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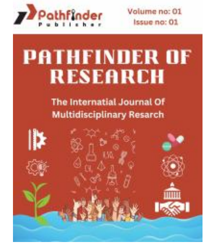

Review Research

Database Management in the Era of Big Data: Trends, Challenges, and Breakthroughs

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ABSTRACT

The rapid development of Big Data has profoundly transformed database management systems, necessitating novel solutions to address the escalating complexity, volume, and variety of data. This analysis examines the principal trends, difficulties, and technological advancements impacting database administration due to the rapid increase in data volume. Significant innovations, including NoSQL databases, cloud computing, distributed architectures, and AI-driven automation, have transformed the methods by which businesses store, process, and analyze extensive datasets. Nevertheless, enduring issues persist, encompassing data security concerns, scalability constraints, and the necessity for enhanced performance. This study brings together recent research to look at how modern database systems have changed over time to deal with these problems and make them more efficient, secure, and able to process data in real time. Additionally, new technologies like blockchain and edge computing are examined for their contributions to improving security and decentralization in database administration. The results underscore the significance of hybrid database models, intelligent automation, and regulatory compliance frameworks in influencing the future of database systems. As enterprises adjust to the needs of Big Data, the integration of new technologies will be essential for achieving scalable, secure, and high-performance database management systems.

1. Introduction

The expansion of big data has revolutionized database administration, requiring strong solutions for data storage, retrieval, and security **(Chen, Mao, & Liu, 2014).** The rapid proliferation of digital information, propelled by social media, e-commerce, the Internet of Things (IoT), and artificial intelligence (AI), has compelled enterprises to pursue more scalable and efficient database systems **(Gandomi & Haider, 2019)**. Conventional relational database management systems (RDBMS) were once the benchmark for managing structured data, ensuring consistency, integrity, and transaction support. Nonetheless, their constraints in managing extensive, high-speed, and diverse datasets have led to the emergence of alternative architectures **(Stonebraker, 2012).** Big data is defined by its volume, velocity, and diversity, which pose challenges to conventional database administration methods. Organizations must handle structured data from relational databases as well as semi-structured and unstructured data from emails, social media, video content, and sensor networks **(Sun, Dong, & Huang, 2018).** This transition has resulted in the use of NoSQL databases, cloud-based solutions, and distributed ledger technologies that offer enhanced flexibility and scalability **(Han et al., 2019).**

In addition to data storage and retrieval, contemporary database administration includes real-time data processing, advanced security measures, and AI driven automation to optimize productivity. Machine learning (ML) and artificial intelligence (AI) are progressively included in database systems to optimize query execution, automate indexing, and improve anomaly detection **(Thakkar et al., 2020).** Concurrently, blockchain technology is being investigated to safeguard database transactions and maintain data integrity in critical areas such as healthcare and banking **(Zheng et al., 2017).** The increasing dependence on cloud-based systems has transformed database management paradigms. Cloud database platforms, such as Amazon Web Services (AWS), Google Cloud BigQuery, and Microsoft Azure SQL Database, enable enterprises to utilize scalable and economical storage solutions without necessitating substantial on-premises infrastructure **(Mell & Grance, 2011).** The emergence of serverless computing allows enterprises to utilize dynamic scalability and automated administration, hence decreasing operational overhead **(Verma et al., 2019).** Organizations gain from diminished maintenance expenses, improved disaster recovery functionalities, and streamlined database management **(Kuddus et al., 2020).** Cloud-based systems provide multi-tenancy, allowing different users to use the same database resources while ensuring data isolation and security **(Li et al., 2020).** One important development is the shift from centralized to distributed and federated database structures. Distributed database systems, shown as Google Spanner, duplicate data over several nodes, hence enhancing fault tolerance and data availability **(Dean & Ghemawat, 2008).** Federated databases provide the smooth integration of diverse databases, improving interoperability in sectors such as healthcare and financial services **(Özsu & Valduriez, 2020).** These architectures provide resistance to system failures and enhance data redundancy; hence, they maintain business continuity and mitigate downtime risks. As international businesses broaden their operations, federated database management systems (FDBMS) are essential for integrating diverse data sources across geographically distributed sites.

Although these gains, considerable problems remain. Scalability is a critical issue as businesses endeavour to process petabyte-scale collections effectively. Conventional databases encounter challenges in sustaining performance while guaranteeing data consistency, requiring novel strategies such as partitioning, caching, and load balancing **(Dean & Ghemawat, 2008).** The vast amount of data produced every day necessitates efficient indexing algorithms and parallel processing methods to improve query execution speeds. Data sharding approaches, which include partitioning big databases into smaller, manageable portions dispersed over numerous servers, have emerged as a feasible alternative **(Brewer, 2012).** Security and data privacy are significant challenges in contemporary database administration. Due to escalating cyber risks and rigorous data protection rules such as the General Data Protection Regulation (GDPR), enterprises are required to establish comprehensive encryption, access control, and compliance frameworks **(Zhang et al., 2020).** The advent of quantum computing involves the implementation of post-quantum cryptography methods to safeguard future database transactions **(Chen et al., 2016).** Quantum decryption techniques may be able to break common encryption methods like AES and RSA. To protect data permanently, we need to look into lattice-based and hash-based cryptographic algorithms. A significant problem in large database administration is ensuring data consistency and transaction integrity. Traditional databases adhere to ACID principles for data dependability; however, several NoSQL systems emphasize availability and partition tolerance, resulting in eventual consistency models **(Han et al., 2019)**. This discrepancy may lead to the retrieval of outdated data from remote nodes, thereby affecting the precision of decision-making. Quorum-based replication and multi-version concurrency control (MVCC) are being investigated to address these challenges while ensuring high availability **(Sunny et al., 2020b).**

Several advancements, such as AI driven databases, blockchain integration, and edge computing, influence the future of database administration. AI-driven systems like Oracle Autonomous Database automate performance optimization and security updates, hence diminishing administrative intricacy **(Oracle, 2021).** AI-driven databases utilize predictive analytics to enhance task allocation, minimizing bottlenecks and augmenting resource usage. Adaptive query processing algorithms that are based on deep learning let computers change their execution plans based on changing data patterns **(Zheng et al., 2017)**. Blockchain-based databases offer decentralized and immutable storage solutions, enhancing security in industries that need elevated data integrity **(Casino et al., 2021).** Hybrid blockchain-database technologies, such as BigchainDB and Hyperledger Fabric, enable organizations to preserve immutable audit trails while ensuring the efficiency of traditional databases **(Androulaki et al., 2018).** These solutions are especially advantageous in financial transactions, supply chain management, and digital identity verification. Moreover, edge computing facilitates real-time data processing near the source, hence minimizing network latency and enhancing efficiency in IoT applications **(Shi et al., 2016)**. Centralized cloud-based database systems have substantial latency challenges due to the immense volume of real-time data generated by IoT devices. Edge computing design facilitates data processing at edge nodes, thereby decreasing reaction times and bandwidth utilization **(Zhang et al., 2020).** The incorporation of edge AI, wherein machine learning models operate directly on edge devices, significantly improves real-time decision-making skills **(Li et al., 2021)**. Edge databases like InfluxDB and Apache Ignite offer time-series data analysis functionalities, rendering them appropriate for predictive maintenance, autonomous systems, and real time analytics applications. The emergence of quantum computing presents both obstacles and possibilities for database administration. Quantum algorithms possess the capacity to transform query optimization and parallel processing, markedly improving database performance **(Gyongyosi & Imre, 2021).** Quantum-enhanced databases might offer exponential improvements in intricate computer processes, including extensive simulations and deep learning model training. When quantum technology is added to current database systems, problems need to be fixed related to fixing errors, making sure qubits are stable, and making algorithms. As companies grow more data-centric, database management systems must evolve to address emerging issues and technological progress **(Chowdhury et al., 2020).**

This review article analyses the principal trends in database administration, the difficulties associated with large data management, and the innovations influencing the future of data storage and retrieval. By comprehending these advancements, researchers and practitioners may manoeuvre through the changing terrain of database technology and enhance their data management techniques for new applications. Future research should focus on making it easier for different database systems to work together, making data processing more energy efficient, and coming up with long-lasting database models that use as little energy as possible and have minimal impact on the environment. In contrast to earlier studies that only looked at certain areas, these compares NoSQL, cloud-native solutions, and AI driven database optimization to find trends, problems, and successes in database administration. This study also delineates research deficiencies in regulatory issues, quantum computing applications, and self-healing databases, establishing a basis for forthcoming database advancements.

2. Research Methodology

2.1 Systematic Literature Review

This study used a systematic literature review (SLR) methodology to analyse trends, difficulties, and advancements in database administration within the context of Big Data. A systematic approach guarantees an organized and replicable technique, reducing bias and enhancing the trustworthiness of results **(Kitchenham, 2004).** We executed the study by conducting a comprehensive examination of peer-reviewed journal publications, conference proceedings, industry reports, and reputable white papers released from 2010 to 2023.

2.2 Sources of Data and Search Technique

An extensive search was performed in prominent digital repositories, including IEEE Xplore, ACM Digital Library, SpringerLink, Scopus, and Google Scholar, to locate pertinent material. The inquiry included phrases like Big Data database management, NoSQL scalability, distributed database security, and AI in databases. We utilized Boolean operators (AND, OR) to enhance the findings, ensuring the incorporation of varied views from several fields **(Webster & Watson, 2002)**. The study employs a multi-source search technique to guarantee thorough coverage of theoretical and empirical studies. The incorporation of industry studies from prominent technology companies like IBM, Oracle, and Microsoft enhances the practical significance of the conclusions.

2.3 Criteria for Inclusion and Exclusion

The selection of sources was governed by rigorous inclusion and exclusion criteria to improve research quality. The studies incorporated in the review concentrated on database administration within Big Data environments, provided empirical evidence or theoretical assessments, and were published in peer-reviewed journals or reputable sources. Furthermore, only papers in the English language were included to ensure analytical consistency. This review rejected non-peer-reviewed literature, studies that only addressed standard RDBMS without including Big Data, and research that lacked methodological openness. By adhering to these requirements, the study guarantees the incorporation of pertinent and high-Caliber sources that enhance a thorough comprehension of the area.

2.4 Data Collection and Analysis

A thematic analysis was used to classify findings into three principal categories: (1) Trends in database administration, (2) Issues associated with Big Data, and (3) Technology advancements. Each chosen research study was rigorously evaluated for its methodology, principal findings, and significance for contemporary database management systems. Finding common themes and patterns in database management research, getting both quantitative and qualitative data from the studies that were looked at, and figuring out how changes in technology affect the efficiency and security of databases were all parts of the data extraction process. This investigation provided insights that synthesized major advances and upcoming solutions in database administration, ensuring a comprehensive grasp of the field's progress.

2.5 Reliability and Accuracy

To augment study validity, many researchers independently evaluated and authenticated the chosen publications prior to synthesis. Consensus-based debate addressed discrepancies in selection or interpretation **(Tranfield et al., 2003)**. The summarized findings were cross-validated with industry reports to guarantee relevance and practical applicability. Inter-rater reliability was also established by having different researchers code themes independently and then iteratively improving the codes to make sure that the results were consistent. This meticulous procedure enhances the study's credibility and mitigates the potential for subjective bias in outcome interpretation.

2.6 Limitations of the Study

Despite the thorough methodology, this review possesses limitations. The dependence on English language sources may create a linguistic bias, thereby excluding important non-English contributions. Moreover, despite efforts to incorporate numerous database technologies, the representation of private systems without open-access documentation may be insufficient. A further issue is the evolving nature of database technology. As database structures perpetually advance, certain emergent technologies may lack comprehensive examination in academic literature. Future research should do longitudinal analyses to monitor changing patterns beyond 2023, integrate multilingual sources for comprehensive coverage, and broaden the scope to include new database architectures that have not yet been extensively examined. These factors will facilitate a broader and more comprehensive grasp of the ever-evolving database management world.

3. Results and Discussion:

3.1 Advancement of Database Management in the Big Data Age

The advent of big data has revolutionized database management systems (DBMS) from conventional relational models to intricate and distributed structures. The advancement of database technology demonstrates the need to manage growing data quantities, defined by the three V's volume, velocity, and variety **(Gandomi & Haider, 2019).** Historically, relational database management systems (RDBMS) like MySQL, Oracle DB, and PostgreSQL have prevailed in data storage because of their organized nature and compliance with ACID (Atomicity, Consistency, Isolation, Durability) principles. As the amount of unstructured and semi-structured data grew, different types of databases (like MongoDB, Cassandra, and CouchDB) and storage systems (like Hadoop, Spark, and Google Bigtable) were created to help with issues of flexibility and scalability **(Stonebraker & Cattell, 2020)**.In addition, database models have improved to multimodal databases, which combine different database types and make it easier for businesses to deal with different types of data structures **(Zikopoulos et al., 2021).** The growing need for real-time analytics has markedly decreased data retrieval latency through the use of in-memory databases like SAP HANA and Redis. These improvements illustrate the evolution of database administration to address the increasing complexity of big data applications **(Sunny et al., 2017).**

3.2 Emerging Trends in Big Data Database Management

Numerous technology advancements are transforming database administration to maximize efficiency, augment security, and expand scalability. These tendencies are propelling the subsequent phase of data management in corporate and research settings.

3.3 Cloud-Hosted Database Solutions

Cloud computing has transformed database management by providing economical, scalable, and remotely accessible options. Cloud-based database services, such as Amazon RDS, Microsoft Azure SQL, and Google Cloud BigQuery, provide enterprises improved storage capacities without requiring costly on-premises infrastructure **(Zhang et al., 2021**). Meanwhile, Database-as-a-Service (DBaaS) solutions let enterprises delegate database maintenance responsibilities to cloud providers, facilitating automatic scalability, backup, and performance optimization. Hybrid cloud systems, which combine private and public cloud databases, are increasingly favoured for their ability to optimize security and cost-effectiveness. Recent surveys indicate that more than 60% of organizations are choosing cloud-native database systems, signifying a transition from conventional on-premise architectures **(Elshawi et al., 2020).** Future advancements will concentrate on multi-cloud interoperability, edge-cloud interaction, and improved AI driven resource optimization to augment database efficiency.

3.4 Integration of NoSQL and NewSQL

NoSQL databases have arisen as an alternative to RDBMS, allowing high-performance storage for unstructured and semi-structured data. NoSQL models, including document stores (e.g., MongoDB), key-value stores (e.g., Redis), and wide-column stores (e.g., Apache Cassandra), offer essential scalability for large data applications **(Stonebraker & Cattell, 2020).** However, a significant difficulty associated with NoSQL databases is their absence of ACID compliance, which is essential for transactional applications. This has resulted in the development of NewSQL databases, such as Google Spanner, CockroachDB, and MemSQL, which integrate the scalability of NoSQL with the transactional integrity of RDBMS **(Pavlo et al., 2021).** NewSQL systems mitigate the constraints of conventional databases while providing high availability and fault tolerance, rendering them an ideal selection for enterprise-level applications. Future advancements in this domain encompass AI-enhanced query optimization, automated indexing, and improved multi-cloud database integration to augment dependability and flexibility.

3.5. Edge computing and distributed databases

Edge computing has become a prominent technique for processing data near its origin, thereby minimizing network latency and enhancing reaction times. Distributed databases like Apache Cassandra and Google Bigtable are now incorporated with edge computing frameworks to provide real-time analytics for IoT applications **(Satyanarayanan et al., 2021)**. For example, smart cities, autonomous vehicles, and industrial IoT systems depend on edge databases for the immediate processing of sensor data. The decentralization of data processing guarantees low-latency replies, diminishes dependence on central cloud databases, and enhances bandwidth efficiency **(Hashem et al., 2020).** In the future, the integration of 5G connections, federated learning, and edge AI will provide enhanced real-time decision-making and bolster security inside dispersed database ecosystems.

3.6 Automated and Artificial Intelligence Driven Database Management

Artificial intelligence (AI) and machine learning (ML) are progressively employed in the optimization of databases and the enhancement of security. AI-driven technologies like Oracle Autonomous Database and IBM Db2 AI automate indexing, performance optimization, and query enhancement **(Shanbhag et al., 2021).** Moreover, AI driven anomaly detection systems enhance cybersecurity by detecting illegal database access and possible threats in real-time. AI-driven query optimizers greatly shorten execution times by predicting changes in workload patterns and adjusting the distribution of resources in the right way **(Gai et al., 2021).** Emerging trends suggest that AI-driven self-healing databases, predictive performance analytics, and automated schema development will be pivotal in database administration, further diminishing human involvement and lowering operating expenses.

3.7 Challenges in Big Data Database Management

Notwithstanding considerable progress, the management of large data databases continues to provide several enduring obstacles, including integration complexity and security issues.

3.7.1 Data integration and interoperability

The operation's major challenge in database administration is the integration of diverse data from many sources. Data silos hinder smooth interoperability among systems, necessitating advanced data integration solutions such as Apache NiFi and Talend **(Hashem et al., 2020).** Furthermore, various database designs (e.g., relational, document-oriented, graph databases) necessitate specific integration methodologies, complicating unified data processing. When managing multi-format datasets from different sources, organizations often run into problems with the Extract, Transform, and Load (ETL) processes **(Zikopoulos et al., 2021).** New technologies, such as AI driven ETL pipelines, automated schema matching, and knowledge graph-based data integration frameworks, are meant to make it easier for systems to talk to each other and integrate data.

3.7.2 Security and Data Privacy Issues

The increasing prevalence of cyberattacks underscores the need for database security. Big data databases include sensitive information, rendering them attractive candidates for ransomware attacks, unlawful access, and insider threats **(Gai et al., 2021).** To alleviate security issues, encryption methods, access control systems, and blockchain based security frameworks are being investigated. Nonetheless, executing these ideas without undermining system performance is a considerable difficulty. Methods of data anonymization and differential privacy have been suggested to improve adherence to international data protection rules, including GDPR and CCPA **(Sivarajah et al., 2020)**. In the future, there may be AI powered cybersecurity surveillance, quantum-resistant encryption methods, and zero trust database security systems that will protect all of your data completely.

3.7.3 Scalability and Performance Enhancement

Big data workloads frequently encounter performance limitations resulting from elevated storage and processing requirements. Even though distributed database systems help with scaling issues, the CAP theorem's trade-offs between consistency, availability, and partition tolerance still cause problems **(Brewer, 2020).** Advanced indexing techniques, including adaptive indexing and concurrent query processing, seek to enhance database performance. Furthermore, in-memory databases and caching methods, such as Redis and Memcached, are employed to enhance data retrieval speeds **(Elshawi et al., 2020).** Future research should focus on AI based models for predicting workloads, advanced indexing techniques, and self-optimizing distributed databases that can adapt to changes in workloads in real time.

3.7.4 Scalability and Performance Enhancement

A major difficulty in big data workloads is performance optimization, stemming from the substantial requirements for storage and processing. Distributed database systems mitigate scaling issues; yet, the trade-offs among consistency, availability, and partition tolerance, as outlined by the CAP theorem, persist as challenges **(Brewer, 2020).** Advanced indexing techniques, including adaptive indexing and concurrent query processing, seek to enhance database performance. Moreover, in-memory databases and caching methods, such as Redis and Memcached, are employed to enhance data retrieval speeds **(Elshawi et al., 2020).** Future research should focus on AI based models for predicting workloads, advanced indexing techniques, and self-optimizing distributed databases that can adapt to changes in workloads in real time.

3.8. *Innovations and Future Pathways*

Innovative advancements are influencing the future of database administration in the big data epoch. As data quantities proliferate, innovative strategies are necessary to improve processing efficiency, security, and scalability. This section examines significant advancements and prospective research avenues that are poised to transform database management systems.

3.8.1 Quantum Computing in Database Processing

Quantum computing possesses the capacity to transform query processing and optimization through the utilization of quantum parallelism. Conventional databases sometimes have difficulties in executing sophisticated queries, particularly with high-dimensional datasets, owing to the constraints of conventional computing techniques. Quantum techniques, like Grover's algorithm, can markedly improve search operations and query execution rates, providing a disruptive effect on big data analytics **(Gyongyosi & Imre, 2021).** The actual application of quantum databases remains nascent, although current research seeks to create hybrid systems that amalgamate quantum computing with traditional database designs. These innovations will enhance query performance, facilitate real-time analytics on extensive datasets, and mitigate processing bottlenecks. Nonetheless, obstacles such as quantum error correction, hardware constraints, and algorithm optimization must be resolved before quantum computing can achieve broad use in database administration **(Islam et al., 2018).**

3.8.2 Blockchain for Secure and Decentralized Data Governance

Blockchain technology guarantees safe, immutable databases through the decentralization of data storage and the removal of single points of failure. Conventional centralized database systems are susceptible to data breaches and illegal alterations, raising concerns over data integrity and security. Decentralized ledger technologies, such as BigchainDB and Hyperledger Fabric, make data less likely to be changed, lower the risk of fraud, and provide clear audit trails. This makes them suitable for important fields like healthcare, banking, and supply chain management **(Casino et al., 2021).** The main use of blockchain in database administration is the enhancement of access control systems. Smart contracts provide automated, trustless transactions and enforce established rules, diminishing reliance on middlemen. Furthermore, blockchain-integrated databases might improve interoperability among distributed systems, facilitating smooth data sharing while maintaining security. Future advancements will concentrate on enhancing blockchain scalability, minimizing energy usage, and combining it with novel database technologies to establish more resilient and efficient data management systems.

3.8.3 Cost-Effective Management of Serverless Databases

Serverless computing is gaining traction since it obviates the necessity for conventional database infrastructure maintenance. In contrast to traditional database systems that need pre-allocated resources, serverless databases dynamically assign processing power according to demand, enhancing resource usage and cost-effectiveness. Serverless databases in the cloud, like AWS Aurora Serverless and Google Firestore, offer managed backend functions, automated scalability, and pay-per-use pricing structures. This lowers operating costs and complexity **(Jonas et al.,**

2019). A primary advantage of serverless databases is their capacity to manage unexpected workloads, rendering them suitable for applications with variable data access patterns. Moreover, serverless architectures improve fault tolerance and disaster recovery through the utilization of multi-region deployments. Nonetheless, issues like latency unpredictability, cold start delays, and vendor lock-in persist as concerns for enterprises contemplating serverless database implementation. Future research must prioritize enhancing query performance, augmenting compatibility with current database systems, and mitigating security issues related to multi-tenant setups **(Sunny et al., 2020a).**

3.8.4 Knowledge Graphs for Sophisticated Data Analysis

Knowledge graphs are becoming a potent instrument for organizing and examining intricate data interactions. Knowledge graphs show entities and how they relate to each other in a network structure, which is different from traditional relational databases that organize data in tables. This makes it easier for semantic search, recommendation systems, and fraud detection. Linked data representations are used by knowledge graphs like Google's Knowledge Graph and Amazon Neptune to provide context-aware data retrieval, which improves AI-driven applications and data analytics **(Hogan et al., 2021).** The main benefit of knowledge graphs is their capacity to enhance the interpretability of natural language processing (NLP) and machine learning models. Knowledge graphs enhance automated reasoning and knowledge discovery by linking heterogeneous datasets through entity connections, making them indispensable for sectors like healthcare, cybersecurity, and finance. Future research should investigate strategies for integrating knowledge graphs with big data ecosystems, optimizing graph query performance, and advancing automated knowledge extraction techniques to fully leverage their capabilities in data analytics.

Table: 1 Comparative Table for Database Models

Database Model	Strengths	Limitations	Best Use Cases
NoSQL	Highly scalable, flexible schema	Weak ACID compliance	Social media, big data analytics
NewSQL	Combines scalability with ACID properties	Higher complexity	Financial transactions, e-commerce
Cloud Databases	Cost-effective, scalable, managed	Vendor lock-in risks	AI applications, multi-tenant SaaS

4. Conclusion

Database administration has advanced considerably due to the increasing intricacies of Big Data. The transition from conventional relational databases to NoSQL, cloud-native, and AI-driven systems has allowed enterprises to effectively manage large-scale data. Nonetheless, issues related to scalability, security, and compliance continue to be significant problems. The incorporation of modern technologies like blockchain and edge computing is continually influencing the future of database systems, offering creative options for real-time processing and data integrity. The amalgamation of AI-driven automation, blockchain security, and hybrid cloud frameworks will transform database architecture in the next decade. Organizations must prioritize scalable, secure, and cost-effective database systems to accommodate the increasing data requirements of sectors such as banking, healthcare, and e-commerce. Policymakers must implement uniform security and regulatory frameworks to alleviate data privacy issues. Future research should concentrate on quantum-resistant encryption and autonomous database optimization to ensure the efficient administration of increasingly intricate data environments.

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Author Contribution
Author took involved in the creation of the study design, data analysis, fieldwork, and execution stages. Every writer gave their consent after seeing the final work.

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A statement of conflicting interests
The authors declare that none of the work reported in this study could have been impacted by any known competing financial interests or personal relationships.

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