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Review Article

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Digital Twin Applications in Biomaterials Science: Toward Predictive Design and Personalized Healthcare

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Abstract
The term "Digital Twin" (DT) is widely used to describe a dynamic digital replica of a real-world system, process, or object. Its active, bidirectional connection with its physical counterpart enables real-time data updates. It is not merely an upgrade of software systems, but a fundamental transformation in how an organization operates and delivers value to its customers. Digital twin technology is emerging as a transformative paradigm in biomaterials science, bridging the gap between computational modeling and real-world clinical applications. This paper explores the integration of Digital Twins (DTs) to move beyond traditional "one-size-fits-all" approaches toward predictive design and personalized healthcare. DT technology enables the prediction of disturbances or changes in physical systems, biological processes, and clinical conditions. With the potential to transform patient diagnosis and treatment, the applications of Digital Twins (DTs) in healthcare and medicine are highly promising. However, achieving their intended objectives remains challenging due to issues such as biological heterogeneity, ethical considerations, and technical limitations. Some of these challenges may be addressed through advances in multimodal deep learning, real-time data integration, and intelligent simulation frameworks. This paper outlines the fundamental concepts underlying Digital Twins (DTs), the requirements for their application in medicine, and their current and future roles in healthcare. This review highlights how advancing DT maturity can enable a shift from reactive medical interventions to proactive, data-driven approaches, ultimately improving patient outcomes and accelerating the translation of laboratory-scale innovations into clinical practice.

Keywords:
digital twins; personalized medicine; precision diagnosis; clinical optimization; biological heterogeneity; physical modeling

1. Introduction

The demand for healthcare services is increasing due to growing public awareness of healthy living, preventive care, and overall well-being. To meet the demand for earlier, faster, more accurate, and more personalized diagnosis and treatment, healthcare professionals are increasingly exploring advanced digital technologies and data-driven approaches. Digital Twin technology represents a cutting-edge strategy with transformative potential in the medical field [1–3].

The term "digital twin" refers to a dynamic virtual representation of a real-world system, process, or entity that is continuously updated through data integration, sensor inputs, and computational modeling. These models are continuously updated based on operational data and the current state of the corresponding physical system. Digital Twins, as opposed to static simulations, represent the current operational state of their physical counterparts. They support proactive interventions, system optimization, and informed decision-making by modeling and forecasting the state, performance, and potential outcomes of the corresponding physical system. Additionally, they can contribute to extending service life [4–6]. Digital Twin technology has gained widespread adoption due to continuous advancements in information technology and has

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progressively expanded across multiple sectors, including manufacturing, urban planning, and healthcare [Figure 1].

In healthcare, Digital Twin technology can provide a deeper understanding of human physiological dynamics by integrating patient-specific data with predictive models. It enables healthcare professionals to develop virtual representations of organs, biological systems, and, potentially, entire individuals. These models can be used to predict how a patient will respond to treatment, simulate disease progression, and evaluate the outcomes of medical interventions before they are administered to a real patient. As a result, care pathways are optimized, individualized treatment plans are developed, and more informed clinical decisions are made.

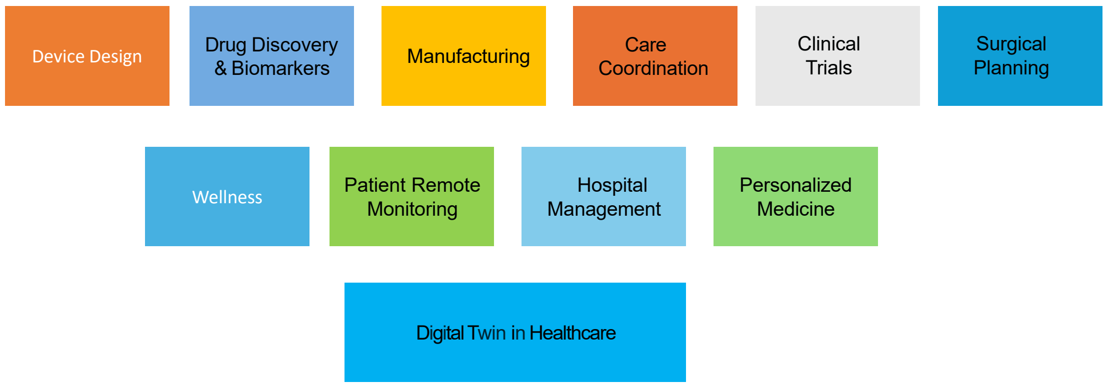

Figure 1: Prevalent healthcare applications of digital twin.

By enabling proactive health interventions and continuous monitoring based on real-time data from virtual models, Digital Twins enhance patient management in healthcare. In this context, the physical entity corresponds to the patient under study in real life and integrates environmental, lifestyle, physiological, and molecular data over time, while the virtual entity serves as a digital replica of the patient or, in some cases, a virtual environment representing multiple digital patients. Because these replicas incorporate key patient-specific characteristics, data from the physical system can be used to simulate biological processes and predict disease progression. The physical and virtual entities interact through a bidirectional connection, enabling continuous updates to parameters representing the state of the physical system. A medical Digital Twin can function as a virtual environment in which clinical decisions are evaluated before implementation in real patients, thereby supporting personalized therapy through dynamic modeling of biochemical pathways, cells, tissues, diseases, and potentially whole-body systems in real time. By considering patients at an individual level, DTs offer opportunities to deliver more personalized treatments and preventive strategies. Developing a medical Digital Twin requires the integration of diverse data sources, including clinical records, real-time physiological changes, and individual omics data [Figure 2]. For instance, Digital Twins (DTs) may enable the generation of customized, on-demand risk profiles for chronic diseases, facilitate personalized lifestyle recommendations to reduce these risks, issue alerts for preventive diagnostic testing, and provide warnings regarding imminent health hazards. They may also allow prediction of the efficacy and potential side effects of specific medications, as well as assessment of individual patient responses to treatment. Thus, Digital Twins may serve as an important technological foundation for advancing individualized medicine [7–15].

Digital Twin technology leverages machine learning algorithms and patient data analysis to enable predictive analytics and preventive interventions. Digital Twins can identify high-risk individuals, forecast disease progression, and recommend preventive actions. This proactive approach enhances patient safety, long-term outcomes, and resource allocation within healthcare systems [16]. Consequently, Digital Twin technology may significantly improve healthcare systems through real-time data integration, advanced analytics, and virtual simulation. Predictive analytics, training simulations, clinical operations, and patient care can all be enhanced through its application. This review focuses on how Digital Twins in healthcare may improve patient outcomes, operational efficiency, and overall healthcare quality.

In recent years, the concept of the Digital Twin has attracted increasing interest from researchers and academics. As commercial and academic research advances, the distinction between Digital Twins and related concepts, such as simulations, digital models, and cyber-physical systems, requires clearer definition. Initially, the scope of the Digital Twin encompassed both physical and virtual entities, along with the interactions between them [17].

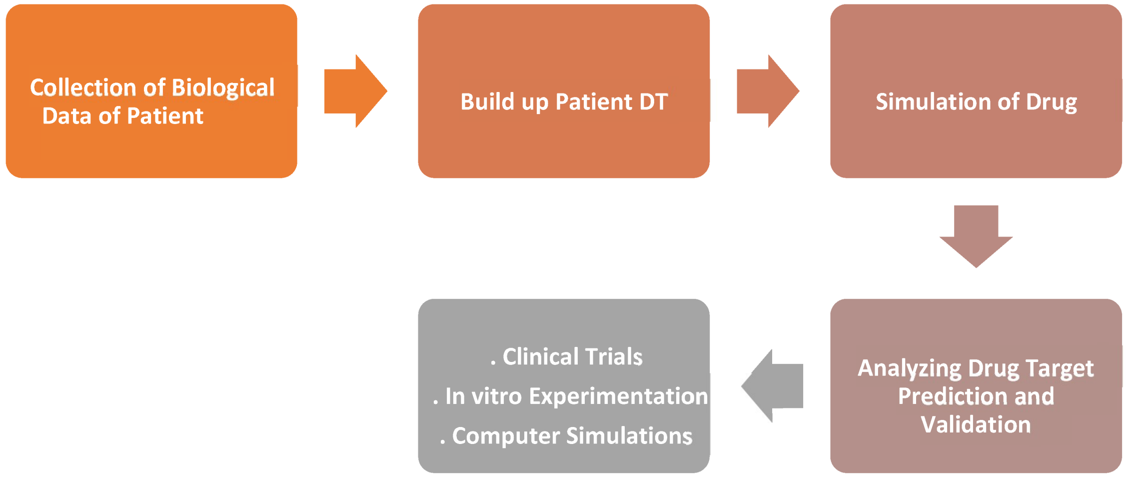

Figure 2: Digital twin in drug discovery through clinical trials.

Rapid advancements in big data analytics, sensor technology, communication systems, the Internet of Things (IoT), and simulation technologies have driven the evolution of this concept [18]. The Internet of Things (IoT) refers to a network of physical objects — "things"— embedded with sensors, software, and other technologies that enable them to connect and exchange data with other devices and systems over the internet. This technological growth has significantly stimulated research on Digital Twins.

The concept was later extended to health and well-being, where a Digital Twin may represent the digital counterpart of a living or non-living physical entity [19]. A Digital Twin is a dynamic concept that represents a virtual model of human organs, tissues, cells, or microenvironments, continuously adapting to real-time data and predicting future states [20]. However, with advances in technology, a Digital Twin has evolved beyond a simple digital model connected to its physical counterpart. Through a closed-loop interaction between the digital and physical environments, it becomes an intelligent and continuously evolving model capable of forecasting future states, including defects, damage, and failures, as well as optimizing processes.

In general, the technologies required for Digital Twins can be categorized into two main approaches: one integrates data and knowledge across multiple scales into a physics-based or mechanical model, while the other employs a data-driven statistical model [21,22]. The numerical model is used to compute structural performance, whereas the analytical model supports structural analysis. In real time, structural insights are extracted from sensor data using artificial intelligence (AI) models trained on numerical simulations and empirical datasets. Artificial Intelligence (AI) refers to the simulation of human intelligence by machines, particularly computer systems. It involves the development of algorithms that enable computers to perform tasks that typically require human cognition, such as learning, reasoning, and problem-solving.

Large companies have adopted Digital Twin technology to enhance production and identify system issues, as it is significantly transforming multiple industries. The healthcare sector is also increasingly embracing this innovative technology. In this context, patients can be represented through Digital Twins as virtualized, standalone entities that can be utilized across various healthcare applications [23,24]. This approach holds considerable potential for improving both hospital operations and individual patient care and diagnosis.

A Digital Twin in healthcare is a computerized model of a real-world entity or process, such as a patient, the human body, or a hospital environment. The development of core technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI), along with the increasing availability of diverse, accurate, and accessible data sources—including behavioral, biometric, emotional, cognitive, and psychological data—has driven growing interest in the study and application of Digital Twins within the healthcare sector [25]. Digital twin technology has the potential to significantly enhance patient care through the use of real- time data integration, advanced analytics, and tailored insights.

Electronic Health Records (EHRs), wearable technologies, medical devices, and genetic data are among the key sources of patient information that can be collected and analyzed using these tools [26]. Digital Twins provide a comprehensive view of the patient by integrating and analyzing this diverse data, enabling healthcare professionals to design personalized treatment plans [17,20,27]. This approach may improve treatment outcomes by considering each patient's unique characteristics, medical history, genetic profile, and real-time physiological data when tailoring therapies and medications [28–30].

Digital Twins can assist medical personnel in making accurate and timely diagnoses [31]. By simulating different diagnostic scenarios through the analysis of patient data and symptoms, Digital Twins can support differential diagnosis and enable the identification of patterns that may not be detected through conventional diagnostic methods alone [26,32]. This leads to more effective and targeted treatments by improving diagnostic accuracy, reducing errors, and enabling earlier intervention. Continuous patient monitoring is made possible through the integration of Digital Twins with real-time data from wearable technologies, remote monitoring systems, and Internet of Things (IoT) devices [33]. Digital Twins can identify early indicators of deterioration or abnormalities by continuously monitoring vital signs, physiological parameters, and other health-related data. This enables healthcare professionals to take preemptive measures, prevent complications, and optimize treatment strategies. Patients with chronic illnesses benefit most from real-time monitoring through Digital Twins, as it supports remote patient management and reduces the need for frequent hospital visits [26,34,35].

Patients can take an active role in their own care with the help of Digital Twins [36]. Access to Digital Twin data, including treatment plans, lifestyle modifications, and self-management strategies, enables patients to take greater responsibility for their health management, resulting in improved engagement [37]. Additionally, Digital Twins can enhance communication and collaboration between patients and healthcare professionals, thereby promoting shared decision-making and patient-centered care [38].

To predict disease progression and treatment outcomes, these technologies utilize machine learning algorithms and predictive analytics [28]. Digital Twins can identify high-risk individuals, forecast potential complications, and recommend preventive measures by analyzing patient data and historical trends. Ultimately, this proactive approach may improve patient safety and long-term outcomes by helping healthcare providers anticipate adverse events, optimize treatment plans, and intervene earlier [39].

Digital Twins can facilitate seamless continuity of care by securely sharing patient data across various healthcare settings and providers [35]. By ensuring that all involved healthcare professionals have access to the most current and comprehensive patient information, this approach supports coordinated care, reduces unnecessary duplication of tests, and minimizes medical errors. Digital Twins may also enhance collaboration and communication among healthcare teams, thereby improving overall patient care [38,40].

2. Digital Twin Technology for the Identification of Health Risks

Digital Twin technology holds significant potential for predictive analytics and preventive healthcare interventions by integrating real-time data with advanced analytical methods. Digital Twins can help forecast disease progression, identify potential health risks, and support pre-emptive interventions by integrating patient data with machine learning algorithms and predictive modeling [17]. Texture analysis methods may further support Digital Twin applications by improving the interpretation and characterization of biological and medical images [41].

A holistic view of an individual's health can be achieved by integrating and analyzing diverse patient data, including medical history, lifestyle factors, genetic information, and real-time physiological measurements [34]. Digital Twins can identify patterns, correlations, and anomalies in data by leveraging machine learning algorithms and advanced analytics. This capability enables healthcare professionals to detect health risks at an early stage, including the onset of chronic diseases, potential adverse drug reactions, and possible complications.

Early detection enables effective mitigation and management of these risks by allowing timely interventions and preventive measures [42]. By utilizing patient data and historical patterns, Digital Twins can model disease progression [20]. They can also develop predictive models to forecast disease trajectories by analyzing patterns, treatment outcomes, and individual patient characteristics. Healthcare professionals can use these insights to anticipate potential side effects, adjust treatment regimens, and optimize therapies to slow or prevent disease progression. By accounting for each patient's unique characteristics, including genetic makeup, lifestyle, and prior treatment responses, Digital Twins enable individualized disease modeling, resulting in more accurate predictions and personalized treatment strategies [43]. Digital Twins can support risk stratification by classifying patients into different risk groups based on their health data and predictive models [44].

Healthcare professionals can allocate resources more effectively, prioritize preventive care, and imple-

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ment targeted interventions by identifying high-risk individuals. Digital Twins provide valuable insights into which patients are most likely to benefit from specific interventions, lifestyle modifications, early screening, or preventive measures. This targeted approach reduces costs, improves patient outcomes, and enhances the efficient allocation of healthcare resources [45]. By providing real-time alerts regarding potential health risks, Digital Twins can facilitate proactive interventions and preventive care [46]. Through continuous monitoring of patient data, Digital Twins can identify early warning indicators, detect deviations from normal health parameters, and support timely clinical interventions. Digital Twin–based preventive care may include lifestyle modification recommendations, medication adherence support, screening reminders, and personalized health guidance [44].

Disease prevalence patterns can be identified through predictive analytics applied to these data. By leveraging Digital Twins, healthcare professionals can develop population-level preventive strategies and targeted interventions, including community-based programs, immunization campaigns, and public health initiatives. This population health approach aims to prevent disease onset, improve health outcomes, and reduce the overall burden on healthcare systems [47,48].

3. Digital Twins for Addressing Clinical Bottlenecks and Optimizing Healthcare Operations

Digital Twin technologies have significant potential to enhance clinical operations within healthcare systems. By creating virtual representations of physical systems and integrating real-time data, Digital Twins enable healthcare providers to improve resource allocation, analyze and optimize workflows, and increase overall operational efficiency [31]. Digital twins provide healthcare professionals with a comprehensive representation of clinical workflows, enabling the evaluation and optimization of healthcare procedures. By integrating data from multiple sources, including administrative systems, medical devices, and electronic health records, digital twins facilitate the identification of bottlenecks, operational inefficiencies, and areas requiring improvement [27].

Through such analyses, healthcare practitioners can improve the efficiency of clinical operations by streamlining workflows, reducing delays, and eliminating unnecessary tasks. Furthermore, by analyzing patient data, historical trends, and real-time information, digital twins enable healthcare systems to optimize resource allocation through insights into patient volumes, demand patterns, and resource utilization [49]. This facilitates the efficient distribution of personnel, equipment, and facilities, thereby ensuring optimal resource utilization and reducing patient wait times. Additionally, digital twins support capacity planning by enabling healthcare institutions to anticipate future demand and make well-informed decisions about resource investments and infrastructure expansion. By applying machine learning algorithms and predictive analytics, digital twins further enhance operational decision-making capabilities. They analyze data from multiple sources, including patient flow, staffing levels, and equipment utilization, to predict future operational scenarios [16]. This enables healthcare practitioners to implement proactive measures, such as rescheduling procedures, optimizing bed allocation, and adjusting staffing schedules, in order to maximize resource utilization and improve patient care [16]. By continuously monitoring key performance indicators, patient flow, and operational data, digital twins can rapidly identify deviations from expected patterns and generate timely alerts [50,51]. This capability minimizes operational disruptions and ensures continuity of care by enabling healthcare professionals to promptly address issues such as equipment malfunctions, staffing shortages, and patient bottlenecks.

In addition, digital twins contribute significantly to patient safety and quality improvement initiatives within clinical operations [52]. Through the analysis of adverse events, near misses, and process variations, digital twins help identify areas for improvement. Healthcare providers can utilize digital twins to standardize procedures, implement evidence-based practices, and monitor adherence to established protocols. Consequently, this approach enhances patient safety, reduces the likelihood of errors, and fosters a culture of continuous improvement within healthcare operations.

Digital Twins can create a shared virtual platform that facilitates communication among departments and healthcare professionals, supports collaborative patient-care planning, and enables real-time data sharing [49,53]. By providing a unified digital environment, digital twins enhance real-time data exchange and teamwork, leading to more efficient communication and coordinated care delivery. This ultimately improves clinical operations and patient outcomes by strengthening interdisciplinary collaboration, reducing delays, and enhancing care coordination. Furthermore, digital twins enable continuous monitoring and iterative improvement of clinical processes by collecting and analyzing operational data over time, thereby providing insights into performance trends. Based on real-time feedback, healthcare providers can evaluate the impact of process modifications, identify patterns, and refine operational strategies. This iterative improvement approach allows healthcare organizations to eliminate inefficiencies, adapt to changing demands, and continuously enhance clinical operations.

4. Digital Twin Technology for Advanced Healthcare Simulation and Training

In the healthcare industry, digital twin technology can provide valuable training and simulation opportunities [54]. By creating virtual representations of real-world systems integrated with real-time data and advanced simulation models, digital twins offer healthcare professionals a safe and realistic environment in which to practice complex procedures, develop clinical skills, and improve decision-making abilities.

This section examines the role of Digital Twins in healthcare training and simulation [55].

Digital twins enable surgeons and other medical professionals to practice and refine their surgical skills within a simulated environment [56]. By replicating surgical procedures and modeling a range of clinical scenarios, digital twins allow clinicians to evaluate different techniques, gain practical experience, and enhance procedural proficiency without exposing real patients to risk. This immersive form of training supports the development of hand–eye coordination, technical surgical skills, and clinical decision-making abilities, ultimately contributing to improved patient outcomes and enhanced patient safety.

Digital twins provide medical professionals with a platform for modeling and evaluating various medical treatments [17]. By simulating both invasive and non-invasive procedures, digital twins enable clinicians to practice and refine their techniques across a range of interventions, including catheter insertions, ultrasound-guided procedures, and other clinical applications. By providing a realistic virtual environment, Digital Twins can help improve clinical confidence, procedural competence, and patient safety during surgical and diagnostic procedures.

Thus, digital twins may be particularly valuable for training healthcare professionals in emergency response situations [57]. By simulating critical events such as cardiac arrests, trauma cases, or mass-casualty incidents, digital twins enable healthcare professionals to practice response protocols, teamwork, and decision-making under high-stress conditions. This form of training enhances preparedness for real-world emergencies, strengthens interdisciplinary coordination, and improves crisis management capabilities, ultimately contributing to better patient outcomes.

Healthcare professionals can develop and refine clinical decision-making skills by using Digital Twins to simulate complex clinical scenarios. By integrating patient data, medical history, and real-time monitoring information, digital twins provide healthcare professionals with realistic cases for analysis, diagnosis, and treatment planning. These interactive simulations offer a valuable educational experience, enabling clinicians to enhance diagnostic reasoning, evaluate multiple treatment options, and make informed clinical decisions within a risk-free environment.

Digital Twins may also support interprofessional collaboration by providing a shared virtual platform for communication, coordination, and multidisciplinary decision-making [58]. Through this platform, healthcare providers can efficiently coordinate patient care, exchange information, and engage in interdisciplinary teamwork. This improves patient outcomes, strengthens collaborative practice, and enhances understanding of each professional's role by supporting comprehensive and well-coordinated care delivery. In addition, Digital Twins can support continuous professional development by enabling scenario-based learning, self-paced training, and repeated practice [Table 1]. By enabling self-paced learning and ongoing training, they promote lifelong learning, support professional growth, and ensure that healthcare professionals remain well-prepared to deliver high-quality care.

Table 1: Classes of digital twin in healthcare (Modified from the reference [59]).

Physical Entity	Mechanism	EndPoint
Lung	Runs simulations of blood and oxygen flow	Predict ventilation requirements
Heart	Simulates the structure and physiologic function of the heart	Customization and optimization of cardiac devices
Heart	Simulates the structure and physiologic function of the heart	Cardiac resynchronization
Heart	simulated TAVR implantations with different aortic prosthesis	Surgical planning

Table 1: *Cont.*

Physical Entity	Mechanism	EndPoint
Spine	Predict Vertebral Fracture after Stereotactic Body Radiotherapy	Optimal radiation plan to minimize treatment side effects
Alzheimer's disease	Predicting the individual outcome in neurological diseases	DT of controls of clinical trial and ultimately clinical interventions
Breast lesions	Image based virtual patients comparing digital mammography to tomosynthesis	Determine which imaging tool is better at detecting breast lesions
Oropharyngeal cancer	Optimal treatment selection	Determine optimal treatment plan for oropharyngeal cancer
Type 2 Diabetes	Disease reversal in type 2 diabetes	Randomized control trial examining twin precision treatment vs. standard of care
Biomanufacturing	Adjust input conditions Key and Critical Process Parameters	Predictive biomanufacturing

Digital twins can also serve as valuable tools for healthcare innovation and research [59,60]. They enable researchers to conduct hypothesis testing, perform simulations, and carry out data analysis. These technologies allow researchers to simulate diverse patient populations, treatment modalities, and disease scenarios, generating insights that may support evidence-based practice and healthcare innovation.

5. Conclusions

In conclusion, Digital Twin technology holds considerable promise for enhancing patient care and improving healthcare systems. By combining real-time data, advanced analytics, and virtual simulations, digital twins enable personalized treatment planning, predictive analytics, improved clinical operations, and immersive training opportunities. Using Digital Twins, medical professionals may monitor patients in real time, support more accurate diagnosis, and take pre-emptive action to reduce the risk of adverse outcomes. Additionally, this approach promotes collaborative decision-making between patients and healthcare professionals and empowers individuals to actively participate in their own care.

Furthermore, digital twins enhance operational efficiency, improve resource allocation, and streamline healthcare operations. The healthcare industry stands to gain significantly from digital twin technology, with potential improvements in patient outcomes, safety, and innovation. However, successful implementation requires addressing challenges related to data privacy, interoperability, data quality, ethics, resource intensity, workflow integration, validation, education, scalability, and cultural change.

List of Abbreviations

AI	Artificial Intelligence
DT	Digital Twin
IoT	Internet of Things

Author Contributions

Conceptualization, methodology, visualization, supervision: A.V.; Validation, formal analysis: R.H.; Investigation, resources, data curation, writing—original draft preparation, writing—review and editing: H.R. All authors have read and approved the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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AI Declaration

The authors acknowledge the use of writing tools (https://quillbot.com/) to assist in refining the academic language and improving the accuracy of the manuscript. The prompts used included requests to improve the academic tone and enhance language accuracy, including grammatical structures, punctuation, and vocabulary.

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