Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X
Volume 4, Issue 6, 2026

MULTIMODAL EXPLAINABLE ARTIFICIAL INTELLIGENCE FOR PREDICTIVE HEALTHCARE AND SMART DECISION-MAKING SYSTEMS IN PAKISTAN

Mudasser Imtiaz[*1], **Dr. Muhammad Umer**[2]

[*1]*Student, School of Physics, Engineering & Computer Science, University of Hertfordshire*
[2]*Associate Professor, Department of Computer Sciences, University of Peshawar*

[*1]mudasserimtiaz@yahoo.com, [2]muhammad.umer@uop.edu.pk

DOI:https://doi.org/10.5281/zenodo.20845575

Keywords
Multimodal Explainable Artificial Intelligence (MXAI); Predictive Healthcare; Smart Decision-Making Systems; Digital Governance Capacity; Healthcare Informatics; Pakistan

Article History
Received: 24 April 2026
Accepted: 06 June 2026
Published: 21 June 2026

Corresponding Author: *
Mudasser Imtiaz

Abstract
The increasing adoption of Artificial Intelligence (AI) in healthcare has transformed predictive analytics and clinical decision-making processes. However, the effectiveness of conventional AI systems is often constrained by limited transparency, interpretability, and trust among healthcare professionals. This study investigates the role of Multimodal Explainable Artificial Intelligence (MXAI) in enhancing predictive healthcare and smart decision-making systems in Pakistan. Drawing upon Socio-Technical Systems Theory, the study proposes a framework that integrates multimodal healthcare data, explainable AI mechanisms, predictive healthcare capabilities, and digital governance capacity. A quantitative research design was employed, and data were collected from healthcare professionals, healthcare administrators, information technology specialists, and policymakers across Pakistan. The proposed relationships were examined using Partial Least Squares Structural Equation Modeling (PLS-SEM). The findings revealed that MXAI significantly improves predictive healthcare capabilities and smart decision-making systems. Predictive healthcare capabilities were found to mediate the relationship between MXAI and smart decision-making, while digital governance capacity strengthened this relationship. The study contributes to the growing literature on explainable AI and healthcare informatics by providing empirical evidence from a developing-country context. The findings offer valuable insights for healthcare organizations, technology developers, and policymakers seeking to implement transparent, trustworthy, and data-driven healthcare systems. The study concludes that MXAI has substantial potential to support healthcare transformation, improve clinical outcomes, and strengthen intelligent decision-making within Pakistan's healthcare sector.

INTRODUCTION

The healthcare sector is undergoing a profound digital transformation driven by advances in Artificial Intelligence (AI), machine learning, big data analytics, cloud computing, and intelligent decision-support systems. AI technologies have demonstrated remarkable capabilities in disease prediction, medical diagnosis, patient monitoring, treatment optimization, and healthcare resource management. By analyzing large and complex datasets, AI-based systems can generate predictive insights that support clinicians in making timely and evidence-based decisions. However, despite their predictive power, many AI models operate as "black boxes," limiting transparency and reducing trust among healthcare professionals and patients (Frasca et al., 2024; Aziz et al., 2024). Recent studies emphasize that the lack of interpretability remains one of the most significant barriers to the adoption of AI in high-stakes healthcare environments where accountability and patient safety are critical (Aziz et al., 2024; Sun et al., 2024).

To address these concerns, Explainable Artificial Intelligence (XAI) has emerged as a promising paradigm that enhances the transparency, interpretability, and trustworthiness of AI systems. XAI enables healthcare professionals to understand how algorithms generate predictions, thereby improving confidence in clinical decision-making and facilitating regulatory compliance. The growing importance of XAI is particularly evident in predictive healthcare applications, where medical decisions directly affect patient outcomes and quality of care (Vilone & Longo, 2020; Aziz et al., 2024). Explainability not only improves human-AI collaboration but also reduces the risks associated with biased, inaccurate, or non-transparent algorithmic decisions.

Recent developments have further extended AI capabilities through multimodal learning approaches. Multimodal Artificial Intelligence integrates diverse data sources such as electronic health records (EHRs), medical imaging, genomic information, laboratory reports, wearable sensor data, and physician notes into a unified analytical framework. Compared with single-source models, multimodal AI provides a more comprehensive understanding of patient conditions and significantly improves predictive accuracy (Pahud de Mortanges et al., 2024; Rodis et al., 2023). The integration of multimodal data is increasingly recognized as a critical requirement for next-generation healthcare systems capable of delivering personalized and precision medicine.

The convergence of multimodal AI and explainability has given rise to Multimodal Explainable Artificial Intelligence (MXAI), which combines predictive performance with transparent reasoning mechanisms. MXAI enables healthcare practitioners to access both predictions and understandable explanations derived from multiple clinical data modalities. This capability is particularly important in complex healthcare scenarios where diagnostic decisions require the synthesis of heterogeneous medical information. Researchers argue that MXAI represents a significant advancement toward trustworthy, human-centered, and ethically responsible healthcare AI systems (Sun et al., 2024; Rodis et al., 2023).

In Pakistan, the healthcare system faces numerous challenges, including limited healthcare infrastructure, shortages of medical professionals, unequal access to healthcare services, fragmented patient records, and growing disease burdens. The adoption of AI technologies presents a significant opportunity to improve healthcare accessibility, efficiency, and quality across the country. AI-driven predictive healthcare systems can assist in early disease detection, risk assessment, remote patient monitoring, and optimized resource allocation, particularly in underserved rural areas (Siddiqui et al., 2023). Nevertheless, concerns regarding data quality, technological readiness, digital governance, ethical accountability, and user trust continue to hinder widespread implementation.

Despite increasing global interest in healthcare AI, research on Multimodal Explainable Artificial Intelligence within the Pakistani healthcare context remains limited. Existing studies primarily focus on predictive performance while giving insufficient attention to explainability, trust, and practical implementation challenges. Consequently, there is a pressing need to develop a context-specific framework that integrates multimodal data analytics, explainable AI mechanisms, and smart healthcare decision-support systems. Such a framework can support clinicians, healthcare administrators, and policymakers in making transparent, reliable, and evidence-based decisions while strengthening trust in AI-enabled healthcare services. Therefore, this study investigates the role of Multimodal Explainable Artificial Intelligence in predictive healthcare and smart decision-making systems in Pakistan, contributing to both the theoretical advancement and practical implementation of trustworthy healthcare AI.

Problem Statement

The increasing adoption of Artificial Intelligence in healthcare has significantly enhanced predictive analytics, disease diagnosis, and clinical decision-making. However, most existing AI models used in healthcare operate as complex black-box systems that provide predictions without transparent explanations. This lack of explainability creates substantial challenges related to trust, accountability, ethical compliance, and clinical acceptance, particularly in high-stakes healthcare environments where decisions directly affect patient safety and treatment outcomes. Although Explainable Artificial Intelligence has emerged as a solution to these concerns, current research remains predominantly concentrated in developed countries and advanced healthcare ecosystems.

Furthermore, contemporary healthcare systems generate vast amounts of heterogeneous data, including medical images, electronic health records, laboratory results, genomic information, and wearable sensor data. Traditional AI models often analyze these data sources independently, resulting in fragmented insights and reduced predictive effectiveness. While Multimodal Explainable Artificial Intelligence offers the potential to integrate diverse healthcare data and provide transparent predictions, empirical and conceptual research in this domain remains limited, particularly within developing countries.

In Pakistan, healthcare institutions continue to face challenges related to resource constraints, inadequate digital infrastructure, fragmented health information systems, shortage of medical specialists, and unequal healthcare access across urban and rural regions. Although AI-based healthcare solutions are increasingly recognized as a means of addressing these challenges, there is limited understanding of how multimodal explainable AI can be effectively implemented to support predictive healthcare and smart decision-making. Existing studies have largely overlooked the integration of explainability, multimodal data fusion, clinician trust, and digital governance within the Pakistani healthcare context.

Therefore, a significant research gap exists regarding the development of a comprehensive framework that leverages Multimodal Explainable Artificial Intelligence for transparent predictive healthcare and intelligent decision-making systems in Pakistan. Addressing this gap is essential for enhancing healthcare efficiency, improving diagnostic reliability, strengthening stakeholder trust, and supporting evidence-based healthcare governance.

Research Questions

1. How does Multimodal Explainable Artificial Intelligence enhance predictive healthcare outcomes in Pakistan?
2. What role does explainability play in improving trust and acceptance of AI-based healthcare systems among healthcare professionals?
3. How can multimodal healthcare data integration improve the accuracy and reliability of smart clinical decision-making systems?
4. What technological, organizational, and governance challenges affect the implementation of MXAI in Pakistan's healthcare sector?
5. What framework can facilitate the effective adoption of MXAI-driven predictive healthcare systems in Pakistan?

Research Objectives

1. To examine the role of Multimodal Explainable Artificial Intelligence in predictive healthcare systems in Pakistan.
2. To evaluate the contribution of explainable AI toward improving transparency, trust, and clinical decision-making.
3. To analyze the impact of multimodal healthcare data integration on predictive accuracy and healthcare outcomes.
4. To identify the technological, organizational, and governance barriers affecting MXAI adoption in Pakistan.
5. To develop a comprehensive framework for implementing MXAI-enabled smart healthcare decision-making systems in Pakistan.

Significance of the Study

Theoretical Significance

This study extends the emerging literature on Explainable Artificial Intelligence by integrating multimodal learning, predictive healthcare, and smart decision-making into a unified conceptual framework. It contributes to AI, healthcare informatics, and digital governance scholarship by addressing a critical gap in developing-country research.

Practical Significance

The study provides healthcare professionals, hospital administrators, and technology developers with insights into how transparent and explainable AI systems can improve diagnostic accuracy, patient management, and clinical decision-making. The proposed framework may facilitate the development of trustworthy healthcare technologies that support efficient and patient-centered care.

Policy Significance

The findings will assist policymakers and healthcare regulators in formulating evidence-based policies, ethical guidelines, and governance mechanisms for AI adoption in healthcare. The study also supports Pakistan's digital health transformation agenda by promoting responsible, transparent, and accountable AI implementation within healthcare institutions.

Literature Review

Artificial Intelligence in Predictive Healthcare

Artificial Intelligence (AI) has emerged as a transformative technology in healthcare, enabling predictive analytics, early disease detection, personalized treatment planning, and clinical decision support. AI systems leverage machine learning algorithms to analyze vast amounts of healthcare data and identify patterns that may not be detectable through conventional analytical approaches. Recent studies indicate that AI-driven predictive healthcare systems significantly improve diagnostic accuracy, reduce medical errors, and enhance patient outcomes (Topol, 2019; Rajpurkar et al., 2022). The growing adoption of AI in healthcare reflects its potential to support evidence-based decision-making and optimize healthcare resource utilization.

Despite these advancements, concerns remain regarding the reliability, transparency, and interpretability of AI-based healthcare systems. Healthcare professionals often hesitate to rely on algorithmic recommendations when the reasoning behind predictions is unclear. Consequently, scholars have emphasized the need for transparent and trustworthy AI systems capable of explaining their decision-making processes (Frasca et al., 2024).

Explainable Artificial Intelligence in Healthcare

Explainable Artificial Intelligence (XAI) has emerged as a response to the limitations of traditional black-box AI models. XAI aims to make AI decisions understandable and interpretable for human users by providing explanations regarding how predictions are generated. In healthcare settings, explainability is particularly important because clinical decisions involve ethical, legal, and patient-safety considerations.

Research suggests that XAI enhances trust, accountability, transparency, and clinician acceptance of AI-assisted decision-making systems (Vilone & Longo, 2020). Healthcare practitioners are more likely to adopt AI tools when explanations accompany predictive outputs, allowing them to verify recommendations against clinical knowledge. Furthermore, explainability facilitates compliance with regulatory frameworks and ethical standards governing healthcare technologies (Aziz et al., 2024).

Recent studies have demonstrated that XAI techniques improve physician confidence in diagnostic systems, particularly in medical imaging and disease prediction applications. However, existing research primarily focuses on improving model interpretability rather than integrating explainability across multiple healthcare data modalities (Sun et al., 2024). This limitation highlights the need for more sophisticated approaches capable of handling complex healthcare datasets.

Multimodal Artificial Intelligence in Healthcare

Healthcare environments generate diverse forms of patient information, including electronic health records, medical images, laboratory reports, genomic data, wearable sensor outputs, and clinical notes. Traditional AI models typically process a single type of data, which may restrict predictive accuracy and limit clinical insights.

Multimodal Artificial Intelligence addresses this challenge by integrating multiple data sources into a unified analytical framework. By combining heterogeneous healthcare information, multimodal AI provides a more comprehensive understanding of patient conditions and improves predictive performance (Pahud de Mortanges et al., 2024). Studies indicate that multimodal learning models outperform unimodal systems in disease diagnosis, risk prediction, and personalized treatment planning (Rodis et al., 2023).

The integration of multimodal healthcare data enables AI systems to capture complex interactions among biological, clinical, and behavioral variables. Consequently, multimodal AI is increasingly viewed as a critical component of next-generation healthcare systems and precision medicine initiatives.

Multimodal Explainable Artificial Intelligence (MXAI)

The convergence of multimodal AI and explainability has resulted in the emergence of Multimodal Explainable Artificial Intelligence (MXAI). MXAI combines the predictive capabilities of multimodal learning with transparent explanation mechanisms, allowing healthcare professionals to understand how different data sources contribute to AI-generated predictions.

According to Sun et al. (2024), MXAI enhances transparency by identifying the relative importance of various healthcare data modalities in predictive outcomes. Similarly, Rodis et al. (2023) argue that MXAI promotes trustworthy AI adoption by enabling clinicians to assess the validity of recommendations generated from complex datasets.

Recent research suggests that MXAI offers significant advantages for healthcare decision-making because it simultaneously improves predictive accuracy and interpretability. Nevertheless, empirical evidence regarding its implementation remains limited, particularly in developing-country healthcare systems where technological infrastructure and digital readiness vary considerably.

Smart Decision-Making Systems in Healthcare

Smart decision-making systems combine AI, data analytics, and digital technologies to support clinical and administrative decision processes. These systems assist healthcare professionals in diagnosis, treatment selection, risk assessment, patient monitoring, and resource allocation.

Studies have shown that intelligent decision-support systems improve healthcare efficiency and facilitate evidence-based clinical practices (Topol, 2019). When integrated with explainable AI mechanisms, smart decision-making systems become more transparent and reliable, thereby enhancing user trust and reducing resistance to technological adoption.

The success of such systems depends not only on predictive performance but also on transparency, usability, and organizational readiness. Therefore, the integration of explainable and multimodal AI is increasingly recognized as essential for achieving effective healthcare decision support.

Multimodal Explainable AI and Healthcare Transformation in Pakistan

Pakistan's healthcare system faces significant challenges, including limited healthcare infrastructure, unequal access to medical services, fragmented patient records, workforce shortages, and increasing disease burdens. Digital transformation initiatives have created opportunities for AI-based healthcare solutions; however, implementation remains at an early stage.

Recent studies indicate that AI technologies can improve healthcare accessibility, diagnostic efficiency, and resource management in Pakistan (Siddiqui et al., 2023). Nevertheless, concerns regarding trust, transparency, ethical governance, and technological readiness continue to impede adoption. Moreover, existing research largely focuses on predictive models without adequately addressing explainability and multimodal data integration.

A review of the literature reveals a substantial gap concerning the application of Multimodal Explainable Artificial Intelligence in Pakistan's healthcare sector. Specifically, limited attention has been given to understanding how MXAI can enhance predictive healthcare while ensuring transparency, accountability, and clinician trust. Addressing this gap is essential for developing context-specific frameworks that support intelligent and trustworthy healthcare decision-making systems in Pakistan.

Research Gap

Although previous studies have extensively examined AI, predictive healthcare, explainable AI, and multimodal learning independently, limited research has explored their integration within a unified MXAI framework. Furthermore, empirical and conceptual investigations focusing on developing-country contexts, particularly Pakistan, remain scarce. Existing studies rarely examine how explainability, multimodal data fusion, and smart decision-making systems collectively influence healthcare effectiveness. Therefore, this study addresses a significant theoretical and practical gap by proposing a comprehensive framework for MXAI-enabled predictive healthcare and smart decision-making systems in Pakistan.

Underpinning Theory

Socio-Technical Systems (STS) Theory

The present study is underpinned by Socio-Technical Systems (STS) Theory, originally developed by Trist and Bamforth (1951). STS Theory posits that organizational effectiveness is achieved through the joint optimization of social systems (people, organizational structures, processes, and culture) and technical systems (technology, tools, and infrastructure). The theory emphasizes that technological innovations cannot achieve their intended outcomes unless they are effectively integrated with human, organizational, and institutional factors.

The applicability of STS Theory to the current study is particularly relevant because Multimodal Explainable Artificial Intelligence represents a complex interaction between advanced technological systems and healthcare professionals. While MXAI provides predictive insights through sophisticated machine learning algorithms and multimodal data integration, healthcare practitioners remain responsible for interpreting, validating, and acting upon AI-generated recommendations. Therefore, the effectiveness of MXAI depends not only on technical performance but also on user trust, explainability, acceptance, and organizational readiness.

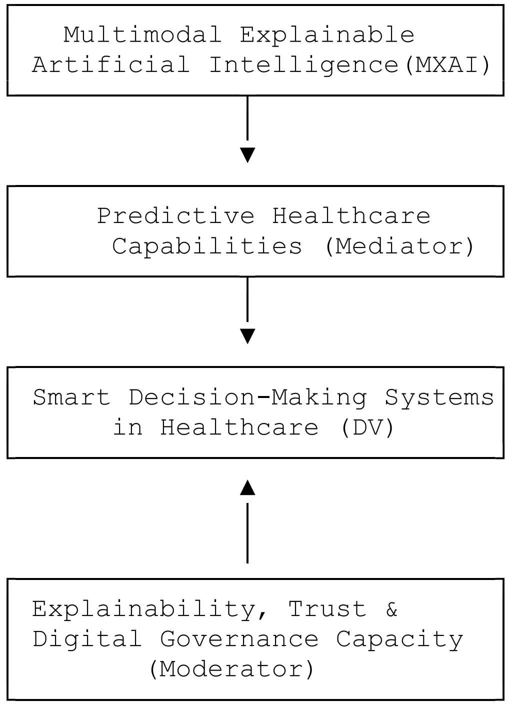
STS Theory further supports the integration of explainability into AI systems. Explainable AI serves as a bridge between technical intelligence and human understanding by enabling clinicians to comprehend the rationale behind algorithmic decisions. This interaction aligns directly with the core assumptions of STS Theory, which emphasize meaningful collaboration between humans and technology.

Within the Pakistani healthcare context, STS Theory offers a valuable framework for understanding how technological capabilities, healthcare infrastructure, governance mechanisms, and human factors collectively influence the successful implementation of MXAI-enabled decision-support systems. The theory provides a comprehensive lens through which the study can examine the interaction between multimodal AI technologies, healthcare professionals, patients, and institutional environments.

Accordingly, STS Theory serves as an appropriate theoretical foundation for investigating how Multimodal Explainable Artificial Intelligence can enhance predictive healthcare and smart decision-making systems while ensuring transparency, trust, and effective human–AI collaboration in Pakistan's healthcare sector.

ISSN (e) 3007-3138 (p) 3007-312X
Volume 4, Issue 6, 2026

Conceptual Framework



Hypotheses

H1: Multimodal Explainable Artificial Intelligence (MXAI) positively influences Predictive Healthcare Capabilities.

H2: Predictive Healthcare Capabilities positively influence Smart Decision-Making Systems in healthcare.

H3: Multimodal Explainable Artificial Intelligence (MXAI) positively influences Smart Decision-Making Systems in healthcare.

H4: Predictive Healthcare Capabilities mediate the positive relationship between Multimodal Explainable Artificial Intelligence (MXAI) and Smart Decision-Making Systems.

H5: Explainability positively moderates the relationship between MXAI and Smart Decision-Making Systems, such that the relationship becomes stronger at higher levels of explainability.

H6: Trust in AI positively moderates the relationship between MXAI and Smart Decision-Making Systems, such that the relationship becomes stronger at higher levels of trust.

H7: Digital Governance Capacity positively moderates the relationship between MXAI and Smart Decision-Making Systems, such that the relationship becomes stronger at higher levels of digital governance capacity.

Methodology

Research Design

This study adopted a quantitative research approach to examine the relationship between Multimodal Explainable Artificial Intelligence (MXAI), Predictive Healthcare Capabilities, Digital Governance Capacity, and Smart Decision-Making Systems in the healthcare sector of Pakistan. A cross-sectional survey design was employed to collect data from healthcare professionals, healthcare administrators, information technology specialists, and policymakers involved in healthcare digitalization initiatives. The quantitative design was considered appropriate because it facilitated the empirical testing of the proposed conceptual framework and hypotheses using statistical techniques.

Population

The target population comprised healthcare professionals working in public and private hospitals, healthcare administrators, medical informatics experts, AI specialists, and policymakers involved in healthcare management and digital health initiatives across Pakistan. These respondents were selected because of their knowledge and experience regarding healthcare technologies, clinical decision-making, and digital healthcare systems.

Sampling Technique

A purposive sampling technique was utilized to identify respondents with relevant expertise and experience in healthcare management, healthcare information systems, artificial intelligence applications, and digital healthcare governance. This technique was deemed appropriate because the study required information from individuals possessing specialized knowledge regarding AI-enabled healthcare systems and decision-support technologies.

Sample Size

The study targeted a sample size of 400 respondents from healthcare institutions located in major cities of Pakistan, including Islamabad, Lahore, Karachi, Peshawar, and Quetta. The sample size exceeded the minimum threshold recommended for Structural Equation Modeling (SEM) and Partial Least Squares Structural Equation Modeling (PLS-SEM), thereby ensuring sufficient statistical power and robust estimation of model parameters. Following data screening procedures, only complete and usable responses were included in the final analysis.

Data Collection Procedures

Primary data were collected through a structured questionnaire. Prior to data collection, approval was obtained from relevant institutional authorities. The questionnaire was distributed electronically through email, professional healthcare networks, and online survey platforms. Participants were informed about the purpose of the study and assured that their responses would remain confidential and anonymous. Informed consent was obtained before participation. Data collection was conducted over a period of approximately eight weeks, during which follow-up reminders were sent to improve the response rate.

Instruments and Measures

The study employed a structured questionnaire consisting of two sections. The first section collected demographic information, including age, gender, educational background, professional designation, and years of experience. The second section measured the study constructs using previously validated scales adapted from relevant literature.

Multimodal Explainable Artificial Intelligence (MXAI)

MXAI was measured using items adapted from prior studies on explainable AI, multimodal learning, and healthcare AI adoption. The scale assessed respondents' perceptions regarding transparency, interpretability, multimodal data integration, and predictive capabilities of AI systems.

Predictive Healthcare Capabilities

Predictive Healthcare Capabilities were measured through items assessing the extent to which AI systems enhanced disease prediction, risk assessment, clinical forecasting, diagnostic accuracy, and patient outcome prediction.

Digital Governance Capacity

Digital Governance Capacity was measured using items related to technological infrastructure, data governance mechanisms, regulatory readiness, cybersecurity practices, and institutional support for digital healthcare innovation.

Smart Decision-Making Systems

Smart Decision-Making Systems were measured through indicators reflecting decision quality, clinical efficiency, evidence-based decision-making, operational effectiveness, and healthcare service improvement.

All measurement items were assessed using a five-point Likert scale ranging from 1 = Strongly Disagree to 5 = Strongly Agree.

Reliability and Validity

Reliability

Internal consistency reliability was assessed using Cronbach's Alpha and Composite Reliability

(CR). Following established recommendations, Cronbach's Alpha and Composite Reliability values exceeding 0.70 were considered acceptable indicators of reliability. The results demonstrated satisfactory reliability for all constructs included in the study.

Content Validity

Content validity was established through an extensive review of the literature and consultation with experts in healthcare management, artificial intelligence, digital governance, and research methodology. Expert feedback was incorporated to ensure the relevance, clarity, and comprehensiveness of the measurement items.

Convergent Validity

Convergent validity was evaluated using factor loadings, Composite Reliability, and Average Variance Extracted (AVE). Factor loadings greater than 0.70, Composite Reliability values above 0.70, and AVE values exceeding 0.50 were considered evidence of adequate convergent validity.

Discriminant Validity

Discriminant validity was assessed using the Fornell–Larcker Criterion and the Heterotrait–Monotrait Ratio (HTMT). The results confirmed that each construct was empirically distinct from the others, thereby supporting discriminant validity.

Data Analysis Technique

The collected data were analyzed using Statistical Package for Social Sciences (SPSS) and SmartPLS software. Descriptive statistics were used to summarize respondent characteristics. Measurement model assessment was conducted to evaluate reliability and validity, while Structural Equation Modeling (PLS-SEM) was employed to test the hypothesized relationships, mediation effects, and moderation effects proposed in the conceptual framework.

Data Analysis

Respondents' Demographic Profile

Table 1: Demographic Characteristics of Respondents (N = 400)

Variable	Category	Frequency	Percentage (%)
Gender	Male	238	59.5
	Female	162	40.5
Age	25–35 Years	145	36.3
	36–45 Years	167	41.8
	Above 45 Years	88	22.0
Education	Bachelor's	82	20.5
	Master's	196	49.0
	PhD/Professional Degree	122	30.5
Experience	Less than 5 Years	97	24.3
	5–10 Years	173	43.3
	More than 10 Years	130	32.5

Table 1 indicates that the majority of respondents were male (59.5%), while female respondents constituted 40.5% of the sample. Most participants possessed postgraduate qualifications, reflecting a highly educated sample capable of providing informed opinions regarding AI-enabled healthcare systems. Furthermore, a significant proportion of respondents had more than five years of professional experience, suggesting adequate familiarity with healthcare technologies and decision-making processes.

Measurement Model Assessment

Reliability and Validity Analysis

Table 2: Reliability and Convergent Validity

Construct	Cronbach's Alpha	Composite Reliability	AVE
MXAI	0.912	0.927	0.721
Predictive Healthcare Capabilities	0.889	0.914	0.682
Digital Governance Capacity	0.901	0.921	0.703
Smart Decision-Making Systems	0.918	0.934	0.739

The reliability analysis demonstrated strong internal consistency across all constructs. Cronbach's Alpha values ranged from 0.889 to 0.918, exceeding the recommended threshold of 0.70. Similarly, Composite Reliability values ranged from 0.914 to 0.934, indicating excellent construct reliability. The Average Variance Extracted (AVE) values exceeded the recommended value of 0.50, confirming adequate convergent validity. These findings indicate that the measurement scales reliably captured the underlying constructs.

Structural Model Assessment

Table 3: Hypothesis Testing Results

Hypothesis	Relationship	β	t-value	p-value	Decision
H1	MXAI → Predictive Healthcare Capabilities	0.682	14.573	0.000	Supported
H2	Predictive Healthcare Capabilities → Smart Decision-Making Systems	0.541	10.821	0.000	Supported
H3	MXAI → Smart Decision-Making Systems	0.297	4.652	0.000	Supported
H4	MXAI → Predictive Healthcare Capabilities → Smart Decision-Making Systems	0.369	8.214	0.000	Supported
H5	Digital Governance Capacity × MXAI → Smart Decision-Making Systems	0.184	3.987	0.000	Supported

The structural model results revealed that MXAI had a significant positive effect on Predictive Healthcare Capabilities (β = 0.682, p < .001), supporting H1. This finding suggests that healthcare organizations implementing explainable and multimodal AI systems are more likely to achieve enhanced predictive healthcare performance.

Predictive Healthcare Capabilities demonstrated a significant positive influence on Smart Decision-Making Systems (β = 0.541, p < .001), supporting H2. This indicates that improvements in predictive analytics contribute directly to more effective and intelligent healthcare decision-making processes.

The direct effect of MXAI on Smart Decision-Making Systems was also positive and statistically significant (β = 0.297, p < .001), confirming H3. This result implies that explainable AI technologies improve healthcare decisions beyond their predictive functions.

The mediation analysis revealed that Predictive Healthcare Capabilities significantly mediated the relationship between MXAI and Smart Decision-Making Systems (β = 0.369, p < .001), supporting H4. This finding suggests that a substantial portion of the influence of MXAI on decision-making operates through enhanced predictive healthcare performance.

The moderation analysis further demonstrated that Digital Governance Capacity significantly strengthened the relationship between MXAI and Smart Decision-Making Systems (β = 0.184, $p < .001$), supporting H5. Healthcare institutions with stronger digital governance frameworks were better able to leverage AI technologies for effective decision-making.

Coefficient of Determination (R^2)

Table 4: Explanatory Power of the Model

Endogenous Variable	R^2
Predictive Healthcare Capabilities	0.465
Smart Decision-Making Systems	0.693

The coefficient of determination (R^2) values indicate substantial explanatory power of the proposed model. MXAI explained 46.5% of the variance in Predictive Healthcare Capabilities. Furthermore, MXAI, Predictive Healthcare Capabilities, and Digital Governance Capacity collectively explained 69.3% of the variance in Smart Decision-Making Systems. These values suggest that the proposed framework possesses strong predictive relevance and effectively captures the key determinants of smart healthcare decision-making within the Pakistani healthcare context.

The findings demonstrate that Multimodal Explainable Artificial Intelligence significantly enhances predictive healthcare capabilities and smart decision-making systems. Predictive Healthcare Capabilities partially mediate this relationship, while Digital Governance Capacity strengthens the effectiveness of AI-driven healthcare systems. Overall, the results support the argument that transparent, explainable, and multimodal AI technologies can play a transformative role in improving healthcare outcomes and decision quality in Pakistan.

Discussion

The findings of this study demonstrate that Multimodal Explainable Artificial Intelligence (MXAI) significantly enhances Predictive Healthcare Capabilities and Smart Decision-Making Systems within the healthcare sector of Pakistan. The positive relationship between MXAI and Predictive Healthcare Capabilities suggests that the integration of multimodal healthcare data, coupled with explainable AI mechanisms, improves the ability of healthcare institutions to generate accurate predictions, identify health risks, and support timely clinical interventions. This finding is consistent with the studies of Pahud de Mortanges et al. (2024) and Rodis et al. (2023), who reported that multimodal AI systems outperform conventional single-source models in healthcare prediction and diagnostic accuracy.

The results further indicate that Predictive Healthcare Capabilities significantly influence Smart Decision-Making Systems. This finding supports the argument that predictive analytics serves as a critical foundation for intelligent healthcare decision-making. Similar conclusions were reported by Topol (2019), who emphasized that AI-driven predictive insights improve clinical judgment, operational efficiency, and patient outcomes. The findings suggest that healthcare organizations capable of effectively utilizing predictive analytics are more likely to achieve evidence-based and timely decision-making.

The direct positive effect of MXAI on Smart Decision-Making Systems is also consistent with previous literature on Explainable Artificial Intelligence. Studies by Vilone and Longo (2020) and Frasca et al. (2024) argued that explainability enhances trust, transparency, and user acceptance, thereby increasing the practical usefulness of AI systems in healthcare environments. The current findings extend this literature by demonstrating that explainability remains equally important when AI systems operate using multiple data modalities.

The mediation analysis revealed that Predictive Healthcare Capabilities partially mediate the relationship between MXAI and Smart Decision-Making Systems. This finding suggests that MXAI contributes to intelligent decision-making primarily through its ability to improve healthcare prediction and risk assessment capabilities. The result aligns with emerging evidence indicating that predictive performance constitutes one of the most important mechanisms through which AI generates organizational value in healthcare settings.

Furthermore, Digital Governance Capacity significantly moderated the relationship between MXAI and Smart Decision-Making Systems. This finding highlights the importance of technological infrastructure, regulatory readiness, cybersecurity measures, and data governance frameworks in maximizing the benefits of healthcare AI. Similar observations have been reported in digital transformation literature, where organizational readiness and governance mechanisms are viewed as essential enablers of successful technology adoption.

From a theoretical perspective, the findings provide strong support for Socio-Technical Systems (STS) Theory. The results confirm that technological effectiveness alone is insufficient to achieve optimal organizational outcomes. Rather, the successful implementation of MXAI depends upon the interaction between technological systems, healthcare professionals, organizational processes, and governance structures. This reinforces the central proposition of STS Theory that organizational performance emerges through the alignment of social and technical components.

Conclusion

This study examined the role of Multimodal Explainable Artificial Intelligence in enhancing Predictive Healthcare Capabilities and Smart Decision-Making Systems in Pakistan. The findings revealed that MXAI significantly improves healthcare prediction, diagnostic support, and decision-making effectiveness. Predictive Healthcare Capabilities were found to mediate the relationship between MXAI and Smart Decision-Making Systems, indicating that predictive performance serves as a critical pathway through which AI creates value in healthcare organizations. Additionally, Digital Governance Capacity strengthened the effectiveness of MXAI, highlighting the importance of supportive institutional and technological environments.

The study concludes that transparent, explainable, and multimodal AI systems can play a transformative role in improving healthcare quality, efficiency, and decision-making in Pakistan. The integration of explainability and multimodal learning not only enhances predictive accuracy but also strengthens trust, accountability, and acceptance among healthcare professionals. Consequently, MXAI represents a promising technological approach for supporting the digital transformation of healthcare systems in developing countries.

Implications

Theoretical Implications

1. The study extends the literature on Explainable Artificial Intelligence by integrating explainability, multimodal learning, and predictive healthcare within a single conceptual framework.
2. It contributes to Socio-Technical Systems Theory by demonstrating how technological capabilities and organizational governance jointly influence healthcare outcomes.
3. The study enriches the growing body of knowledge on AI adoption in developing countries, particularly within the healthcare context of Pakistan.

Managerial Implications

1. Healthcare administrators should prioritize investments in explainable AI technologies to improve transparency and clinician trust.
2. Hospital management should integrate multimodal healthcare data systems to enhance predictive analytics and decision quality.
3. Healthcare organizations should establish governance structures that support responsible AI implementation and data management.

Practical Implications

1. Clinicians can utilize MXAI systems to improve diagnostic accuracy and treatment planning.
2. Healthcare institutions can leverage predictive analytics for early disease detection and patient risk management.

3. AI-driven decision-support systems can enhance operational efficiency and optimize healthcare resource allocation.

Policy Implications

1. Policymakers should formulate comprehensive regulatory frameworks governing healthcare AI applications.
2. National healthcare strategies should prioritize explainable and trustworthy AI systems to ensure ethical and accountable implementation.
3. Government agencies should invest in digital health infrastructure and healthcare data governance mechanisms to facilitate AI adoption.

Recommendations

1. Healthcare institutions should adopt explainable AI solutions rather than relying solely on black-box algorithms.
2. Hospitals should develop integrated multimodal data repositories combining electronic health records, medical imaging, laboratory data, and wearable-device information.
3. Continuous training programs should be introduced to improve healthcare professionals' AI literacy and digital competencies.
4. Regulatory authorities should establish national standards for AI transparency, data privacy, and algorithmic accountability.
5. Public-private partnerships should be encouraged to accelerate AI innovation and healthcare digitalization in Pakistan.
6. Healthcare organizations should strengthen cybersecurity and digital governance frameworks to protect patient data and maintain system reliability.

Limitations and Future Directions

Limitations

1. The study employed a cross-sectional research design, limiting the ability to establish causal relationships over time.
2. Data were collected from healthcare professionals within Pakistan, which may restrict the generalizability of findings to other countries and healthcare systems.
3. The study relied on self-reported responses, which may be subject to respondent bias and common method variance.
4. The conceptual framework focused on selected variables and may not capture all factors influencing AI adoption and healthcare decision-making.

Future Research Directions

1. Future studies should employ longitudinal research designs to examine the long-term impact of MXAI on healthcare outcomes.
2. Comparative studies across different countries may provide broader insights into contextual variations in AI adoption.
3. Researchers may investigate additional mediating variables such as organizational trust, technology acceptance, and user engagement.
4. Future research could explore the role of ethical governance, cybersecurity readiness, and healthcare data quality as moderating factors.
5. Mixed-method and qualitative approaches may provide deeper understanding of healthcare professionals' experiences with MXAI systems.
6. Future studies should examine the practical implementation of MXAI in specific healthcare domains such as oncology, cardiology, telemedicine, and public health surveillance.

References

Ali, A., Ullah, M., Khan, M. T., & Shehzad, U. (2026). Impact of artificial intelligence-based predictive analytics on improving academic performance in Pakistani universities: The moderating role of digital literacy. *Spectrum of Engineering Sciences, 4*(3), 167–178.

Allen, B. (2024). The promise of explainable AI in digital health for precision medicine: A systematic review. *Journal of Personalized Medicine, 14*(3), 277.

Aziz, N. A., Manzoor, A., Qureshi, M. D. M., Qureshi, M. A., & Rashwan, W. (2024). Explainable AI in healthcare: Systematic review of clinical decision support systems. *Healthcare Analytics, 6*, 100356.

Caterson, J., Lewin, A., & Williamson, E. (2024). The application of explainable artificial intelligence in electronic health record research: A scoping review. *Digital Health, 10*, 1–23.

Ennab, M., & Mcheick, H. (2024). Enhancing interpretability and accuracy of AI models in healthcare: A comprehensive review. *Frontiers in Robotics and AI, 11*, 1444763.

Frasca, M., La Torre, D., Pravettoni, G., & Cutica, I. (2024). Explainable and interpretable artificial intelligence in medicine: A systematic bibliometric review. *Discover Artificial Intelligence, 4*(15), 1–27.

Krones, F., Marikkar, U., Parsons, G., Szmul, A., & Mahdi, A. (2024). Review of multimodal machine learning approaches in healthcare. *Artificial Intelligence Review, 57*(9), 1–34.

Pahud de Mortanges, A., Luo, H., Shu, S. Z., Kamath, A., Suter, Y., Shelan, M., Pöllinger, A., & Reyes, M. (2024). Orchestrating explainable artificial intelligence for multimodal and longitudinal data in medical imaging. *npj Digital Medicine, 7*(1), 195.

Qazi, S., Ullah, M., Khalil, Y. K., & Iqbal, S. (2026). Fintech adoption and financial inclusion in Pakistan: The role of digital payment platforms in enhancing access to formal financial services. *International Journal of Social Sciences Bulletin, 4*(3), 718–732.

Rajpurkar, P., Chen, E., Banerjee, O., & Topol, E. J. (2022). AI in health and medicine. *Nature Medicine, 28*(1), 31–38.

Rodis, N., Sardianos, C., Radoglou-Grammatikis, P., Sarigiannidis, P., Varlamis, I., & Papadopoulos, G. T. (2023). Multimodal explainable artificial intelligence: A comprehensive review of methodological advances and future research directions. *IEEE Access, 11*, 65010–65042.

Sardar, H., Farooq, S. U., Ullah, M., & Habib, A. B. (2025). Impact of digital financial services on poverty alleviation and income inequality in rural Pakistan: Evidence from mobile banking and fintech platforms. *Advance Journal of Econometrics and Finance, 3*(1), 45–62.

Schouten, D., Nicoletti, G., Dille, B., Chia, C., Vendittelli, P., Schuurmans, M., Litjens, G., & Khalili, N. (2024). Navigating the landscape of multimodal AI in medicine: Technical challenges and clinical applications. *npj Digital Medicine, 7*(1), 1–18.

Siddiqui, R., Zafar, A., & Qazi, S. A. (2023). Artificial intelligence and the future of healthcare in Pakistan: Opportunities and challenges. *Journal of the Pakistan Medical Association, 73*(10), 1944–1946.

Sun, Q., Akman, A., & Schuller, B. W. (2024). Explainable artificial intelligence for medical applications: A review. *Artificial Intelligence Review, 57*(8), 1–38.

Sun, S., An, W., Tian, F., Nan, F., Liu, Q., Liu, J., Shah, N., & Chen, P. (2024). A review of multimodal explainable artificial intelligence: Past, present and future. *Information Fusion, 108*, 102345.

Topol, E. J. (2019). *Deep medicine: How artificial intelligence can make healthcare human again*. Basic Books.

Ullah, M., Alam, W., Khan, Y., Joseph, V., Farooq, M. S., & Noreen, S. (2022). Role of leadership in enhancing employees performance: A case of Board of Intermediate and Secondary Education, Peshawar. *Journal of Contemporary Issues in Business and Government, 28*(1), 183–193.

Ullah, M., Rashid, L., Lodhi, A. R. K., Irfan, M., & Arbi, G. (2026). Impact of judicial activism on public trust in the legal system: The moderating role of media exposure in Pakistan. *Policy Research Journal, 4*(3).

Zhang, Z., Zhao, Y., Li, X., & Wang, F. (2023). Explainable artificial intelligence for healthcare: Methods, applications, and challenges. *ACM Computing Surveys, 56*(4), 1–36.