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Digital twins for coastal resilience: the Hong Kong blueprint

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A B S T R A C T

Coastal megacities face escalating vulnerabilities to extreme storm surges driven by climate change, necessitating transformative solutions to ensure sustained resilience. This perspective paper examines the Hong Kong Coastal Twin (HKCT) initiative as a paradigmatic case for developing next-generation digital twin systems. We advocate for an integrated, multi-layered technical architecture that synergizes multi-resolution digital modeling, physics-based multiscale simulations of wave–soil–structure interactions, and artificial intelligence (AI)-powered forecasting to enable near-real-time hazard assessments. Beyond technical innovation, we emphasize the critical role of interdisciplinary collaboration, uniting academia, government agencies, and industry partners, to co-create validatable, operational decision-support systems. Positioning HKCT within a broader global context, we argue that such digital twin frameworks offer a transferable blueprint for enhancing coastal resilience worldwide. By synthesizing advanced computational mechanics, AI, remote sensing, and smart management strategies, HKCT exemplifies how digital transformation can safeguard hyper-dense coastal cities against escalating climate risks while fostering sustainable urban development.

Introduction

The development of an advanced digital twin for coastal Hong Kong is driven by an urgent confluence of acute environmental vulnerability, immense economic stakes, and a pre-existing foundation of technological readiness and institutional capacity. As a hyper-dense, globally integrated port city, Hong Kong faces escalating climate risks that directly threaten its population, infrastructure, and status as a critical hub in global capital flows. Rising sea levels, intensified typhoons, and the increasing frequency of compound flooding events, where storm surges combine with heavy rainfall and wave overtopping, pose a severe threat to the low-lying coastal zones of Hong Kong (UN-Habitat, 2024). Historical events, such as the significant flooding experienced during multiple super typhoons in recent years, have highlighted the limitations of existing defense systems against changing climatic patterns, underscoring the need for more advanced predictive and adaptive tools (Choy et al., 2020; Zhang et al., 2023). Research conducted by the Civil Engineering and Development Department (CEDD) has focused specifically on analyzing coastal flood hazards from tropical cyclones, providing a foundational understanding of the threats the digital twin aims to mitigate (Qian et al., 2021; AECOM, 2022).

Beyond the environmental imperative, the economic case for a coastal digital twin is compelling. The economy of Hong Kong is deeply intertwined with its maritime activities; enhancing its resilience through initiatives like developing a "Smart Port" is crucial for maintaining its competitive edge as an international transportation center. Any disruption to port operations or critical urban infrastructure due to a climate-related event would have cascading consequences, not only for Hong Kong but for the broader regional and global economy. This economic reality provides a strong incentive for investment in advanced risk management technologies. Furthermore, the Hong Kong Special Administrative Region (HKSAR) Government has demonstrated explicit political support for forward-looking technological development, including the establishment of "Eight Centers" and a focus on environmental protection through blueprints like "Hong Kong 2035" (OGCIO, 2019; Hong Kong SAR, 2021). This strategic direction creates a favorable policy environment for large-scale projects like a digital twin.

Crucially, Hong Kong possesses a robust foundation for digitalization. It is recognized as an early adopter of Internet of Things (IoT) technologies and boasts advanced Information and Communications Technology (ICT) infrastructure. The Smart City Blueprint for Hong Kong, introduced in 2017, established a clear strategic roadmap with over 76 initiatives across six key areas, namely "Smart Mobility", "Smart Living", "Smart Environment", "Smart People", "Smart Government"

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and “Smart Economy”, signaling a long-term commitment to leveraging technology for urban improvement (Hong Kong SAR, 2020). This initiative has fostered a regulatory framework that increasingly emphasizes data privacy and cybersecurity, which are essential considerations for a system managing sensitive geospatial and operational data. The presence of world-class academic institutions ensures a steady supply of intellectual capital and technical expertise. Local top universities are already engaged in cutting-edge research relevant to the digital twin’s objectives, including sustainable smart campuses, satellite remote sensing for weather and climate, and the integration of Building Information Modeling (BIM) with digital twin technology (Wang et al., 2024). This combination of pressing need, economic motivation, and pre-existing technological and institutional assets makes Hong Kong a uniquely suitable proving ground for a digital twin designed to enhance coastal resilience.

A multi-pillar technical architecture for predictive digital twinning

HKCT represents a pioneering effort to develop a predictive digital twin system for the complex coastal environment of Hong Kong. Moving far beyond static three-dimensional visualization, HKCT creates a dynamic, intelligent simulation platform. At its core, HKCT integrates multiscale and multiphysics modeling with state-of-the-art AI models, real-time sensor networks, and advanced computer graphics, all working in concert to provide scientists, engineers, and authorities with unprecedented capability to predict, assess, and manage the impacts of extreme storm surges and other coastal hazards.

As illustrated in Fig. 1, HKCT features a dynamic, high-fidelity virtual replica of the Hong Kong coastline that integrates real-time data from sensors, satellites, and weather stations with advanced hydrodynamic and flood inundation models. The system is designed to continuously simulate and visualize impacts of various coastal hazards, such as storm surges, sea-level rise, and flooding, under different scenarios. This will enable city planners and emergency managers to run scenario analyses, assess risks to infrastructure and communities, provide early warnings, test mitigation strategies (e.g., seawalls or nature-based solutions), and guide critical decision-making for resource allocation and emergency response. Crucially, HKCT is intended to maintain a continuous bidirectional feedback loop between physical and virtual systems, a defining characteristic of digital twins (NASEM, 2023), ensuring models improve over time by learning from actual events.

The predictive power of HKCT rests upon *three interconnected methodological pillars* that together form a comprehensive technical architecture. The *first pillar* comprises a ***heterogeneous data fabric and multi-resolution sensing infrastructure*** that continuously feeds the digital twin with diverse streams of information. This includes traditional in-situ monitoring networks, such as hydrometric stations and weather stations operated by the Hong Kong Observatory (HKO), augmented by a dense network of urban IoT sensors deployed across the landscape. Complementary remote sensing technologies provide additional layers of data, with satellite imagery offering wide-area coverage for monitoring basin-scale phenomena like sea-level changes. Unmanned Aerial Vehicles (UAVs) and Light Detection and Ranging (LiDAR) systems serve as a critical bridge between macro and micro scales, delivering high-resolution data essential for precise shoreline detection, rapid post-event flood mapping, and detailed structural inspections of coastal infrastructure (Wang et al., 2024).

The *second pillar* provides the ***high-performance computational backbone*** necessary to process the immense volume and velocity of incoming data while running sophisticated simulations. A hybrid computing architecture leverages cloud-native platforms for elastic orchestration, integrated with Graphics Processing Unit (GPU)-accelerated High-Performance Computing (HPC) resources for high-throughput parallel processing (Rogeiro et al., 2018; Zhao et al., 2022). This computational foundation is essential for executing the computationally intensive, high-fidelity physics-based models that underpin the predictive capabilities of the system, particularly for simulating complex coastal processes such as storm surge propagation, wave dynamics, overtopping, and levee breaching (AECOM, 2022).

The *third pillar* introduces an innovative ***AI-driven simulation core*** that merges physical laws with data-driven learning through Physics-Informed Machine Learning (PIML) (Karniadakis et al., 2021), which integrates fundamental principles of geomechanics and fluid dynamics directly into neural network architectures to ensure robustness and physical consistency. To overcome the prohibitive computational costs of running high-fidelity models in real-time, HKCT employs fast, accurate surrogate models trained on extensive simulation outputs, enabling rapid scenario analysis, probabilistic forecasting, and timely decision support through cutting-edge architectures such as transformer-based neural operators and adaptive graph neural networks (Bodnar et al., 2025; Sun & Zheng, 2026). Among these, we focus on transformer-based neural operators (Alkin et al., 2024) for their ability to capture long-range spatiotemporal dependencies in storm surge

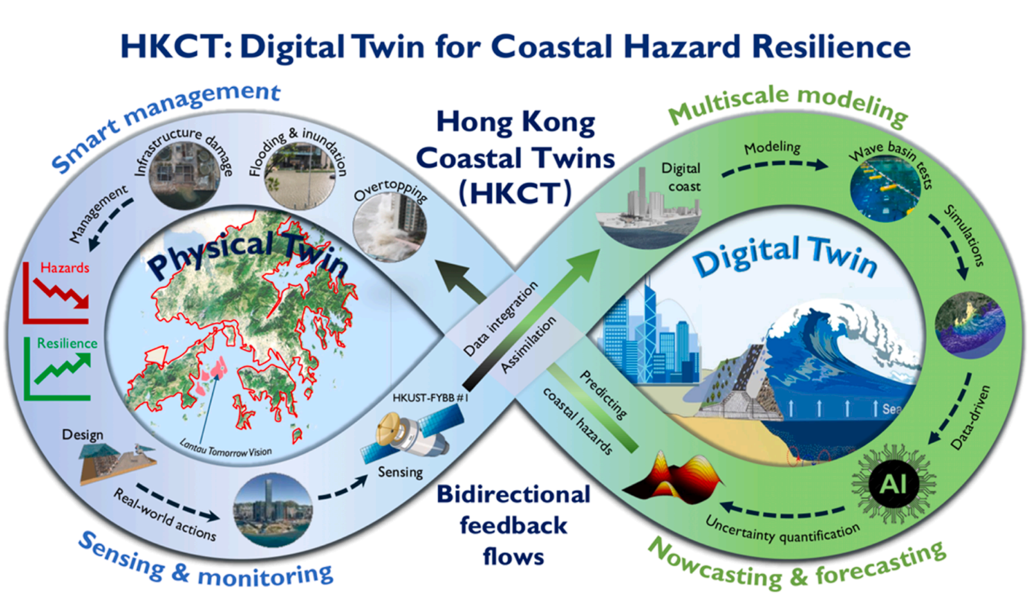


Fig. 1. Schematic of HKCT for coastal hazard resilience, illustrating bidirectional feedback flows between physical coastal systems and their digital counterparts.

propagation, and PIML for embedding physical conservation laws directly into the learning process. A critical point, however, is that PIML promotes physical consistency rather than rigorously guarantees it, which is a distinction that becomes especially consequential when the model extrapolates beyond the training data regime.

The development of HKCT is structured into four major interconnected tasks that progress systematically from foundational digitalization to operational implementation:

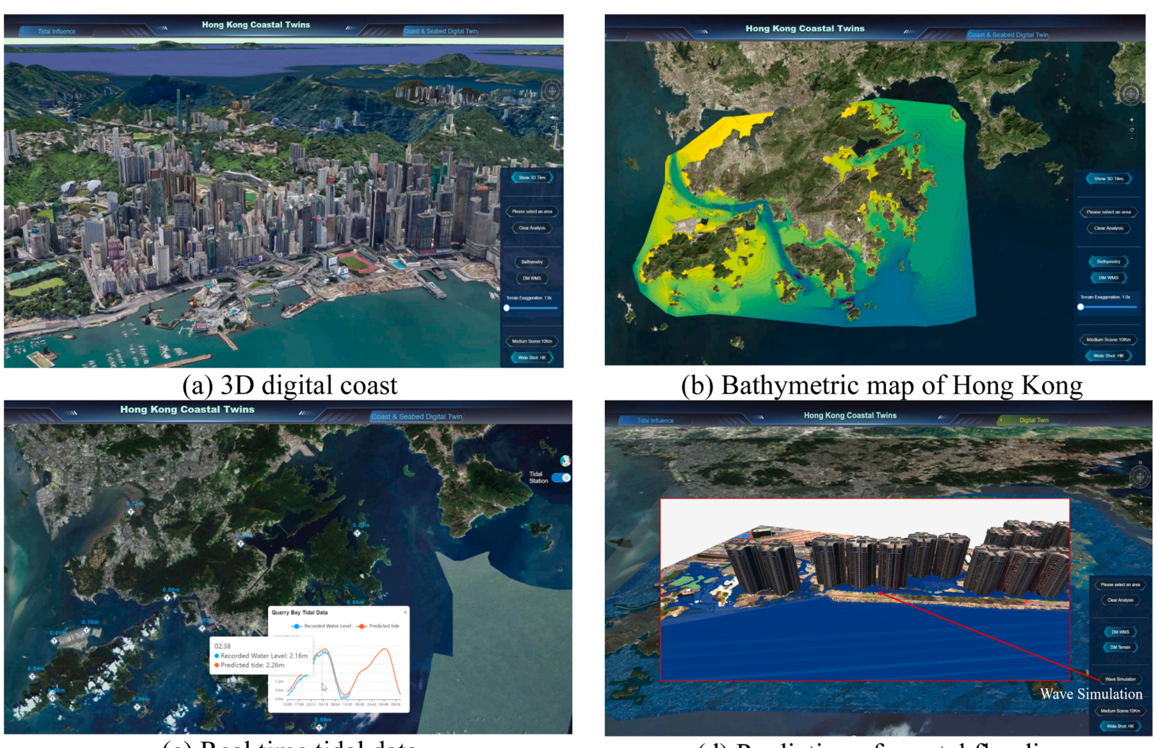
- **Task A** focuses on multi-resolution digitalization of the Hong Kong coastal zone. It establishes a virtual representation using Geographic Information System (GIS) services and satellite data, while integrating ultra-high-fidelity digital models for high-consequence areas via LiDAR and photogrammetry (see Fig. 2a) (Huang et al., 2018; Chen et al., 2023). The system also incorporates nearshore bathymetric data (Fig. 2b) alongside real-time weather and oceanographic feeds, such as tidal levels (Fig. 2c).
- **Task B** develops the core physics-based simulation engine. It creates a coupled regional ocean-atmosphere-wave model for the Pearl River Estuary that simulates extreme storm surges. This regional model is then adaptively downscaled to specific local coastal areas where high-resolution, multiphysics geotechnical models are applied to simulating complex wave-soil-pore water-structure interactions (Chen & Curcic, 2016; Kerns & Chen, 2022; Lai et al., 2023; Zhai & Jeng, 2024). Rigorous validation of these models is performed using large-scale physical experiments including wave basin, flume, and centrifuge tests informed by comprehensive site investigations.
- **Task C** synthesizes the outputs of the preceding tasks to establish the operational HKCT backbone. It integrates an advanced AI framework incorporating neural operators, uncertainty quantification, and active and transfer learning techniques (Qu et al., 2023; Zhao et al., 2025). This framework fuses physics-based simulation data with real-time sensor feeds including high-definition radar and tropical cyclone data from HKO to enable near-real-time predictions of wave overtopping, coastal flooding, and inundation (Fig. 2d).
- **Task D** implements the fully realized HKCT as an operational decision-support tool. It will automatically identify high-risk local areas during extreme weather, and is expected to provide end-users with actionable intelligence for early warnings and emergency response. The tool will also serve as a platform to assess the in-situ performance of existing coastal defenses and to drive innovative, resilient designs for future infrastructure.

Through this comprehensive integration of physics-based modeling, real-time sensing, and cutting-edge AI, HKCT (whose current implementation status is summarized in Table 1) will provide an unprecedented capability to predict and manage the impacts of extreme storm surges, making a significant contribution to enhancing the sustainability and resilience of the coastal geosystems of Hong Kong in the face of a changing climate.

Balanced discussion. The integrated architecture we propose is not without substantial challenges, and we consider candid

Table 1
Maturity levels of the three technical pillars and four tasks in the HKCT framework.

Component	Maturity level	Key status
Pillar I: Data Fabric	Partially Implemented	Existing monitoring networks + remote sensing; IoT integration in prototype
Pillar II: Computation	Partially Implemented	Cloud-HPC hybrid tested in sub-projects
Pillar III: AI Core	Research Phase	Some individual AI models published; full framework under development
Task A: Digitalization	Operational	GIS/satellite basemaps ready; high-fidelity models for selected areas
Task B: Physics Engine	Validated	Some regional & geotechnical models published; coupling in testing
Task C: AI Integration	Research Phase	AI components prototyped; real-time fusion ongoing
Task D: Decision Support	Conceptual	Conceptual design done; deployment pending



(a) 3D digital coast

(b) Bathymetric map of Hong Kong

(c) Real time tidal data

(d) Prediction of coastal flooding

Fig. 2. Selected snapshots in the HKCT.

acknowledgment of these limitations to be as valuable as outlining the vision itself. First, the scarcity of observational data for rare, high-impact storm surges and compound flood events poses a fundamental hurdle: machine learning models trained on historically mild conditions may extrapolate poorly under non-stationary future climates, and the validity of such extrapolations remains an active research frontier (e.g., via physics-informed constraints and generative data augmentation). Second, uncertainty does not reside in a single module but cascades across the entire modeling chain, from global climate projections and regional hydrodynamic downscaling to local geotechnical and drainage simulations. Translating this multi-source uncertainty into interpretable, decision-relevant metrics (e.g., probabilistic flood maps with confidence intervals) without overwhelming end-users is a non-trivial design problem that we are tackling through ensemble forecasting and interactive visualization. Third, the trade-off between computational cost and predictive accuracy is inherently context-dependent: real-time early warning systems may tolerate higher approximation errors, whereas infrastructure design demands near-physical fidelity, necessitating adaptive model selection that dynamically chooses between high-fidelity solvers and neural surrogates based on the use case and available compute. Fourth, technical interoperability is often overshadowed by institutional friction; data silos among Hong Kong's government departments, rooted in legacy systems, security protocols, and divergent mandates, remain resistant to purely technological fixes, and we are actively working with stakeholders to co-design formal data-sharing agreements and API standards. Fifth, and perhaps most critically, the benefits of a digital twin are not automatically distributed equitably. Without deliberate, equity-oriented design, such as prioritizing sensor deployment in low-income coastal communities and co-developing alert systems with local residents, there is a real risk that the HKCT will serve the well-resourced while leaving the most vulnerable populations underprotected. These challenges do not diminish the potential of the HKCT; rather, they define our priority for future work, including physics-informed neural operators, probabilistic uncertainty quantification, adaptive fidelity switching, multi-agency governance frameworks, and community-engaged participatory modeling (Raissi et al., 2019). We present them not as caveats to the blueprint, but as essential design parameters that will determine its real-world success and replicability.

Interdisciplinary collaboration for co-creation and implementation

Successful development of a city-scale digital twin for coastal Hong Kong hinges on synergistic collaboration across multiple domains: geomechanics and coastal engineering for physical process modeling; oceanography and geospatial technologies (GIS/remote sensing) for environmental monitoring; data science, AI, and computer graphics for computational analytics; and public policy for governance and implementation. Its operational deployment further requires a robust collaboration among academia, industry, and government. This socio-technical system needs more than just advanced technology; it demands structured partnerships to ensure the co-creation of knowledge, validation of models, and alignment with operational needs.

University-industry collaboration serves as a primary innovation engine, allowing academic researchers to explore fundamental scientific questions while ensuring resulting technologies maintain industrial relevance and pathways to practical applications. This innovation pipeline feeds directly into government agencies responsible for public safety and infrastructure management. Formalized partnerships between research institutions and government departments are critical for grounding the digital twin in real-world requirements. For instance, Memoranda of Understanding (MOUs) between the CEDD and HKUST cover research into novel construction materials and innovative landslide mitigation techniques. These collaborations provide the twin with access to vital operational data, opportunities for field validation, and direct input from end-users who rely on its outputs for emergency decision-making.

Within government itself, the model must facilitate coordination across multiple agencies, including CEDD, Drainage Services Department (DSD), Marine Department (MD), and HKO, to break down data silos and ensure holistic approaches to urban resilience. To manage the complexity of such large-scale endeavors, it is essential to develop a clear governance framework. This framework should provide structured approaches for assessing the current state of HKCT, guiding future development, and navigating governance implications. It promotes transparency and helps build consensus around the goals and ethical use of the digital twin.

Practical implementation requires user-friendly interfaces that deliver actionable information to non-expert stakeholders, including emergency personnel and the public, without specialized training. Deliberative governance encouraging broad stakeholder participation helps ensure the technology serves the public good and addresses needs of all communities, particularly for the most vulnerable (Douguet et al., 2025). Ultimately, the success of HKCT will be measured not only by advanced computational models but by the strength and effectiveness of the collaborative ecosystem it fosters.

Global relevance and a blueprint for transferability

While tailored to the unique conditions of Hong Kong, the digital twin framework being developed offers a globally transferable blueprint for other coastal megacities grappling with similar climate-induced challenges. Many urban centers worldwide face common pressures: rising sea levels, increased storm intensity, and complex risks from compound flooding events where multiple hazards interact. Specific research and technological solutions emerging from the Hong Kong context, such as AI models for predicting storm surge and rainfall impacts, are directly applicable elsewhere. By documenting technical choices, collaborative processes, and governance structures, the Hong Kong case study provides a replicable playbook for cities seeking to build resilient futures.

Positioning the Hong Kong project within a global context highlights both the uniqueness of local solutions and the value of shared learning. Other cities have pioneered valuable digital twin initiatives: the Port of Rotterdam leverages IoT and augmented intelligence to optimize vessel turnaround and berth utilization, demonstrating the power of this technology in logistics and supply chain management (Klar et al., 2023); the digital twin of Venice specifically supports sustainability and resilience efforts focused on protecting the historic city from flooding (Villani et al., 2025); the Virtual Singapore platform of Singapore showcases a mature, dual-tier governance model balancing national strategic interests with public access (Beckman & Massi, 2025). Examining these global practices allows the Hong Kong project to learn from established best practices while emphasizing its own innovations in AI and coastal hydrodynamic modeling.

For a digital twin to be truly transferable, several key enablers must be considered. First, adoption of open standards for data exchange is paramount. Adherence to geospatial API standards, such as those developed by the Open Geospatial Consortium (OGC), ensures data and models remain interoperable and integrable with systems in other jurisdictions. Second, technical architecture should be designed with modularity in mind. By developing distinct, interchangeable modules (e.g., separate components for storm surge, wave overtopping, and urban heat island effects), the system can be adopted incrementally, allowing other cities to start with components most relevant to their immediate needs.

Finally, and perhaps most importantly, transferability extends beyond code and algorithms. The successful collaboration and governance frameworks developed in Hong Kong are equally critical to replicate. Fostering trust and facilitating knowledge exchange among academia, industry, and government, is as vital as technical advancement. International cooperation, supported by frameworks like the UN Ocean Decade (UNESCO, 2025), can provide key platforms to engage stakeholders worldwide to share knowledge, align standards, and build capacity, turning the Hong Kong's experience into a valuable contribution to global urban resilience. The transferability of the HKCT framework, while promising, is contingent upon several enabling conditions. Cities with established coastal monitoring infrastructure (tide gauges, weather radars, and IoT sensor networks), along with a governance mandate for cross-agency data sharing are best positioned to adopt the proposed architecture. For municipalities with sparser observational networks or fragmented institutional landscapes, however, the blueprint would require substantial upfront investments in both hardware and inter-organizational protocols before the full suite of AI-driven predictive capabilities can be operationalized.

Placed alongside international counterparts, the HKCT framework occupies a distinct niche. For example, Rotterdam's digital twin emphasizes adaptive delta management and nature-based interventions; Venice's system prioritizes heritage protection through mobile barrier operations; and Singapore's platform focuses on integrated urban drainage and real-time flood alerts. What differentiates HKCT is its explicit coupling of multi-scale physics-based modeling, spanning atmospheric, hydrodynamic, and geotechnical processes, with neural operator surrogates and real-time data assimilation, all orchestrated to address *compound* coastal hazards. This integrative design, which systematically links storm surge, rainfall-induced flooding, and groundwater response within a single predictive framework, remains largely absent from existing initiatives and constitutes the primary methodological contribution of this work.

Importantly, we do not present HKCT as a universal solution. Rather, we offer it as a modular and adaptable reference architecture, one that can be selectively customized depending on local data availability, computational resources, and institutional priorities. The challenges of data scarcity, uncertainty propagation, and equitable benefit distribution, discussed earlier, are not afterthoughts but integral design drivers that will shape the next phase of our research. By openly sharing both the opportunities and the unresolved difficulties, we hope this blueprint encourages not uncritical replication, but informed adaptation, and in doing so, contributes to a more resilient and equitable future for coastal megacities worldwide.

CRediT authorship contribution statement

Jidong Zhao: Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Shiwei Zhao:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Tongming Qu:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization.

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.

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Data availability

No data was used for the research described in the article.

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