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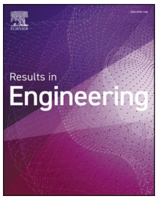

Internet of things (IoT) driven structural health monitoring for enhanced seismic resilience: A rigorous functional analysis and implementation framework

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ABSTRACT

Civil engineering infrastructures are increasingly becoming exposed to seismic loads, and at such a stage there is an increased need for alternative methods to fortify and enhance the resilience. The present study deals with the intricate linkage of internet of things (IoT) devices and the resilience of structures in a seismically affected zone. From the literature, the role of adaptive structural control, data acquisition and transmission, early warning systems, integration with building standards and codes, and real-time analytics and monitoring have been found to be the topmost aspects of ensuring resilience to seismic events. The seismically affected area of concern provides an in-depth analysis of the practical applications of the IoT in buildings in a seismic area. A survey was distributed to 239 respondents, and a very solid 58.99 % response rate proved the interest and participation of the respondents in the study. Using Partial Least Squares Structural Equation Modelling (PLS-SEM), the researchers frame a measurement model which is applied to analyze the reliability and validity of the IoT constructs. Further, the bootstrap resampling mechanisms are adopted to test the five hypotheses rigorously. The findings establish robust connections between adaptive structural control, data acquisition, early warning systems, integration with building codes and standards, real-time monitoring and analytics, and IoT, contributing to enhanced seismic resilience. Infrastructure developers can draw management implications from these findings, while empirical researchers can utilize the verified framework to guide future studies.

1. Introduction

Within the field of civil engineering, the vulnerability of systems to the results of seismic forces continues to be a non-stop source of difficulty. In response to this trouble, incorporating technologies that might be connected to the internet of things (IoT) has arisen as a potentially powerful path for strengthening structures against the hazards due to earthquakes. It is becoming evident that the combination of IoT and structural engineering provides real-time monitoring talents and a paradigm change in how we approach layout and maintenance [1,2].

With the IoT in the construction marketplace projected to attain USD 16 billion by 2024, reflecting an incredible compound annual growth fee (CAGR) of 26.0 %, the global adoption of IoT technology in production is witnessing giant growth. This is specifically authentic within the realm of seismic resilience [3,4]. As an example of this surge, the growing deployment of sensors in structural tracking systems is a superb instance. The global marketplace for structural health monitoring is expected to enlarge at a compound annual increase price of 17.9 % between the years 2017 and 2024 [5,6]. Particularly noteworthy is the reality that early warning systems that employ the IoT, including the shake alert earthquake early caution system developed by using the U.S. geological survey, play a key component in decreasing the volume of the damage resulting from seismic occurrences by using giving essential seconds to mins of word [7]. Retrofitting projects that use the IoT era

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have proven measurable blessings in relation to the resilience of buildings in regions that might be at risk of earthquakes [8]. IoT applications are predicted to reduce construction prices by 20–25 % [9]. This highlights the long-term cost-effectiveness of integrating IoT for structural strengthening towards seismic pressures [10]. In addition to the on-the-spot safety benefits, this can reduce construction costs by 20–25 % [11]. Collectively, these figures spotlight the growing acknowledgment of the IoT′ critical position in strengthening structures internationally [12]. This popularity is assisting to inspire a trajectory of technical developments that contribute to creating strong and sustainable infrastructure on a global scale [13].

Despite the development that has been finished in integrating the IoT and seismic resilience, there may nevertheless be a full-size research gap that must be investigated. The research aims to address the lack of empirical analysis on the role of IoT in enhancing seismic resilience in specific geographic contexts. There has been a sea exchange in civil engineering toward new strategies of making buildings extra resistant to earthquakes because of how susceptible they may be [14]. Seismic resilience has been given unique attention in active zones, filling an essential understanding vacuum at the same time as the use of IoT in construction is increasing worldwide [15]. The effects of the IoT on buildings in seismically active regions have yet to be thoroughly tested in previous studies [16].

This paper seeks to address the gap in understanding regarding the role of IoT in enhancing seismic resilience by examining various aspects of its involvement. It is a locally specific voice from communities of residents, discussing the strengths and weaknesses of the seismic environment in which they live [17]. With an urgent need to improve buildings against seismic threats, the study helps address existing knowledge gaps in the ongoing conversation regarding the application of IoT devices to the field through empirical study within the local context. In narrowing the range of study, the autonomous community of residents answers a calling gap in the existing literature, and helps bring to light knowledge that might not otherwise be singled out in a larger study of the impact of IoT devices on the ability to recover from seismic events. The focus is to provide a nuanced look for the complex relationship between technology and seismic resilience, from basic seismic engineering principles to applied use of IoT devices in structural health monitoring. Through a comprehensive investigation, this manuscript explores the transformative potential of IoT in enhancing the seismic resilience of buildings. The number one objective of this analysis is to bridge the modern research gaps and offer specific insights. Engineers and stakeholders are furnished with the information essential to make knowledgeable picks, which allows for reducing structural weaknesses at some stage in seismic occurrences. This is made feasible using the integrated network of sensors and gadgets, including current information analytics.

This expanding field may be traversed across the subsequent pages, highlighting areas where the extra look is vital and exposing particular insights that contribute to the boom of the difficulty. This can be executed to shed light on it. In addition to contributing to the instructional debate, the objective is to motivate tendencies in structural engineering development. The collaborative synergy between traditional engineering ideas and cutting-edge IoT technology can create constructed surroundings that are safer and extra resilient. This could fill the current literature gap and constitute a great leap forward in mitigating seismic activity's effect on groups. The revolutionary capacity of the IoT in reinforcing homes and shielding lives in the face of seismic troubles is being unraveled, and this study can be followed by way of specific insights that signal a tremendous contribution to the sector.

The manuscript structure comprises six main sections: Introduction, providing an overview of the research background, motivation, aim, and objectives; Literature Review, offering a comprehensive review of relevant literature on IoT integration into seismic resilience efforts; Methodology, describing the research methodology, including data collection, analysis techniques, and the proposed model for enhancing seismic resilience through IoT integration; Results, presenting the findings of the study, including the evaluation of the proposed model and the validation of hypotheses; Discussion, which discusses the implications of the findings, theoretical contributions, practical implications, and future research directions; and Conclusion, summarizing the main findings of the study, highlighting its contributions, and suggesting avenues for future research.

2. Literature review

The IoT has also been used as one of the alternatives as far as the evidence of the resilience of earthquakes is concerned. The flexible structural control is fundamental in the setting up of systems in the direction of the sustainable ends of the seismic strains [18]. Changing a structure's attributes in real-time to control fluctuations in environmental elements, such as seismic occurrences, is referred to as adaptive structural control [19]. IoT technology, which provides instant statistics on the conduct of a structure through seismic activities, makes it possible to have more flexibility [20]. Rattle displacements and accelerations are just a few traits that may be continuously monitored using sensors hooked up throughout the structure [21]. Because of this, adaptive management structures can make changes with the proper current impact. The IoT, together with adaptable structural manipulation, makes it feasible for homes to respond dynamically to seismic stresses, therefore minimizing the risk of damage and ensuring the structural integrity of the created environment [22].

The advent and deployment of early caution structures is one of the outstanding contributions of IoT to earthquake resilience. Anticipating and reacting to seismic activities before their most depth is a transformative factor in minimizing viable harm [22]. IoT sensors strategically positioned in and around buildings can identify early symptoms of seismic occurrences, supplying crucial seconds to minutes of improved notice. This prior notification could be beneficial for executing emergency reaction techniques, ensuring steady evacuation, and starting up adaptive management measures [23]. IoT-powered early warning systems are no longer the most effective in protecting lives; however, they are essential in decreasing structural harm. Integrating seismic early warning systems into the broader IoT structure demonstrates a proactive strategy to improve structural resilience towards seismic pressures [24].

Strict adherence to production norms and standards is critical for ensuring homes' seismic resilience. IoT technology provides a manner to results easily integrate with and enhance adherence to those rules [25]. IoT-enabled devices offer a huge quantity of statistics by constantly monitoring structural traits, which may be analyzed compared to mounted building guidelines. The real-time comments loop allows for detecting any vulnerabilities or deviations from set standards [26]. The versatility of IoT in this unique state of affairs permits buildings to not only fulfill present seismic rules but additionally adapt to adhere to revised requirements. Incorporating IoT into building guidelines guarantees a flexible and adaptable technique for the durability of structures, according to the advancing comprehension of seismic hazards and the most beneficial construction methods [27].

The essential element of IoT's influence on the capability of systems to resist seismic events lies in its functionality for on-the-spot monitoring and evaluation. The network of sensors is connected, and facts regularly go with the flow of information, permitting engineers and stakeholders to get in-depth expertise on a structure's behavior at some point during seismic occurrences [28]. This real-time monitoring now encompasses not only the event itself but also consists of the previous and publish-event tiers, offering an intensive look at the lifecycle [29]. IoT allows engineers to extract practical insights, evaluate the circumstances of systems, and make appropriately informed selections using statistics analytics [19,30]. Through ongoing monitoring and analysis, structural problems may be swiftly detected, permitting early interventions, renovation, and retrofitting [31]. The outcome is a proactive and statistics-driven strategy to guarantee the non-stop integrity of homes towards seismic pressures [32].

To summarize, using IoT technology in structural engineering has a profound effect on improving earthquake resilience [10]. By incorporating adaptive structural control, actual-time monitoring, and analytics, every aspect contributes to a holistic strategy for strengthening systems in opposition to seismic pressures [33]. Integrating IoT technology with those vital elements now reduces possible harm at some point during seismic events and brings about a fundamental trade-off in our knowledge and method to the troubles caused by seismic activity [33]. The ongoing progress in the era has highlighted the importance of IoT in safeguarding the structural stability of our built environment, particularly in earthquake resilience [34]. This serves as proof of the potential for groundbreaking breakthroughs within civil engineering.

3. Methodology

Five steps comprise the manuscript methodology: (1) Comprehensive literature review of IoT factors crucial for seismic resilience; (2) Design of a structured questionnaire to validate hypotheses and gather insights on the perceived significance of identified IoT factors; (3) Use of Structural Equation Modelling (SEM) to develop a measurement model, assessing reliability and validity of IoT constructs; (4) Extension of SEM to construct a structural model, examining causality. This analytical approach thoroughly examines IoT's seismic fortification efficacy, providing valuable insights to academics and businesses, as shown in Fig. 1.

3.1. Factors identification and hypothesis development

The application of IoT technologies is attracting significant attention in civil engineering due to its capacity to improve the seismic resistance of structures. A systematic search was created in the Scopus database by merging the general phrases "IoT" or "IoT" with the subject areas "Earthquake engineering" and "Seismic," along with a crucial feature called "Structural health monitoring." An initial collection of 1562 documents was received, representing research works in which IoT technologies have been explored, suggested, or implemented to improve infrastructure safety and seismic resilience through real-time monitoring.

The timeframe was restricted to articles from 2018 to the present to examine the literature's most recent status. This filtered subset, which had 789 documents served as the primary analysis corpus [6,8]. From 104 publications in the base year 2018 to 135 articles by 2023, preliminary findings show a continually expanding research output. Unbelievably, five articles have already been registered for 2024 by the halfway point of the year, demonstrating the growing global importance of IoT applications for earthquake strengthening.

A detailed temporal study reveals that 2022 had a peak in publication activity with 152 papers, with 145 documents published earlier in 2021. This represents the post-pandemic recovery of total research productivity [8,9]. Based on a breakdown by country, European countries are leading the way, with Italy with 239 articles, continuing its historical susceptibility to earthquakes. USA uses its IT superiority to follow closely behind with 152 docs. China registers 115 items from the infrastructure and academic sectors. Turkey, Greece, Portugal, Japan, India, Taiwan, France, Greece, and India comprise the top 10 countries regarding paper volume between 2018 and 2024.

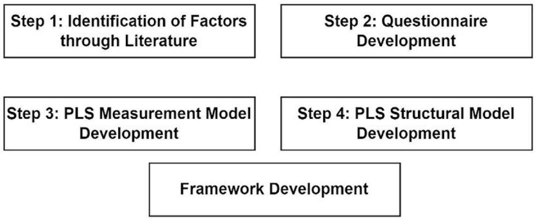

Fig. 1. Flow chart of the study.

The combined publication and national statistics demonstrate a significant increase in technical research projects examining IoT technologies to strengthen structure earthquake resistance [2,4]. Specifically, a disruptive paradigm that has gained prominence is the integration of networked sensors, controllers, platforms, and algorithms for real-time analytics [3,5]. However, further stratification is required on a finer thematic dimension, particularly application scenarios, to drive this research throughout the regions. Standardization and regulations should also be considered to expedite acceptance [1,3].

One of the main features of IoT technologies is adaptive structural control, which involves networked sensors, actuators, and controllers that dynamically modify a structure's physical attributes in response to seismic vibrations [33]. This reduces structural damage by enabling efficient energy dissipation and improved re-centering capability. According to recent studies, semi-active and active control systems integrated with the IoT allow quick seismic data analysis to start preventive measures [35].

Ensuring dependable data flow is essential for conducting insightful analysis. The research emphasizes that reliable data-gathering components and secure communication methods are necessary to transfer vibration data over large geographic networks [36]. The resilience of fiber optic sensory networks to electromagnetic interference makes them highly promising. IoT-enabled earthquake early warning systems provide prompt community communication before the onset of damaging seismic waves [36]. This supports readiness actions such as directing automatic equipment shutdown. In recent research, early warning algorithms are used to quickly analyze P-waves' arrival time and strength by quickly analyzing their first characteristics [37].

Adaptive structural control, data collection and transmission, early warning systems, integration with regulations, and real-time analytics and monitoring are the five main variables that have been discovered. Every factor has related technological capabilities or subcomponents [3,5]. Using tick or cross symbols, the importance of these subcomponents is mapped across the primary factors. For example, sensors are an essential sub-component for real-time analytics and earthquakes, as well as data trade and acquisition.

Nevertheless, policy integration and adaptive control are unrelated to sensors [10,11]. The interdependencies and overlaps between the several options IoT can give for reinforcement against seismic activity in terms of detection, mitigation, planning, and structural reaction capabilities are crucially revealed by this classification [12]. This serves as the foundation for an extensive roadmap.

Integration with codes and standards is essential for IoT to be used for seismic strengthening and construction requirements to be followed. Current research directions highlight the necessity of updating building codes to standardize the deployment of IoT advances. Policy revisions must appropriately consider related ethical and legal factors [25]. IoT analytics-enabled real-time structure health monitoring and predictive analysis improve post-earthquake damage and future vulnerability assessments. A review of the literature demonstrates how well-supervised and deep-learning algorithms work to produce insightful information about seismic risk from recorded IoT data [38].

According to functional analysis, IoT is a critical component of seismic reinforcement, supported by timely data collection and transmission, predictive algorithms, adaptive mechanisms, and policy integration. To address these technological and regulatory concerns in a global context, more research is required [39,40]. Collaboration between academics from technology, architecture, and public policy is necessary for integration.

3.2. Questionnaire design

A unique questionnaire was created to determine how IoT affects seismic resilience in areas, which are very vulnerable to earthquakes.

The research tested 5 seismic resilience elements: adaptive structural management, facts seize and transmission, early caution systems, integration with constructing codes and standards, and real-time tracking and analytics based on contemporary literature. The five-point Likert scale questionnaire assessed 239 contributors' evaluations and stories. The Likert scale allowed respondents to voice their views at the highlighted criteria, allowing for a first-class-grained exam of attitudes towards IoT generation in seismic resilience. The survey had a significant reaction fee of 58.99 %. This high response indicates that members are interested and informed of the topic, highlighting the neighborhood's significance.

A significant component of the look is its emphasis on seismically active zones, related cities with precise seismic vulnerability. These towns in seismically energetic zones are great locations to assess IoT's realistic programs in nearby buildings. According to Beyond research, the response rate of 58.99 % is entirely appropriate, indicating sizeable player involvement. This muscular response is predicted to provide a comprehensive dataset on seismic hotspot citizens' perspectives on IoT integration for structural resilience. After analyzing the replies, the research expects to find tendencies, choices, and concerns about questionnaire variables. This observation will add to local seismic resilience discourse and impact structural engineering regulations and practices in seismically sensitive places.

3.3. *Measurement model*

Partial Least Squares Structural Equation Modelling (PLS-SEM) evaluation utilizing SmartPLS four for size version construction entails surveying, questionnaires, or different facts-amassing strategies. The measuring version is essential to the research model, incorporating latent variables and their connections. Data import and version setup use SmartPLS. Indicators' loadings and AVE for every latent variable decide convergent validity. To determine discriminant validity, use the Fornell-Larcker criteria or HTMT ratio of correlations. These opinions may additionally need version adjustment. Standard errors and self-belief stages for course coefficients are acquired through bootstrap resampling, and worldwide suit indices are used to assess the version. Path coefficients, loadings, and significance ranges are pronounced, together with study topics and theories. Results are sturdy to model parameters with sensitivity analyses. The version needs to be refined iteratively.

3.4. *Structural model*

Bootstrap resampling is used for the duration of the structural model analysis section of the Partial Least Squares Structural Equation Modelling (PLS-SEM) using SmartPLS four to look at 5 hypotheses critical to the studies. The process entails generating many resamples from the initial dataset, making it viable to evaluate the consistency and reliability of the anticipated parameters. Several statistical measures are computed for every route coefficient. These encompass the authentic pattern (O) coefficient, the Sample Mean (M) coefficient derived from the bootstrap resamples, the Standard Deviation (STDEV) of the resampled coefficients, the t-statistic, and the p-cost. Using those metrics, one can also know the reliability of the connections among variables inside the model. To calculate the t-statistic, divide the difference between the unique sample coefficient and the sample suggested by the standard deviation. This will come up with an individual pattern coefficient. Indicating statistical importance and presenting self-belief in recognizing or rejecting every hypothesis, a low p-value provides proof of statistical significance. This exhaustive bootstrap analysis facilitates a comprehensive knowledge of the structural hyperlinks within the version, which complements the overall validity and trustworthiness of the conclusions of the studies.

4. Results and analysis

A thorough IoT study on structural seismic resilience is shown in the findings. The questionnaire results reflect the perceived relevance and efficacy of IoT elements. Next, Structural Equation Modelling (SEM) analysis validates and verifies the measurement model produced previously. The structural model reveals complex IoT factor-seismic resilience correlations. Path coefficients, significance levels, and goodness-of-fit indices are specified to explain variable interactions. The practical implications of the findings and their congruence with current literature are discussed in detail in this part, providing a solid platform for seismic resilience strategy research and implementation.

4.1. *Factor evaluation for SEM*

In Table 1, IoT variables affect the seismic resilience of buildings. Data Acquisition and Transmission" construct (D.T.) incorporate low-power IoT sensors, wireless protocols, on-device analysis, contingency communication channels, and encryption for safe data transfer. The "Real-Time Monitoring and Analytics" construct (R.M.) continuous seismic activity observation, on-site data processing utilizing analytics tools, adaptive sampling, redundant monitoring systems, and visualization tools for rapid reaction. The "Integration with Building Codes and Standards" construct (B.C.) focus on IoT to improve building code compliance, integrating sensors for real-time structural health monitoring, applying IoT data for resilience evaluation, incorporating automated systems, and integrating IoT infrastructure with existing building protocols The "Adaptive Structural Control" construct (S.C.) focus on IoT-based dynamic seismic response, real-time monitoring with intelligent devices, data analytics for structural integrity evaluation, adaptive structural adjustments, and control systems optimization. Finally, the "Early Warning Systems" construct (E.W.) is related to IoT-based early warning systems, sensor networks for real-time monitoring, data analysis for timely alerts, redundant communication channels, and infrastructure shutdowns for earthquake preparedness.

4.2. *Demographic details of respondents*

The respondents' demographic information offers an all-encompassing depiction of the individuals involved in the study, as shown in Fig. 2. The age distribution illustrates a harmonious representation, as 15 % of the participants are aged 18–25, 25 % are aged 26–35, 25 % are aged 36–45, 20 % are aged 46–55, and 15 % are aged 56 years or older. Educational attainment exhibits variation, as 28 % possess a Ph.D., 54 % own a master's degree, and 18 % have obtained a bachelor's degree. Regarding their professional positions, 65 % of the respondents classify themselves as civil engineers, 15 % as project managers, 10 % as safety engineers, and 10 % as individuals occupying the "Other" category. The respondents demonstrate a wide range of professional experience: 13 % have participated in the field for 0–5 years, 36 % have accumulated 6–10 years, 33 % have 11–15 years, 11 % have 16–20 years, and 7 % have more than 20 years of experience. The diverse demographic makeup of the participants guarantees an all-encompassing and comprehensive viewpoint regarding the elements that impact seismic resilience within the scope of the research.

4.3. *Measurement model development*

The findings of the convergent validity study are shown in Table 2. This analysis evaluated the reliability and consistency of the measurement model for each concept. The value of Cronbach's alpha, which is a measure of internal consistency, may vary anywhere from 0.783 to 0.93, indicating that the constructs' dependability is excellent. While the composite reliability measures (rho-a and rho-c) are more than 0.77, the robustness of the constructs is strengthened by the fact that they are greater than the suggested threshold of 0.7. The average variance

Table 1
Identified factors for IoT in seismic resilience of structures.

Constructs	Assigned Code	Variables	References
Data Acquisition and Transmission	DT1	Implement low-power IoT sensors to gather seismic data in real-time.	[4,6]
	DT2	Leverage wireless protocols to transmit data efficiently.	[10,12]
	DT3	Enable on-device analysis during seismic events to facilitate prompt decision-making.	[1,5]
	DT4	Implement contingency communication channels to guarantee the dependability of data transmission.	[25,27]
	DT5	Enable encryption to ensure data security and furnish intuitive interfaces to facilitate real-time data interpretation.	[7,9]
Real-Time Monitoring and Analytics	RM1	Incorporate real-time monitoring systems to ensure seismic activities are continuously observed.	[5,7]
	RM2	Leverage analytics tools to perform on-site data processing and analysis, augmenting decision-making velocity.	[9,11]
	RM3	Enable adaptive sampling techniques to capture real-time data efficiently.	[9,11]
	RM4	Incorporate redundant monitoring systems to guarantee uninterrupted coverage and dependability.	[3,5]
	RM5	Incorporate visualization tools to facilitate prompt response and interpretation of seismic events.	[6]
Integration with Building Codes and Standards	BC1	Leverage the capabilities of the IoT to improve and ensure compliance with established building codes and standards.	[7,9]
	BC2	By integrating sensors into structures, real-time structural health monitoring can be achieved, ensuring adherence to safety regulations.	[5,6]
	BC3	Apply IoT data to evaluate and enhance the resilience of buildings by industry benchmarks.	[2,3]
	BC4	Incorporate automated systems that modify building parameters by safety protocols and seismic events.	[5,8]
	BC5	Effectively integrate IoT infrastructure with pre-existing building protocols to bolster the overall resilience of structures.	[25,27]
Adaptive Structural Control	SC1	Incorporate IoT technology into adaptive structural control to dynamically react to seismic events.	[19,21]
	SC2	Incorporate intelligent measuring devices into structures to monitor their conditions in real time.	[22,29]
	SC3	By applying data analytics, one can evaluate the structural integrity of a given structure and detect possible vulnerabilities that may arise because of seismic activity.	[25,28]
	SC4	Implement actuators and adjustable components to adjust structural elements dynamically according to environmental alterations.	[24,27]
	SC5	Enable adaptive control systems by structural safety regulations to optimize building stability and minimize damage.	[22,23]
Early Warning Systems	EW1	Develop early warning systems that detect seismic waves using IoT.	[19,20]
	EW2	Install an IoT sensor network in seismically active locations to track ground movements in real-time.	[4,5]
	EW3	Analyze sensor data with powerful algorithms to inform you seconds to minutes before more harmful seismic waves arrive.	[2,3]
	EW4	Make redundant communication channels for quick and reliable early alerts to authorities and the public.	[25,26]
	EW5	Automate critical infrastructure shutdowns to improve earthquake preparation and reduce damage.	[16,27]

extracted (AVE), a measure of convergent validity, has a range from 0.572 to 0.792, indicating that their indicators capture a significant percentage of the variation of the constructs. These findings collectively point to a high degree of convergent validity for each construct. This substantiates the reliability and consistency of the measurement model in terms of its ability to capture the essence of the identified factors associated with adaptive structural control, data acquisition and transmission, early warning systems, integration with building codes and standards, and real-time monitoring and analytics.

Heterotrait-Monotrait (HTMT) ratio discriminant validity analysis findings are in Table 3. Each construct's square root of the average variance extracted (AVE) and HTMT ratios off th3 diagonal are shown in the table. The pattern shows that diagonal elements are consistently higher than off-diagonal components, indicating discriminant validity. The square root of AVE for each construct (on the diagonal) surpasses the focal construct and other constructs' HTMT ratios. This shows that the latent variables are unique since the common variation within each construct is larger than the shared variance across constructs [8,10]. These results indicate that the measurement model's constructs—Adaptive Structural Control (S.C.), Data Acquisition and Transmission (D.T.), Early Warning Systems (E.W.), Integration with Building Codes and Standards (B.C.), and Real-Time Monitoring and Analytics (R.M.)—are distinct and reliably measured.

Table 4 shows the discriminant validity cross-loading criteria, which details the correlations between variables and constructs. The table shows each variable's cross-loading across constructs, indicating relationship strength. IoT-SC5 has strong associations with Adaptive Structural Control (S.C.), IoT-DT2 with Data Acquisition and Transmission (D.T.), IoT-EW3 with Early Warning Systems (E.W.), and IoT-RM4 with Real-Time Monitoring and Analytics. IoT-SC3 and SC4 have lesser correlations with their target constructions.

This detailed analysis confirms the measurement model's discriminant validity by examining each variable's distinct contribution to its construct while minimizing interference from other constructs.

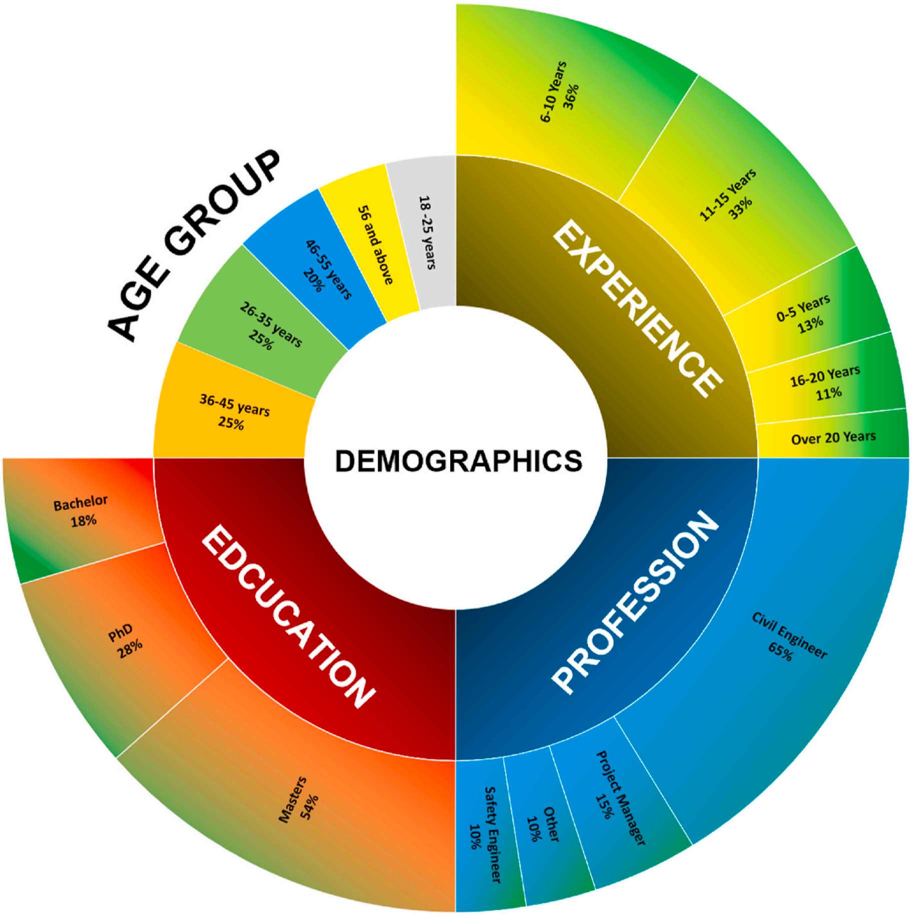

Fig. 2. Demographic details of respondents involved in this study.

Table 2
Convergent validity including Cronbach alpha, composite reliability, and average variance extracted.

Constructs	CA	CR (rho-a)	C.R. (rho-c)	(AVE)
Adaptive Structural Control	0.868	0.925	0.897	0.638
Data Acquisition and Transmission	0.93	0.96	0.949	0.792
Early Warning Systems	0.783	0.777	0.801	0.572
Integration with Building Codes and Standards	0.908	0.912	0.932	0.734
Real-Time Monitoring and Analytics	0.882	0.891	0.914	0.681

AVE = Average variance extracted; CA=Cronbach alpha; CR=Composite reliability.

Table 3
Discriminant validity through HTMT analysis.

Constructs	SC	DT	EW	BC	RM
Adaptive Structural Control = SC					
Data Acquisition and Transmission = DT	0.168				
Early Warning Systems = EW	0.307	0.139			
Integration with Building Codes and Standards = BC	0.135	0.092	0.359		
Real-Time Monitoring and Analytics = RM	0.277	0.183	0.256	0.34	

Table 4
Cross-loading criterion for discriminant validity.

Variables	SC	DT	EW	BC	RM
IoT-BC1	0.178	0.134	0.144	**0.862**	0.251
IoT-BC2	0.081	0.036	0.381	**0.913**	0.296
IoT-BC3	0.134	0.101	0.122	**0.83**	0.217
IoT-BC4	0.043	0.07	0.369	**0.901**	0.265
IoT-BC5	0.1	0.013	0.285	**0.768**	0.274
IoT-DT1	0.175	**0.861**	0.191	0.088	0.195
IoT-DT2	0.172	**0.966**	0.095	0.065	0.13
IoT-DT3	0.184	**0.962**	0.114	0.082	0.178
IoT-DT4	0.181	**0.969**	0.1	0.081	0.143
IoT-DT5	0.009	**0.65**	0.024	0.057	0.091
IoT-EW1	−0.162	0.096	**0.771**	0.205	0.093
IoT-EW3	−0.173	0.077	**0.744**	0.185	0.072
IoT-EW5	0.239	0.104	**0.753**	0.265	0.309
IoT-RM1	0.194	0.149	0.116	0.272	**0.79**
IoT-RM2	0.176	0.153	0.183	0.229	**0.806**
IoT-RM3	0.312	0.148	0.261	0.252	**0.864**
IoT-RM4	0.213	0.206	0.282	0.286	**0.886**
IoT-RM5	0.092	0.026	0.195	0.213	**0.775**
IoT-SC1	**0.796**	0.206	0.121	0.157	0.064
IoT-SC2	**0.869**	0.157	0.034	0.084	0.296
IoT-SC3	**0.756**	0.06	−0.129	−0.004	0.116
IoT-SC4	**0.654**	0.086	0.02	0.024	−0.121
IoT-SC5	**0.895**	0.131	0.026	0.14	0.342

4.4. Structural model development

Each route loading in the structural model shows the intensity and direction of the latent construct link, revealing how IoT elements affect earthquake resilience, as shown in Fig. 3. A robust and sustainable model would have all route loadings statistically significant with p values < 0.005. A substantial favorable path loading between Adaptive Structural Control (S.C.) and Integration with Building Codes and Standards (B.C.) may indicate that adaptive structural control

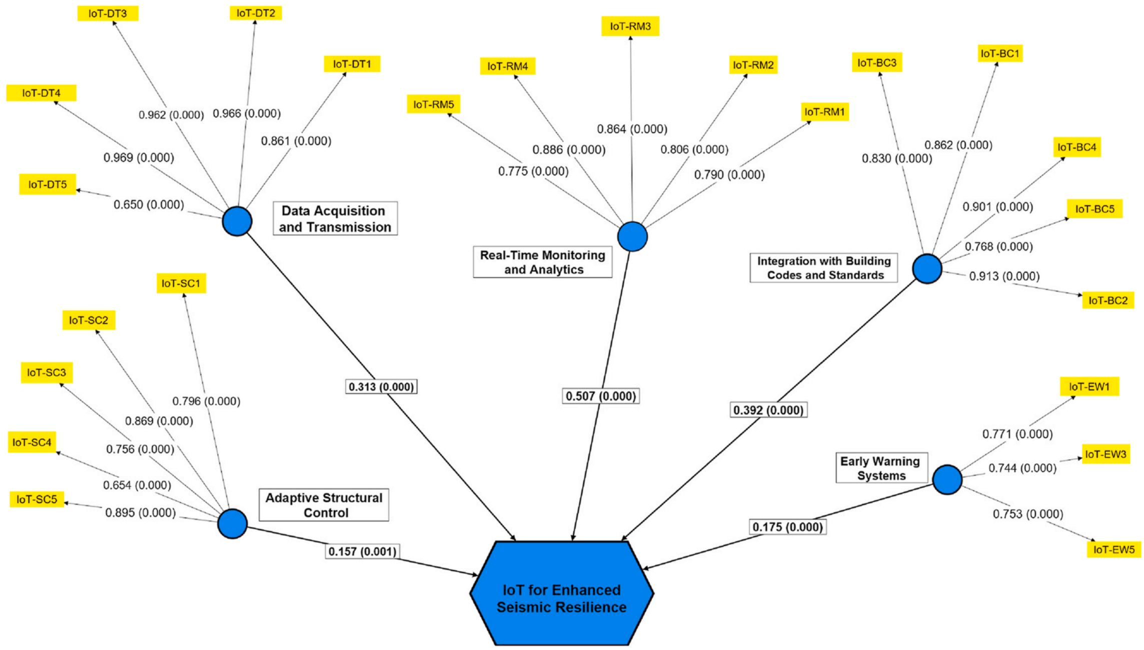

Fig. 3. Path loadings with p values.

enhancements increase compliance. Significant negative route loadings between Early Warning Systems (E.W.) and Real-Time Monitoring and Analytics (R.M.) suggest that as E.W. improves, R.M. use drops. These sustained, statistically significant route loadings demonstrate the structural model's dependability, helping us understand how IoT elements affect earthquake resilience in the defined circumstances [9,10].

The model seems well-supported if all route loadings are statistically significant, with t-statistic values showing reliability, as shown in Fig. 3. The significance and reliability of latent concept associations may be determined using the t-statistic, which assesses parameter estimate standard deviations. The route loading between Adaptive Structural Control (S.C.) and Integration with Building Codes and Standards (B.C.) has a positive t-statistic, indicating that adaptive structural control improvements favorably affect B.C. compliance. The path leading between Early Warning Systems (E.W.) and Real-Time Monitoring and Analytics (R.M.) has a negative t-statistic, suggesting that early warning system improvements reduce R.M. use [4,6]. The structural model shows the robustness of these correlations with statistically significant t-statistic values for all route loadings, helping to understand how IoT elements affect seismic resilience in the examined setting.

Table 5
Hypothesis testing results indicate the SEM analysis response against each hypothesis.

Hypothetical Relation	(O)	(M)	SD	T stats	P value
Adaptive Structural Control - > IoT for Enhanced Seismic Resilience	0.157	0.159	0.047	3.303	0.001
Data Acquisition and Transmission - > IoT for Enhanced Seismic Resilience	0.313	0.303	0.055	5.699	0
Early Warning Systems - > IoT for Enhanced Seismic Resilience	0.175	0.175	0.027	6.453	0
Integration with Building Codes and Standards - > IoT for Enhanced Seismic Resilience	0.392	0.387	0.04	9.69	0
Real-Time Monitoring and Analytics - > IoT for Enhanced Seismic Resilience	0.507	0.502	0.034	14.713	0

(O)= Original sample; (M) = Sample mean; SD = Standard deviation.

Table 5 summarizes the findings of the hypothesis testing using structural equation modeling (SEM) analysis, which evaluated the linkages between constructs in the context of improving seismic resilience via the integration of the IoT [4,6]. The t-statistic values and the P values indicate the importance of each association. All hypotheses are supported, and the findings suggest that improvements in Adaptive Structural Control, Data Acquisition and Transmission, Early Warning Systems, Integration with Building Codes and Standards, and Real-Time Monitoring and Analytics all significantly and positively contribute to enhanced seismic resilience through the integration of the IoT. The high t-statistic values and the low P values highlight these associations' robustness and statistical importance in the investigated model.

Table 6 provides an analysis of the model's predictive capabilities, with a particular emphasis on the concept of "IoT for Enhanced Seismic Resilience." The build has 14150 units of variability, represented by the Sum of Squares of the Originals (SSO). After considering the variability that cannot be explained, the Sum of Squares of the Errors (SSE) comes to 11775.42. This indicates that the model can forecast roughly 16.8 % of the variability in "IoT for Enhanced Seismic Resilience." Therefore, the Predictive Relevance (Q^2) that was acquired was calculated as $1 - \frac{SSE}{SSO}$. It measures how well the model predicts observed data by comparing the model's prediction accuracy against a baseline [5,6]. A higher Q^2 value indicates better predictive performance, suggesting that more variance in the observed data is explained by the model and in this case it was found to be 0.168. It is possible to examine further considerations and adjustments to improve the model's accuracy in predicting the stated construct, even though this implies a modest degree of predictive effectiveness [9,11].

Fig. 4 depicts the final framework for incorporating IoT capabilities in seismic resilience for buildings. This framework has been carefully evaluated, indicating all the variables with their rankings and also constructs with their impact on IoT implementation. High Cronbach's alpha and composite reliability are two indicators that demonstrate the

Table 6
Predictive relevance.

Construct Relevance	S	SSE	Q^2 (=1-SSE/SSO)
IoT for Enhanced Seismic Resilience	14150	11775.42	0.168

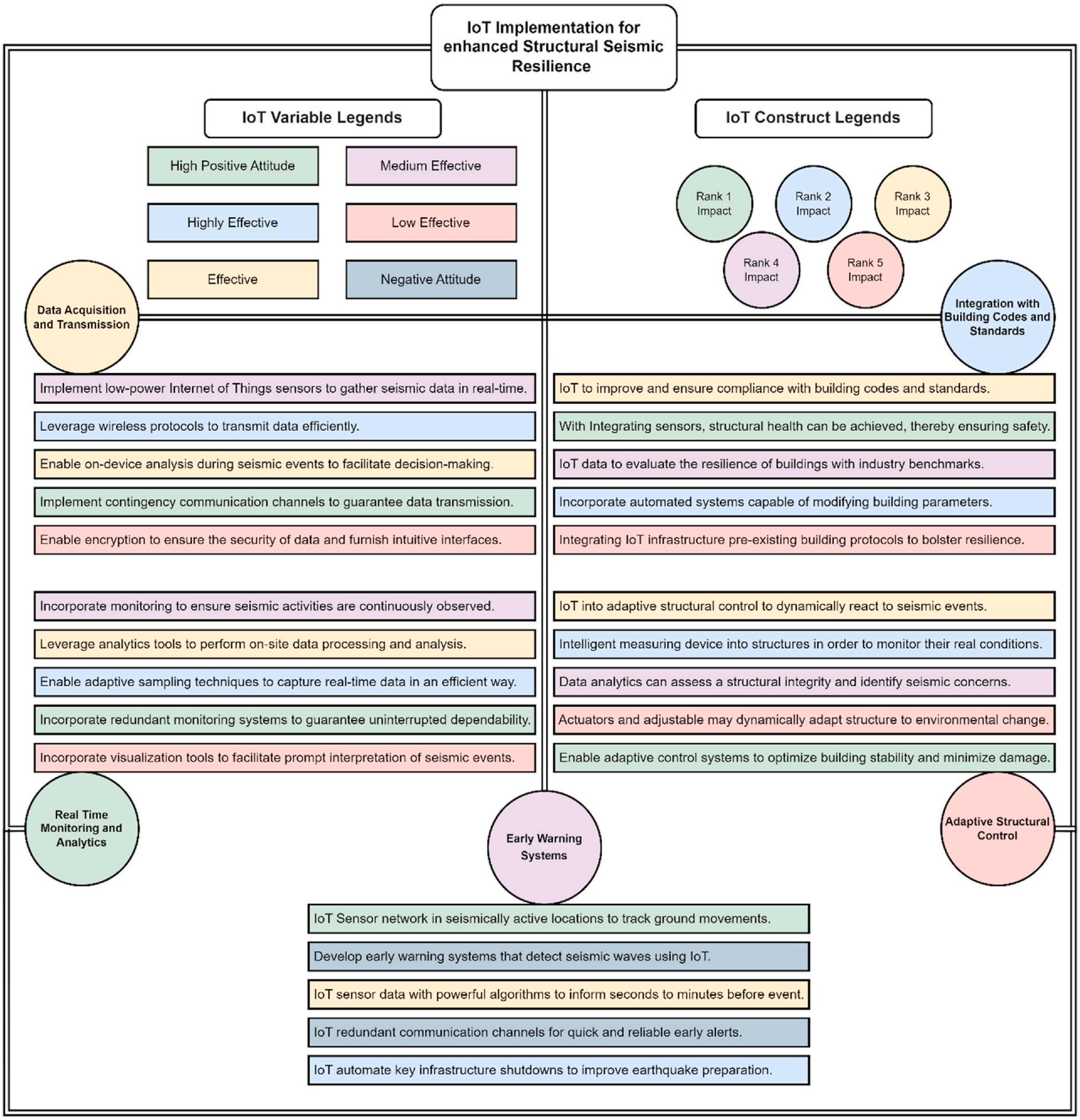

Fig. 4. Final framework of the study.

existence of convergent validity. The HTMT, Fornell-Larcker, and cross-loading studies are used to illustrate the discriminant validity of the test [2,4]. The structural model, backed by solid t-statistics and sustained path loadings, reveals the linkages between the important constructs within the database. Testing the hypothesis demonstrates that Adaptive Structural Control, Data Acquisition and Transmission, Early Warning Systems, Integration with Building Codes and Standards, and Real-Time Monitoring and Analytics all favor the IoT for Enhanced Seismic Resilience. Based on the predictive relevance study, the capacity to foresee variability seems modest. Within the context of enhancing seismic resilience in buildings, this all-encompassing framework functions as a solid guide for strategically adopting the IoT.

5. Discussion

A Functional Analysis of IoT” examines the complex relationships among critical constructs to offer a practical analysis of IoT's contribution to seismic resilience. The observation utilizes a rigorous method, which includes numerous steps: building and validating a dimension model, analyzing structural fashions, testing hypotheses, and evaluating predictive relevance. The assessment model validates and establishes the authenticity and accuracy of the identified constructs, whereas the examination of the well-known structural version shows the complicated relationships among those constructs. Hypothesis trying out is an exhaustive technique that assesses the proposed relationships, even as predictive relevance analysis determines the version's ability to expect variability. The subsequent discourse gives a complete analysis of the interpretation of every hypothesis, clarifying the significant discoveries and their broader ramifications for the strategic software of IoT in the seismic fortification of structures.

5.1. *Adaptive structural control - > IoT for enhanced seismic resilience*

For Enhanced Seismic Resilience, the hypothesis postulated a tremendous correlation between Adaptive Structural Control and IoT. The consequences of the analysis imply a statistically massive path loading (T stats = 0.303, P < 00.001). This presents aid for the claim that incorporating IoT technologies into systems that enhance seismic resilience is undoubtedly impacted by enhancements in adaptive structural management. This result is consistent with the speculation that adaptive control measures improve the effectiveness and speed of IoT structures in the face of seismic hobby.

5.2. *Data acquisition and transmission - > IoT for enhanced seismic resilience*

This hypothesis postulated that the integration of IoT and records acquisition and transmission could result in an improvement in seismic resilience. The findings reveal a drastically giant route loading (T stats = 5.699, P value = 0), emphasizing that development in statistics acquisition and transmission plays a substantial role in utilizing the IoT to enhance seismic resilience. The optimization of records acquisition and transmission strategies is critical for improving the capacity to reveal and make decisions in actual time amidst seismic occasions.

5.3. *Early warning systems - > IoT for enhanced seismic resilience*

The speculation posited that the combination of IoT and Early Warning Systems could contribute to improving seismic resilience. The analysis reveals a statistically considerable route loading (T stats = 6.453, P value = 0), confirming that incorporating early warning systems significantly improves the effectiveness of IoT technologies in strengthening structures toward seismic activities. This emphasizes the essential function that timely alerts play in enhancing the seismic resilience of IoT applications.

5.4. ***Integration** with building codes and standards - > IoT for enhanced seismic resilience*

This speculation predicted that Integration with Building Codes and Standards and IoT for Enhanced Seismic Resilience might show a tremendous correlation. The findings imply a considerably improved path loading (T stats = 9.69, P value = 0), which shows that the seamless incorporation of IoT technology with nicely set constructing codes and standards appreciably enhances the resistance of structures to seismic activities. IoT packages must follow regulatory frameworks to boost seismic resilience, as demonstrated by this result.

5.5. *Real-time monitoring and analytics - > IoT for enhanced seismic resilience*

For Enhanced Seismic Resilience, the hypothesis proposed an astounding correlation among Real-Time Monitoring and Analytics and IoT. The analysis results display a high course loading (T records = 14.713, P value = zero), suggesting that the utilization of IoT technology to decorate seismic resilience is considerably aided by real-time monitoring and analytics. This highlights the criticality of right away reading and interpreting statistics to maximize the performance of IoT programs in the face of seismic pastimes.

The analysis of every speculation presents persuasive evidence that Adaptive Structural Control, Data Acquisition and Transmission, Early Warning Systems, Integration with Building Codes and Standards, and Real-Time Monitoring and Analytics are crucial IoT additives to enhance the seismic resilience of systems. The consequences of this take a look at offer giant contributions to the fields of academia and industry by using losing mild at the problematic interplay of features among those constructs and their cumulative impact on seismic resilience.

6. Implications of the study

6.1. *Empirical implications*

The studies establish a framework that may be utilized to understand and incorporate IoT into techniques to improve seismic resilience. This framework is a basis for subsequent empirical investigations, permitting students to discover contexts and beautify them to excellent environmental and structural attributes.

6.2. ***Managerial** implications*

The findings offer practical suggestions for infrastructure improvement agencies and government, presenting managerial implications. Integrating IoT technology into real-time monitoring and structural making plans is an essential administrative method that improves readiness and agility in the face of seismic incidents.

7. Limitations of study

Despite the good output of the research, it is utmost to realize the limitations of this research. Primary limitations to this research were that it was conducted in a limited area, and it covered only a sample of 141 participants. This, in turn, will tend to restrict the generalization of the results to other geographical and demographic conditions. Other researchers may use these results as a precedent for generalizing these findings to other geographical regions for the purpose of enhancing the external validity of this model with an improved sample size.

8. Conclusion

The research article analyzes the use of Internet of Things (IoT) technology in building up resilience against seismic activity. The structural adaptive control, real-time monitoring, early warning systems, data acquisition and transmission, and building standards and codes integration indicated as the key features. The research study finds that all of the features make a substantial contribution towards making buildings resilient against seismic activity. The structural adaptive control and real-time monitoring provide dynamic response and quick analysis of data, which are crucial at a time when the building has experienced occurrence of an earthquake. The early warning systems provide instant information to be acted upon, whereas the use of building standards integration provides the feature of compliance and safety. The research study captures the key contribution of IoT technology towards reducing the seismic risks and providing improvement towards structural resilience. Future research has to look at these results within other geographical places of implementation for further research validity of the results. All in all, the use of IoT in structural preparation and monitoring emerges as a strategic tool to build up preparation and resilience against seismic incidents.

CRediT authorship contribution statement

Abdullah Alsehaimi: Writing – review & editing, Supervision, Project administration, Funding acquisition, Formal analysis, Data curation. **Moustafa Houda:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Funding acquisition, Conceptualization. **Ahsan Waqar:** Writing – review & editing, Writing – original draft, Conceptualization. **Saleh Hayat:** Writing – review & editing, Software, Methodology, Data curation. **Faizan Ahmed Waris:** Writing – review & editing, Software, Methodology. **Omrane Benjeddou:** Visualization, Validation, Supervision, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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