TABLE 4. Fornell-larcker scale.

	BIU	BSR	PCO	EDB	RAD	TEP	TRI
BIU	**0.854**						
BSR	0.687	**0.837**					
PCO	0.440	0.249	**0.769**				
EDB	0.287	0.380	0.391	**0.868**			
RAD	0.440	0.678	0.398	0.190	**0.806**		
TEP	0.185	0.314	0.574	0.578	0.687	**0.855**	
TRI	0.283	0.373	0.391	0.336	0.512	0.602	**0.821**

TABLE 5. Heterotrait-monotrait ratio (HTMT).

	BIU	BSR	PCO	EDB	RAD	TEP	TRI
BIU							
BSR	0.750						
PCO	0.391	0.336					
EDB	0.513	0.924	0.330				
RAD	0.391	0.331	0.144	0.075			
TEP	0.294	0.446	0.328	0.124	0.779		
TRI	0.385	0.373	0.406	0.706	0.307	0.385	

D. HYPOTHESES TESTING USING PLS-SEM

The analysis of the research model involved an examination of the variance explained (R^2 value) for each pathway and the statistical significance of each relationship. Illustrations in Figure 4 and detailed metrics in Table 7 elucidate the normalized coefficients of the pathways and their respective significances. A holistic assessment of the proposed nine hypotheses was executed through the application of Structural Equation Modeling (SEM) [60], which underscored the constructs' moderate prognostic efficacy [61].

Empirical analysis validated hypotheses H1 through H10, with R^2 values indicating the predictive strength for variables such as BIU, EDB, and TEP lying in the range of 0.467 to 0.668, as recorded in Table 6.

TABLE 6. R^2 of the endogenous latent variables.

Constructs	R^2	Results
EDB	0.654	Moderate
BIU	0.476	Moderate
TEP	0.668	Moderate

Further dissection of the results highlighted the pivotal influence of four factors— PCO, BSR, TRI, and RAD—on both EDB and TEP. Notably, positive impacts were observed from PCO, BSR, TRI, and RAD on EDB, with coefficients $\beta = 0.663$ ($P < 0.05$), $\beta = 0.341$ ($P < 0.01$), $\beta = 0.543$ ($P < 0.001$), and $\beta = 0.616$ ($P < 0.05$) respectively, corroborating hypotheses H1, H3, H5, and H7. Concurrently, significant influences of PCO, BSR, TRI, and RAD on TEP were substantiated with coefficients $\beta = 0.751$ ($P < 0.05$), $\beta = 0.493$ ($P < 0.001$), $\beta = 0.625$ ($P < 0.001$), and $\beta = 0.782$ ($P < 0.001$) respectively, affirming hypotheses H2, H4, H6, and H8.

Moreover, the interplay between EDB and TEP was found to significantly propel the Behavioral Intention towards the Usage of 3D holograms in science education (BIU), with EDB and TEP exhibiting notable positive effects on BIU, $\beta = 0.818$ ($P < 0.001$) and $\beta = 0.264$ ($P < 0.05$) respectively, lending support to hypotheses H9 and H10.

In summation, the empirical findings of this study delineate the critical roles played by the factors of PCO, BSR, TRI, and RAD in influencing both EDB and TEP, which subsequently exert a significant impact on the inclination to adopt 3D holograms within the sphere of science education.

E. HYPOTHESES TESTING USING CLASSICAL ML

The results of this study lend robust support to the first, third, fifth, and seventh hypotheses, underscoring the effectiveness of various Machine Learning (ML) techniques in analyzing and validating the hypotheses. Specifically, the research employed advanced ML algorithms such as Bayesian networks, Neural Networks, and decision trees to scrutinize the proposed conceptual framework and forecast the dynamics within [25], [62]. The predictive accuracy of these models was rigorously evaluated using Weka software (version 3.8.3), which utilized sophisticated classifiers including J48, OneR, and BayesNet [26], [63]. Among the classifiers, J48 emerged as the standout performer, particularly in assessing the variable Ease of Doing Business (EDB) as depicted in Figure 5. Its superior capability was highlighted through an impressive 82.38% accuracy rate achieved during a ten-fold cross-validation process, marking it as the most reliable predictive tool among those tested. Furthermore, J48's excellence was consistently demonstrated across various performance metrics, achieving an 80.37% rate in precision, an 81.16% rate in recall, and an 80.32% F-Measure. These figures not only attest to the classifier's robustness in handling the data but also to its comprehensive proficiency in accurately predicting and validating the hypotheses, thereby

TABLE 7. Hypotheses-testing of the research model (significant at p** < = 0.01, p* < 0.05).

H	Relationship	Path	*t*-value	*p*-value	Direction	Decision
H1	PCO -> EDB	0.663	6.523	0.017	Positive	Supported *
H2	PCO -> TEP	0.751	7.309	0.011	Positive	Supported *
H3	BSR -> EDB	0.341	13.452	0.001	Positive	Supported **
H4	BSR -> TEP	0.493	16.532	0.000	Positive	Supported **
H5	TRI -> EDB	0.543	15.926	0.000	Positive	Supported **
H6	TRI -> TEP	0.625	17.155	0.000	Positive	Supported **
H7	RAD -> EDB	0.616	3.401	0.040	Positive	Supported *
H8	RAD -> TEP	0.782	19.992	0.000	Positive	Supported **
H9	EDB -> BIU	0.818	15.513	0.000	Positive	Supported **
H10	TEP -> BIU	0.264	5.011	0.043	Positive	Supported *

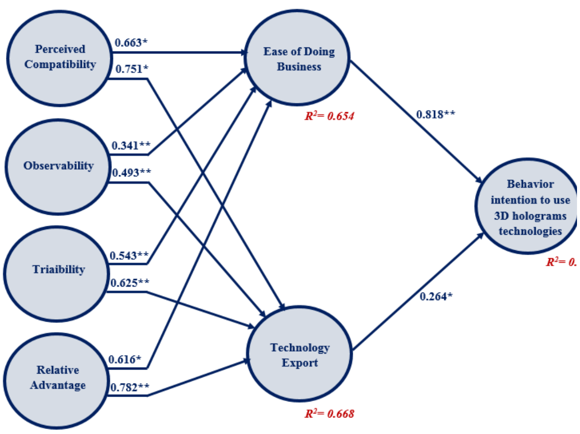

FIGURE 4. Path coefficient of the model (significant at p** < = 0.01, p* < 0.05).

contributing valuable insights into the research's underlying theoretical framework.

The outcomes of this investigation also align with the second, fourth, and sixth hypotheses presented within the study, further validating the comprehensive scope and robust methodology of the research. Notably, the J48 algorithm distinguished itself once again by demonstrating exceptional predictive prowess, this time in relation to the variable Technology Export Performance (TEP). Its accuracy in forecasting TEP reached an impressive 88.54%, as detailed in Figure 6. This high level of precision underscores the J48 algorithm's significant capability in navigating the complexity of the dataset and extracting meaningful predictions that resonate with the established hypotheses. Such accuracy not

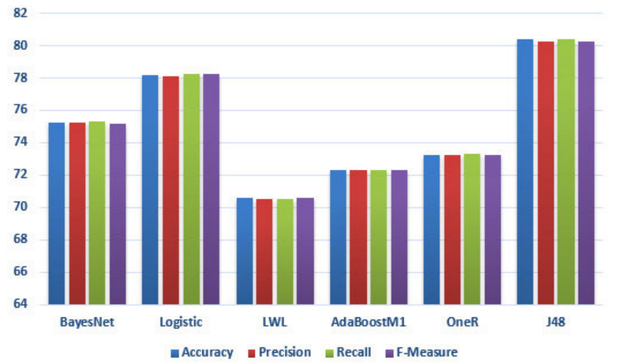

FIGURE 5. Impact of PCO, BSR, TRI, & RAD on EDB.

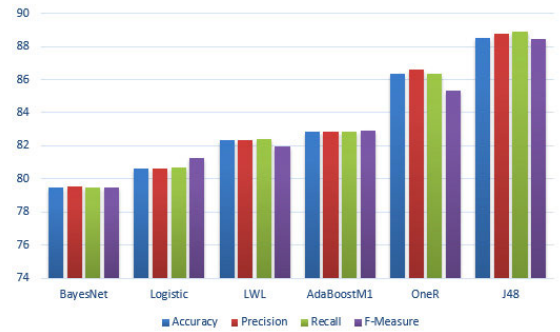

FIGURE 6. Impact of PCO, BSR, TRI, & RAD on TEP.

only reflects the algorithm's efficacy in handling specific variables but also illustrates its broader applicability and reliability within the context of the study's analytical framework. By consistently providing high-performance outcomes across multiple hypotheses and variables, the J48 algorithm substantiates its role as a critical tool in the predictive analysis, offering valuable insights that contribute to the overarching understanding of the research questions at hand.

The J48 algorithm demonstrated superior efficacy in forecasting the variable Innovation (IN) based on the features of Ease of Doing Business (ED) and Technology Export (TE). It achieved a remarkable accuracy rate of 87.71% in these predictions, as detailed in Figure 7. This high level of precision not only underlines the algorithm's robust predictive capabilities but also confirms the validity of the ninth and tenth hypotheses posited in this study. The success of J48 in accurately estimating the IN variable showcases the potential of machine learning algorithms to provide insightful analyses that enhance our understanding of complex relationships within research models.

F. HYPOTHESES TESTING USING DEEP ANN

In this study, the Artificial Neural Network (ANN) assessment was meticulously conducted using SPSS, integrating critical predictors identified through Partial Least Squares Structural Equation Modeling (PLS-SEM). These included 'BSR, PCO, EDB, RAD, TEP, and TRI' as key variables in the ANN analysis. The architecture of the deep ANN model was delineated across Figures 8, 9, and 10, showcasing a structure with one output neuron and multiple input

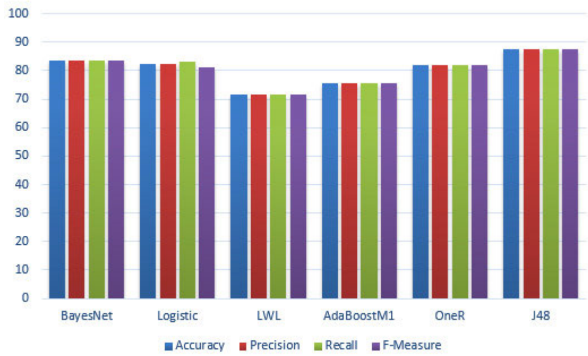

FIGURE 7. Impact of EDB & TEP on BIU.

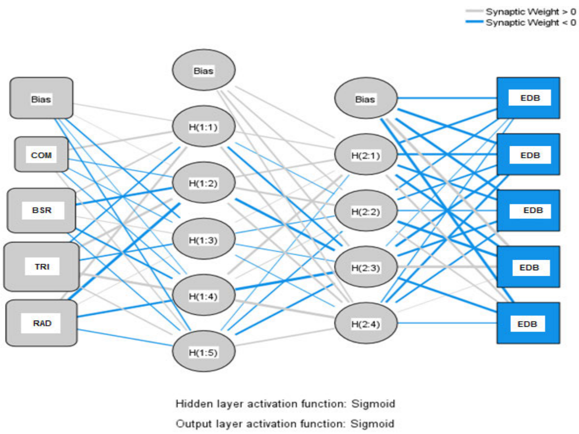

FIGURE 8. ANN model.

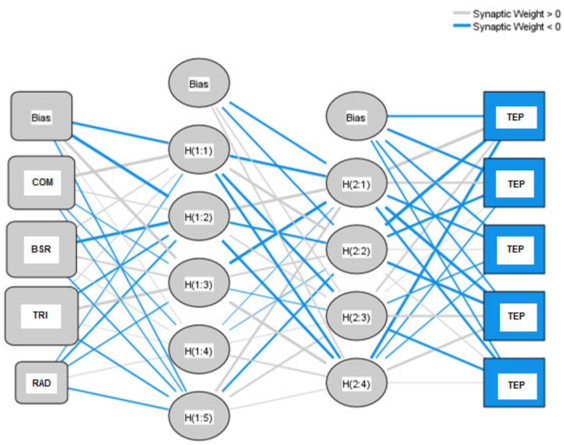

FIGURE 9. ANN model.

neurons [64], including BSR, PCO, EDB, RAD, TEP, and TRI, with BIU serving as the model's output neuron.

To construct a sophisticated model, a two-layer hidden architecture was utilized, optimizing the deep learning process for the output neuron [65]. The model incorporated hidden neurons and utilized the sigmoid activation function to process outputs. To ensure the reliability and generalizability of the model, input and output variables were standardized to fall within the range of 0 to 1. Furthermore, to mitigate the risk of overfitting within the ANN models, a ten-fold cross-validation approach was adopted, dividing the dataset

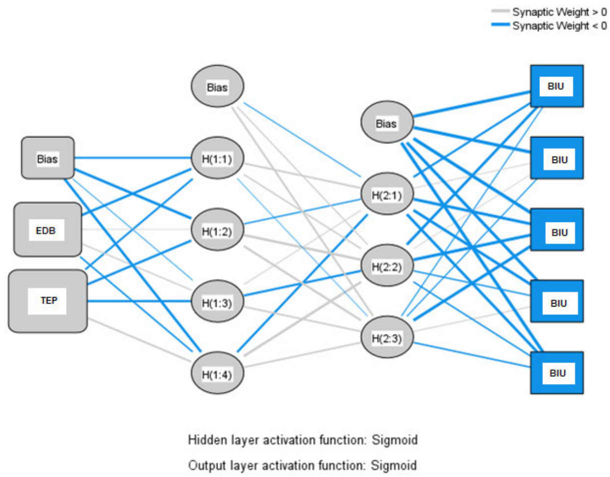

FIGURE 10. ANN model.

into a 70:30 split between training and testing phases [66], respectively.

The performance of the Neural Network models was further refined by calculating the Root Mean Square Error (RMSE), providing a quantitative measure of the model's accuracy. The deep ANN model demonstrated commendable performance, recording an RMSE of 0.1485 for the training set and 0.1424 for the testing set. Such results indicate a high level of precision in the model's predictive capability, as further evidenced by the low standard deviation in RMSE scores—0.0031 for the training data and 0.0063 for the testing data. These findings underscore the deep ANN model's efficacy in accurately capturing and predicting complex relationships within the dataset, contributing valuable insights into the predictive dynamics of the studied variables.

G. SENSITIVITY ANALYSIS

The analysis highlighted in Table 8 reveals that the intention to adopt 3D holography (BIU) emerges as the paramount predictor influencing user behavior. Following closely, TEP and EDB stand out as the second and third most significant predictors, respectively, in shaping the intention to utilize 3D holography (BIU). The process to ascertain the relative importance of each predictor involves normalizing their mean values against the percentage of the highest mean, providing a clear comparison of their impact. The efficacy and precision of the deep Artificial Neural Network (ANN) analysis were rigorously evaluated using a goodness-of-fit metric, analogous to the R-squared value utilized in Partial Least Squares Structural Equation Modeling (PLS-SEM) [67]. The comparative analysis of the results indicates that the deep ANN model exhibits superior predictive capabilities ($R^2 = 96.2\%$) when juxtaposed with the outcomes from PLS-SEM ($R^2 = 47.6\%$) and traditional Machine Learning (ML) algorithms ($R^2 = 87.7\%$). This finding underscores the advanced performance of deep ANN in modeling the endogenous constructs under study. The superior predictive power of deep ANN, especially in delineating complex, non-linear relationships between constructs, highlights its effectiveness

TABLE 8. Independent variable importance.

	Importance	Normalized Importance
BSR	.186	53.7%
PCO	.245	62.1%
EDB	.349	77.3%
RAD	.293	69.8%
TEP	0.637	100.0%
TRI	0.328	74.2%

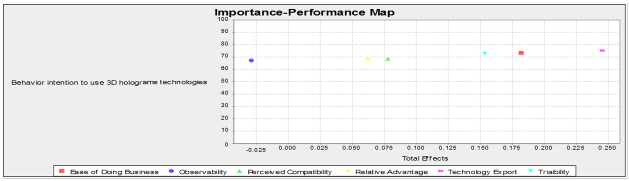

FIGURE 11. IPMA Output.

over both PLS-SEM and conventional ML algorithms. This distinction is particularly relevant in the context of behavioral studies where the dynamics of User Intention and Technology Adoption are influenced by a myriad of interrelated factors. Deep learning's capacity to accurately capture and analyze these intricate relationships offers a significant advantage, providing deeper insights into the factors driving the adoption of innovative technologies like 3D holography.

H. IMPORTANCE-PERFORMANCE MAP ANALYSIS

The application of Importance-Performance Matrix Analysis (IPMA) in conjunction with Partial Least Squares Structural Equation Modeling (PLS-SEM) significantly enhances the interpretative depth of the latter's testing, marking a notable advancement in the field [68]. In this study, the focal point of employing IPMA is the behavioral intention variable. IPMA diverges from traditional analysis by simultaneously evaluating performance metrics and the significance of path coefficients. This dual analysis offers a comprehensive view of how target factors, such as behavioral intentions, are influenced by various determinants and how these factors fare in terms of performance, as reflected through the average scores of latent constructs.

IPMA's utility is exemplified in Figure 11, which maps out the importance and performance metrics of several key variables: BSR, PCO, EDB, RAD, TEP, and TRI. According to the findings presented in Figure 11, TEP emerges as the variable with the highest importance and performance ratings, closely followed by EDB. On the other end of the spectrum, TRI is noted for having the lowest performance score, despite securing the third position in terms of importance. Conversely, BSR received the lowest score in terms of its importance measure, delineating a nuanced landscape of factors contributing to behavioral intentions in the context of this research.

VI. DISCUSSION

The central objective of this investigation was to explore the utilization of 3D holography within academic spheres, with a particular focus on its application in science teaching. This exploration was steered by the identification of two pivotal elements that significantly guide the adoption process of such technology in educational realms. The study illuminated that the ease with which educational institutions can integrate new technologies and their capacity to disseminate these technologies play a crucial role in the uptake of 3D holographic applications. The framework of diffusion theory offers a lens through which several determinants of adoption are viewed, delineating the extent of their influence on the embrace of 3D holography.

Through rigorous analysis, the research identified that the operational fluidity of educational entities and the dissemination efficacy of new technologies are instrumental in the adoption process. To test the proposed hypotheses, the study harnessed a composite methodological approach, integrating PLS-SEM with Machine Learning strategies and advanced neural network algorithms. This multifaceted approach revealed that deep learning neural networks substantially enhance the predictive accuracy for technology adoption. The analysis unearthed a profound synergy between operational fluidity and technological dissemination, with the findings suggesting that perceptions of 3D Holograms are shaped by both human-centric and technical factors. The receptiveness to 3D Holograms is seen to escalate in environments where there is a seamless operational approach and an effective technology transfer strategy in place.

Leveraging the EDB metric offers insights into the optimal environments conducive to fostering innovation. Contrary to previous studies suggesting a direct, significant impact of EDB on technology adoption, recent findings present a nuanced view. This metric underscores a heightened propensity among individuals and organizations towards embracing new technologies. Through the lens of EDB, the capability of entities to navigate pivotal business challenges is showcased, underlining a correlation between technological readiness and business success. The premise that streamlined business operations facilitate quicker technological adoption is supported by this analysis.

Furthermore, contemporary examinations into the dynamics of TEP have shifted focus towards the intricate process involving the creation and dissemination of technologically advanced products and services. This encompasses a broad spectrum from electronic gadgets to comprehensive tech solutions and support, all of which demand considerable investment in terms of time and resources. The relationship between these elements and the adoption of 3Dholography, especially in the context of TEP, emerges as critically influential. This insight points towards the substantial role both product development and service provision play in the broader adoption of 3D holography technologies.

The statistical analysis conducted as part of this study has illuminated key relationships among the variables outlined in the conceptual framework, offering critical insights towards achieving the research objectives. Notably, the analysis identified significant correlations among BSR, PCO, EDB, & RAD, and the EDB. One of the primary findings is the pronounced connection between the variables of BSR, PCO, EDB, & RAD, and the TEP. This relationship suggests that when technology aligns with governmental needs without imposing undue burdens, its adoption is naturally facilitated. Literature [69] supports this by highlighting the link between the awareness of a technology's relative advantages—such as accessibility, user convenience, service quality, network reliability benefits, and simplicity—and its adoption rates. The perceived value and the innovation's advantage over existing solutions are critically tied [70], underscoring the importance of user perception in the adoption process. The theory of Innovation Diffusion posits that an innovation's spread is accelerated by its perceived benefits over current practices.

Furthermore, compatibility has emerged as a pivotal determinant in the adoption of technology [71], [72], with a notably strong correlation with the adoption of 3D holography. Studies [73] suggest that innovations that do not align well with existing systems or practices are less likely to be adopted unless a significant effort is made to overcome such barriers and capitalize on new opportunities. Thus, compatibility not only serves as a crucial predictor of adoption rates at the governmental level [74], [75] but also functions as an early indicator of an innovation's potential for widespread acceptance, emphasizing its critical role in forecasting adoption success.

A. THEORETICAL AND PRACTICAL IMPLICATIONS

This study represents a novel contribution to information systems (IS) research, primarily because it integrates ML algorithms to predict aspects of 3D Holograms application, utilizing a hybridized approach. The methodology, underpinned by a rigorous conceptual framework, leverages both Partial Least Squares Structural Equation Modeling (PLS-SEM) and ML algorithms to validate the proposed research model. According to existing literature [25], PLS-SEM is adept at predicting outcomes and assessing the integrity of conceptual models. In tandem, Arpaci [54] has demonstrated ML's capability to forecast outcomes based on a set of predictors. What sets this research apart is its synthesis of various ML techniques, such as decision trees, Bayesian networks, and Neural Networks, with the J48 decision tree algorithm emerging as the most efficacious, particularly in categorizing data into discrete classes based on relevant predictors [25]. Moreover, the study employed a non-parametric approach to ascertain the significance of model coefficients using PLS-SEM, while the Artificial Neural Network (ANN) models showcased a superior ability to predict, attributed to their deep architecture that adeptly captures non-linear relationships between variables.

In the realm of user adoption, factors such as the simplicity of interaction and the technological transferability significantly influence user confidence and willingness to engage. These elements have concrete implications for delivering solutions within educational settings, enhancing the implementation of 3D holographic applications. The study found that compatibility positively correlates with the intention to utilize 3D holography in science education. Elevating the adoption likelihood could be achieved if application developers are encouraged to integrate more features that enhance compatibility. Therefore, developers and coders are urged to consider infusing additional interactive tools and features that extend beyond the standard offerings of educational institutions. Concurrently, the interplay between the ease of training and the perceived advantages has shifted perceptions of educational systems, paving the way for more progressive and accessible educational infrastructures. Establishing a transparent framework that promotes the adoption process, through widespread dissemination of information on public platforms and targeted marketing initiatives, could lay the groundwork for a future-oriented, innovation-rich learning ecosystem. These technologies, when applied as educational tools, pave the way for a forward-thinking pedagogical approach.

B. MANAGERIAL IMPLICATIONS

The advent of 3D holography marks a revolutionary leap in educational methodologies, poised to metamorphose conventional pedagogical landscapes into realms of heightened interaction and immersive learning experiences. The insights gleaned from this research underscore the managerial benefits that could accrue to the educational sector through the strategic implementation of innovative 3D holographic technologies. The findings illuminate the quintessential role that innovation and advancement play in the evolution of educational paradigms. Leadership within academic institutions is thus encouraged to champion the adoption of 3D holography, endorsing its potential to enrich the learning experience.

The implications of this study extend to the administrative strategies that can facilitate a seamless integration of 3D holography within educational frameworks. The research highlights the necessity for management teams to anticipate and navigate the complexities and potential challenges that accompany the introduction of such sophisticated technologies. Issues such as the ergonomic implications of prolonged interaction with holographic content, along with safeguarding measures, are critical considerations that can influence the rate and success of technology adoption.

Furthermore, the results advocate for a concerted effort from developers and educational leaders to address and mitigate any adverse effects that might stem from the use of 3D holography, such as physical discomfort or safety concerns. To amplify the adoption and effective utilization of 3D holography, application developers and educational technologists are advised to refine and enhance the user interface and experience. This includes the design of intuitive controls, ergonomic viewing platforms, and the implementation of safeguards that prioritize user comfort and protection.

In addition, there is a call for the development of educational content that is specifically tailored to leverage the strengths of 3D holography, fostering an environment where the abstract becomes tangible and the complex more comprehensible. By doing so, educational institutions can harness the transformative power of 3D holography, not only to facilitate cutting-edge learning experiences but also to foster a culture of technological adeptness and readiness for future innovations. As this technology continues to evolve, ongoing research and development will be paramount in ensuring that the integration of 3D holography in education is both efficacious and aligns with the overarching goal of enhancing student engagement and learning outcomes.

C. LIMITATIONS AND SUGGESTIONS FOR FUTURE STUDIES

This study is not without its constraints. A significant limitation arises from the circumscribed nature of the research model, which is confined to a predetermined set of variables serving as metrics to gauge the influence of 3D hologram technology adoption in the domain of science education. Future investigations could expand upon this framework by integrating a broader array of factors that encapsulate the multitude of outcomes anticipated from the deployment of 3D holographic tools in educational settings. It is also pertinent to note the limitations in the generalizability of this study's findings, as the data were sourced from a singular national context. To enhance the external validity of these findings, subsequent studies across varied geographic and cultural landscapes would be instrumental. Such research endeavors would contribute substantially to a more comprehensive and nuanced comprehension of this contemporary and significant topic. Additionally, this inquiry illuminates the pertinence of the Diffusion of Innovations (DOI) theory in understanding the assimilation of 3D holographic technology by institutions in developing regions. Prospective scholarly work might consider employing alternate theoretical frameworks to yield insights that not only augment but also provide a contrast to the current research narrative.

VII. CONCLUSION

The integration of 3D holographic technology is set to revolutionize operational frameworks across various governmental sectors, offering significant gains in terms of efficiency. The study establishes a link between the constructs of Compatibility, Observability, Trialability, and Relative Advantage with the successful adoption metrics outlined in the Diffusion of Innovations (DOI) theory, particularly within educational settings. The findings reveal that compatibility plays a pivotal role in the ease of integrating new technologies and their subsequent exportation. The degree to which an innovation aligns with existing values and practices is a key determinant of its compatibility, hence its substantial impact on adoption rates. The study posits that when 3D holographic technology meets the strategic objectives of government operations, it is readily embraced, facilitating the transition from existing protocols to more advanced alternatives. Furthermore, the study highlights the significance of Trialability in the adoption process of 3D holographic technology within the realm of science education. The opportunity for potential adopters to experiment with the technology is a powerful driver for its acceptance. According to the study's insights, the provision to test and evaluate 3D holography significantly sways the decision-making process in its favor. Anticipating the adoption of this technology by government entities in the educational sector could lead to advanced functionalities that serve not only current needs but also lay a foundation for future innovation and growth. Concluding, the research advocates for a strategic deployment of 3D holographic applications across a spectrum of governmental institutions. Such a move is anticipated to not only catalyze immediate operational enhancements but also to underpin long-term planning and development, cementing the role of 3D holography in the technological evolution of government functions.

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