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Enhancing community engagement with digital twins: Technological adoption in marine debris management

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A R T I C L E I N F O

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A B S T R A C T

This research investigates the adoption of digital twin technology for marine debris management in Bali, focusing on the regions of Denpasar, Badung, Gianyar, and Tabanan. Digital twin technology involves creating virtual models that replicate physical environments and processes, enabling real-time monitoring and simulation. This capability is particularly crucial in Bali, where marine debris presents significant ecological and economic challenges. Digital twin technology offers a strategic advantage by allowing detailed scenario analysis and optimization of management strategies. Using Structural Equation Modeling (SEM), the study evaluates the influence of four key factors within a community resilience framework on the willingness to adopt digital twins: risk perception, planning capability, coping ability, and interest level. The findings suggest that heightened awareness through targeted workshops and campaigns significantly boosts the community's willingness to engage with digital twin technology, highlighting the impact of risk perception. In terms of planning capability, strong processes such as the creation of action plans and task forces are crucial for integrating digital twins into marine debris management strategies. Additionally, robust coping mechanisms, which benefit from access to advanced technologies for real-time response, correlate with a greater readiness to adopt digital twins. Lastly, active community involvement in environmental initiatives indicates a higher propensity to support innovative technological solutions, underscoring the importance of interest level. The study emphasizes the critical role of these factors in creating an environment conducive to the adoption of digital twin technology in Bali. By enhancing these aspects of the community resilience framework, the region can more effectively leverage digital twins to address its marine debris problem. This research offers valuable insights for policymakers, practitioners, and researchers

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dedicated to enhancing sustainability and resilience through advanced technological interventions.

1. Introduction

Digital twin technology represents a cutting-edge approach to managing complex environmental issues (Bibri et al., 2024). By creating a virtual replica of physical systems, digital twins enable real-time monitoring, simulation, and optimization of environmental processes (Segovia & Garcia-Alfaro, 2022). Digital twins can provide comprehensive insights into waste accumulation patterns and predict the impacts of different management strategies (Kroell et al., 2024; Sengupta & Dreyer, 2023). This technology can integrate data from various sources, including satellite imagery, sensors, and citizen reports, to offer a dynamic and interactive tool for environmental management. Effective environmental management, particularly for issues like marine debris, requires active community engagement (Ferreira et al., 2021; Wu, 2022). Communities play a crucial role in both contributing to and solving environmental problems (Radoine et al.; Nahiduzzaman et al., 2015; Hasan et al., 2018, 2022; Castro-Arce and Vanclay, 2020; Sofiyah, Sianipar, et al., 2025; Sofiyah et al., 2025; Kamana et al., 2024). Engaging the community ensures that management strategies are contextually relevant, culturally appropriate, and more likely to be supported and sustained over time. Community engagement involves raising awareness, fostering a sense of responsibility, and empowering individuals to participate in decision-making processes (Muhamad Khair et al., 2020; Wang et al., 2020). Furthermore, digital twin technology, which originated from the convergence of physical and digital worlds, involves creating detailed digital replicas of physical entities or systems (Javaid et al., 2023; Liu et al., 2021; Qi et al., 2021; Singh et al., 2021). These replicas are dynamic, continuously updated with data from their physical counterparts, enabling real-time monitoring, simulation, and analysis (Kherbache et al., 2021; Kušić et al., 2023). The technology utilizes various data sources, to build models that predict how a physical object or system behaves under different conditions (Attaran & Celik, 2023; Mihai et al., 2022).

Globally, digital twin technology has been applied across multiple sectors, showcasing its versatility and impact (Vetrivel et al., 2024). In manufacturing, it is used to optimize production lines and prevent equipment failures before they occur, significantly improving efficiency and reducing downtime (Bafandegan Emroozi et al., 2024; Roosefert Mohan et al., 2021; Shahin et al., 2023; Soori et al., 2023). In healthcare, digital twins simulate medical scenarios for patients (Elayan et al., 2021; Sun et al., 2023; Vallée, 2023), allowing healthcare providers to test potential interventions and predict patient responses to treatments without any risk. In urban planning, cities around the world use digital twins to enhance the sustainability of infrastructure projects (Allam & Jones, 2021; Ferré-Bigorra et al., 2022; Jiang et al., 2022; Peldon et al., 2024). These digital models help city planners visualize the outcomes of various urban development scenarios, enabling better decision-making (Mazzetto, 2024). In the marine environment, The Ocean Cleanup project developed a digital twin model of its cleanup system to simulate and optimize the use of netted screens for collecting plastic debris in the Great Pacific Garbage Patch (Rakotonirina et al., 2023). Another important initiative is the European Digital Twins of the Ocean (DTO) project, this project emphasizes setting data standards and targeting high-conservation-value areas through a 'nested enterprise' approach (Tzachor et al., 2023). Under the EU Green Deal, DTO is building a system to connect multiple ocean digital twins using a shared framework, these systems are tested in pilot areas to support region-specific decision-making (Vasilijevic et al., 2024). In the field of solid waste management, digital twins are helping address challenges such as high waste generation and poor collection services. In South Africa, a prototype urban digital twin (UDT) was developed to improve waste collection planning, this system includes community participation and is scalable for areas with limited resources (Cárdenas-León et al., 2024). Beach waste management has also adopted digital twin applications. The BIOBLU project created an Intelligent Hierarchical Cyber-Physical System (IHCPS) to automate beach cleanups. The BeWastMan case study demonstrated how this approach works in practice (Cicceri et al., 2023). In urban logistics, digital twins are used to support transport planning and policymaking. One study shows their usefulness in managing urban freight systems (Marcucci et al., 2020). Another case in South Africa applied digital twins to optimize waste collection routes (Cárdenas et al., 2024). In Dublin, Ireland, a public digital twin of the Docklands area allows citizens to engage with proposed changes in skyline and green spaces, this interactive platform helps residents better understand and contribute to urban development (White et al., 2021).

The relevance of digital twin technology to marine debris management in Bali is particularly significant due to the island's acute challenges. Bali's marine ecosystems, human health, and local economy, particularly the tourism sector, are heavily impacted by marine debris (Boakes et al., 2022; Suhardono et al., 2024). Digital twin technology provides a strategic advantage in this context by enabling detailed scenario analysis and optimizing management strategies (Yan et al., 2022). It offers valuable insights into waste accumulation patterns and evaluates the effectiveness of various management approaches, aiding local authorities and organizations in making informed decisions and implementing targeted interventions. This technological application enhances operational efficiency and supports sustainable environmental practices (Chen et al., 2023; Tzachor et al., 2022), making it an essential tool for tackling marine debris issues in Bali. Bali, an island renowned for its natural beauty and vibrant tourism industry, is particularly affected due to its dense population and high tourist influx (Rajendra, 2020; Ramadhani et al., 2024). These regions represent a mix of urban and coastal environments, making them ideal for studying the dynamics of marine debris management and the potential of digital twin technology. The local economy's reliance on tourism amplifies the need for effective debris management to maintain Bali's environmental health and appeal. Despite the growing recognition of marine debris as a critical environmental issue and the potential of digital twin technology to enhance environmental management (Riaz et al., 2023; Seyyedi et al., 2024), there is a notable gap in the literature concerning the specific integration of digital twins in marine debris management, particularly in the context of community engagement. While extensive research has been conducted on the individual aspects of marine debris impacts and community-based environmental initiatives (Loizidou et al., 2021; Owens, 2018; Suryawan, Sianipar, & Lee, 2024; Vince & Hardesty, 2018), the intersection of these elements with advanced digital technologies remains underexplored.

Most existing studies focus on traditional methods of marine debris management and the roles of community awareness and participation (Hartley et al. 2021a, 2021b; Hung et al., 2022; Bettencourt et al., 2023). However, these approaches often overlook the transformative potential of digital twin technology, which can provide real-time data, predictive analytics, and interactive simulations to optimize debris management strategies. There is limited empirical evidence on how digital twins can be effectively implemented in community settings, particularly in coastal regions with high tourism activity like Bali. Moreover, the role of community engagement in adopting digital twin technology has not been thoroughly investigated. Previous research has predominantly addressed community involvement in environmental conservation through educational campaigns and volunteer programs (Ardoin et al., 2023; Barnason et al., 2022; Burgos-Ayala et al., 2022; Leyshon et al., 2021), but the specific factors that influence the willingness to adopt advanced technologies such as digital twins have not been systematically studied. Understanding these factors is crucial for developing effective strategies integrating technological innovation with community-driven environmental management.

This research aims to develop a comprehensive framework to understand the factors that influence a community's willingness to adopt digital twin technology for effective marine debris management. Focusing on four key constructs the study employs Structural Equation Modeling (SEM) to test the relationships between these factors. SEM is particularly chosen for its robustness in modeling complex relationships and handling multiple variables. The utilization of digital twin technology in environmental management, particularly for marine debris, is a central theme of this research. Digital twins enable real-time, accurate monitoring and simulation of marine debris dispersion and accumulation. This capability allows for precise assessments of impacts on ecosystems and human health, as well as facilitates timely and effective interventions. By simulating various community resilience scenarios, stakeholders can visualize the outcomes of different strategies, enabling the selection of the most efficient and effective approaches. A crucial element of this research is its emphasis on community engagement. The study demonstrates how digital twins can significantly enhance community involvement by providing clear visual representations of environmental challenges and the tangible benefits of proposed solutions. This improved understanding and visualization help foster community support for marine debris initiatives, which is essential for the sustainability of these efforts. Moreover, digital twins serve as powerful tools for policymakers and planners in Bali, offering detailed data and predictive insights. The technology's capacity to forecast long-term impacts of marine debris and assess the effectiveness of management strategies supports more informed, data-driven decision-making processes. This research enriches both academic and practical understanding by integrating elements of community engagement and technological innovation. It provides practical solutions that can be implemented to enhance the resilience and effectiveness of marine debris management in Bali and other similar settings. By advancing the theoretical discourse, this study also offers actionable insights for improving environmental management practices, highlighting the potential of digital twin technology to enhance understanding and provide practical solutions for marine debris management.

2. Literature review and hypothesis framework

Digital twin technology is increasingly recognized for its transformative potential across various sectors of environmental management. This technology involves creating digital replicas of physical systems to simulate, monitor, and analyze data in real time. Recent studies, such as those by Petri et al. (2023), illustrate how digital twins can model complex environmental systems to forecast the impacts of different interventions. This capability makes them essential for strategic environmental planning and management. In urban sustainability, digital twins play a crucial role by integrating and analyzing data from diverse sources to enhance planning outcomes, as discussed by Tzachor et al. (2023). This functionality helps in optimizing urban infrastructure and resource management, contributing to more sustainable urban environments. In marine debris management, digital twins are instrumental in mapping debris accumulation and optimizing cleanup processes. Research by Owens et al. (2022) and Rapada et al. (2021) demonstrates that digital twins provide in-depth insights into the dynamics of marine environments, aiding in the development of effective mitigation strategies through precise monitoring and predictive analytics. The technology's application extends to disaster risk management, where it enhances preparedness and response capabilities. Studies by Wu and Li (2022) and Seyyedi et al. (2024) explore how digital twins can simulate disaster scenarios, allowing for the real-time evaluation of response strategies. This capability significantly boosts the resilience and responsiveness of environmental management systems to cope with adverse events. The successful adoption of digital twins in environmental management also hinges on several key factors, including the technological infrastructure available, the organizational readiness to integrate new technologies, and the external pressures that motivate innovation, as highlighted by Zhang et al. (2020). These elements are critical in ensuring that digital twin technology can be effectively implemented to meet the demands of modern environmental challenges.

Hypothesis 1 (H1) posits that the perception of risk positively influences the willingness to adopt digital twin technology, drawing from the Protection Motivation Theory. This theory suggests that individuals are more likely to engage in protective behaviors when they perceive a threat to be severe and believe themselves to be susceptible to its effects (Clubb & Hinkle, 2015; Ezati Rad et al., 2021; Kim & Crimmins, 2020). In the context of this study, the hypothesis is examined through activities designed to enhance community awareness of the significant impacts of marine debris on their environment and livelihoods. Various activities aimed at increasing community understanding of marine debris risks are implemented, including community workshops, public awareness events, and social media campaigns (Gacutan et al. 2022b, 2022a). These initiatives serve multiple functions, they educate the public on the severity of marine debris, illustrate the consequences of inaction (Agamuthu et al., 2019; Vince & Stoett, 2018), and showcase how digital twin technology can be a proactive tool in managing these environmental challenges (Petri et al., 2023). Community workshops on marine debris impacts play a crucial role in educating the public about the severity of marine debris and its consequences on the environment and local livelihoods (Owens et al., 2022). These workshops are expected to enhance the community's perception of risk, fostering support for digital twin technology as a proactive management tool. Public awareness events, which highlight the issues related to marine sustainability and the benefits of digital twin technology, are equally important (Tzachor et al., 2023). Higher attendance at these events indicates greater exposure to information, elevating the community's awareness of marine debris risks. Social media campaigns are also instrumental in disseminating information quickly and widely (Rapada et al., 2021). Campaigns that focus on the impacts of marine debris and promote the use of digital twin technology can significantly influence public perception of risk. Additionally, surveys assessing perceived risk of marine debris provide insights into the community's concerns and knowledge, helping to tailor educational efforts more effectively.

Hypothesis 2 (H2) proposes that enhanced planning capability positively influences the willingness to adopt digital twin technology, based on principles from the Theory of Planned Behavior. This theory emphasizes that an individual's behavior is determined by their intentions, which are influenced by their attitudes towards the behavior, the social norms surrounding it, and their perceived control over the behavior (Badawi et al., 2024; Panwanitdumrong & Chen, 2021; Xu et al., 2024). In this context, **planning capability** refers to the community's strategic readiness to address marine debris issues effectively (Suryawan, Suhardono, & Lee, 2024). This capability is enhanced by incorporating digital twin technology into planning processes. Digital twins allow for precise modeling and simulation of marine environment (Brönner et al., 2023; Zhang et al., 2024), enabling planners to identify critical intervention areas and coordinate responses more effectively. This use of technology in planning is crucial because it provides a clear, data-driven basis for decision-making, which can improve the efficiency and effectiveness of interventions (Bibri et al., 2024). Establishing marine debris task forces that utilize digital twin technology can also strengthen planning capability (Riaz et al., 2023). These task forces coordinate cleanup efforts and ensure that strategic plans are effectively implemented. Involvement in simulation exercises for marine debris response provides hands-on experience with digital twin tools, further bolstering the community's confidence in using these technologies. Comprehensive training programs for debris management incorporating digital twin technology are essential for equipping community members with the skills and knowledge to effectively address marine debris.

Hypothesis 3 (H3) centers on how coping ability influences the willingness to adopt digital twin technology, drawing from Resilience Theory. This theory highlights the capacity of systems to endure and adapt in the face of environmental stresses and shocks (Juan-García et al., 2017; Shi et al., 2021). The hypothesis posits that enhancing coping mechanisms with digital twin technology equips the community to more effectively respond to and manage marine debris incidents. Digital twin technology plays a critical role in all these areas by providing real-time data and predictive analytics (Botín-Sanabria et al., 2022; Li et al., 2022). These capabilities enhance the community's ability to anticipate, react to, and manage the challenges posed by marine debris more efficiently. Firstly, access to cleanup technologies integrated with digital twin simulations offers valuable insights that improve decision-making and operational efficiency. These technologies allow for a deeper understanding of debris accumulation patterns and the effectiveness of various management strategies (Martínez-Vicente et al., 2019; Maximenko et al., 2019), which can significantly influence the community's readiness to adopt new solutions. Community self-help initiatives and emergency response protocols supported by digital twins enable coordinated and rapid responses to incidents (Yang et al., 2024). Providing basic cleanup tools is also crucial, as it ensures community members have the necessary resources to participate in cleanup activities (Battisti et al., 2020). Strengthening these coping mechanisms enhances community resilience and capability to manage marine debris, thereby increasing the likelihood of adopting digital twin technology.

Hypothesis 4 suggests that the level of interest within a community significantly influences its willingness to adopt digital twin technology, as explained by Social Cognitive Theory. This theory emphasizes that behavior is often shaped by learning from one's environment through observation, imitation, and modeling (Lee & Tseng, 2024; Zaman et al., 2024). In this study, community engagement in waste management initiatives and involvement in policy advocacy are critical avenues through which community members can directly witness the advantages of digital twin technology (Peldon et al., 2024; Yang et al., 2025). For instance, cultural engagement activities such as festivals and educational programs not only raise awareness about environmental management (Geng et al., 2024; Paatlan & Ranga, 2025; Thi Thanh Nguyen et al., 2024), but also serve as platforms for showcasing the practical benefits of digital twin technology in real time. These events help cultivate a sense of collective responsibility and provide demonstrative examples of how technology can lead to more effective environmental management (Suryawan & Lee, 2024). These activities also provide platforms to introduce and demonstrate the benefits of digital twin technology. Developing marine waste management initiatives and strong policy efforts signal the community's proactive stance in addressing marine debris (Gallo et al., 2018). Volunteer participation in cleanup programs indicates a high level of community engagement and readiness to adopt new technologies that enhance these efforts.

Fig. 1 illustrates the conceptual framework that guides this study, mapping the relationships between the four key constructs and their influence on the willingness to adopt digital twin technology in marine debris management. This diagram visually represents how each construct contributes to enhancing community preparedness and responsiveness to environmental challenges through the adoption of advanced digital solutions. Together, these constructs form a comprehensive view of how digital twin technology can be integrated into marine debris management strategies to enhance community responsiveness and sustainability efforts. The pathways indicated in the figure show the hypothesized positive influences (+) of each construct on the community's willingness to adopt this innovative technology.

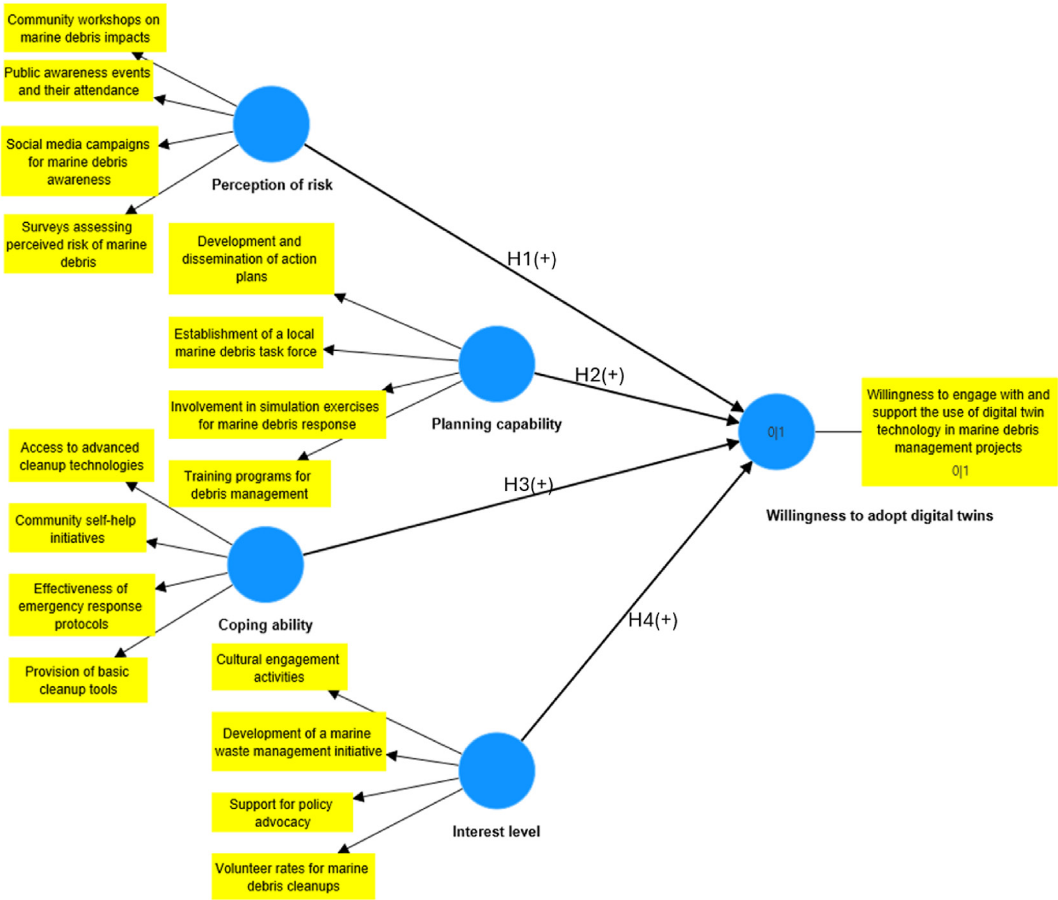

Fig. 1. Hypothesis framework.

3. Method

3.1. Study location

This research was conducted in the metropolitan area of Bali (Fig. 2), which includes the regions of Denpasar, Badung, Gianyar, and Tabanan. These areas are significant urban and coastal environments in Bali, where the effects of marine debris are particularly evident due to high levels of tourism and various local economic activities. A diverse socio-economic landscape, rapid urban development, and ecological sensitivity characterize the metropolitan Bali area (Suryawan et al., 2024; Suryawan, Suhardono, Rahman, Phan, & Lee, 2025; Suhardono et al., 2024). These factors make it an ideal location for studying the dynamics of marine debris management and community engagement. Denpasar, as the capital city of Bali, is a central hub for administrative and commercial activities, influencing waste management practices and policies. Badung, known for its tourism hotspots such as Kuta and Nusa Dua, faces significant challenges in managing marine debris due to the influx of tourists. Gianyar, home to cultural sites and eco-tourism, presents a unique blend of traditional practices and modern waste management challenges. Tabanan, with its agricultural base, highlights the interplay between rural practices and urban waste management needs. Together, these regions offer a comprehensive setting for examining the complexities of marine debris management in a metropolitan context.

3.2. Survey design and execution

To deepen the understanding of socio-cultural and economic factors influencing technology adoption in marine debris management, this study expanded its methodological approach by integrating qualitative insights alongside quantitative data. From October to December 2022, interviews were conducted with a diverse group of ten key stakeholders, including local community leaders, NGO representatives, researchers, government officials, and youth leaders. These discussions were designed to provide richer insights into community perceptions and attitudes toward the adoption of digital twin technology, delving into the intricate dynamics that quantitative methods alone might overlook. The qualitative insights gathered from these interviews were essential for understanding the nuanced views and potential barriers to technology adoption within the community. Stakeholders provided valuable perspectives on the

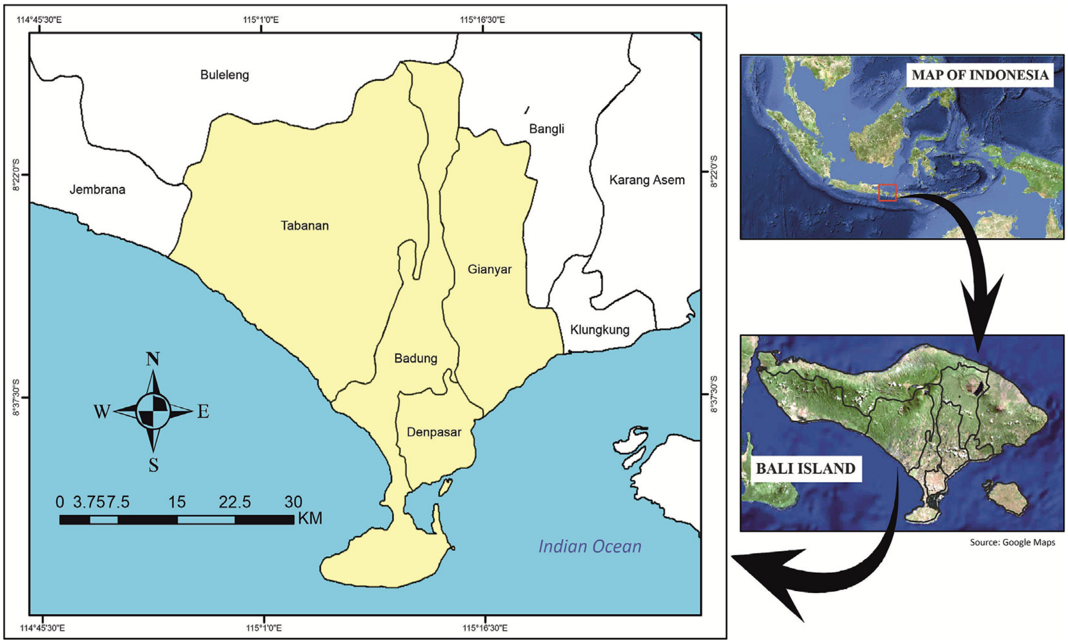

Fig. 2. Geographic location of the study area in the metropolitan region of Bali.

socio-cultural context, economic factors, and the specific challenges and opportunities in marine debris management in Bali. This qualitative data was then integrated into the overall analysis to enrich the understanding of community resilience frameworks and to tailor the survey instruments. To ensure the reliability of these instruments, a pretest was conducted in April 2023 with 50 individuals from the target population. This step was crucial for validating the effectiveness of the survey questions, ensuring they were appropriately framed and culturally relevant. Feedback from the pretest led to adjustments in the survey design, enhancing its capacity to capture meaningful data regarding community preferences for marine debris management strategies. The main survey, conducted over five months from August to December 2023, aimed to gather detailed data on the community's perceptions, planning capabilities, coping abilities, and interest levels concerning digital twin technology. The survey incorporated structured questions directly developed from the research model's identified constructs. These included assessing risk awareness through social media campaigns, community workshops, public surveys, and attendance at public events; evaluating planning capability through the involvement in training programs, the establishment of local marine debris task forces, and the development and dissemination of action plans; measuring coping ability through the provision of basic cleanup tools and access to advanced cleanup technologies; and determining interest level through engagement in cultural activities and the development of marine waste management initiatives. The integration of interview data with the survey results allowed for a comprehensive analysis that not only quantified the community's readiness and willingness to adopt digital twin technology but also provided a deeper understanding of the underlying reasons for their preferences. This approach helped in formulating recommendations for policymakers and practitioners on how to effectively implement digital twin technology in marine debris management by aligning with the community's resilience framework and preferences.

In this study, a representative sample of 647 residents from the metropolitan area of Bali was selected using stratified random sampling, which considered key demographic variables such as age, gender, education level, and occupation. This sampling method was specifically chosen to ensure a diverse cross-section of the community was accurately represented, enhancing the generalizability of the findings with a 4 % margin of error. The balance in composition across these strata ensured that the sample mirrored the demographic makeup of the broader community, allowing for more precise and culturally relevant insights. The demographic data collected in this study was used primarily for descriptive purposes to illustrate the socio-economic composition of the respondents. For instance, the sample included nearly equal representation of males (321, 50.16 %) and females (319, 49.84 %), ensuring gender balance. The respondents were also distributed across various income levels, with 22.03 % earning less than IDR 2.500.000 monthly, and smaller proportions distributed through higher income brackets up to more than IDR 10,000,000, which was represented by 13.91 % of the sample. Additionally, the sample included a mix of residents from coastal (328, 51.25 %) and inland (319, 48.75 %) areas, as well as those living in non-permanent (246, 38.44 %) and permanent (401, 61.56 %) residences. The age distribution was fairly even, with the largest groups being those aged 20–29 (250, 39.06 %) and 30–39 (255, 39.84 %), followed by those aged 40–49 (142, 22.19 %). Trained enumerators conducted the surveys face-to-face, utilizing both Bahasa Indonesia and Balinese to ensure clarity and effectiveness in communication. This approach not only facilitated accurate data collection but also helped in building trust and ensuring that respondents were comfortable in sharing their views.

This research thoroughly addressed the ethical and societal implications of deploying digital twin technology, particularly focusing on critical issues such as data privacy and equitable access. The study highlighted potential risks, including data breaches and unequal access to technological benefits, which could exacerbate social inequities. To counter these risks, the research proposed a set of strategies aimed at bolstering the study's integrity and comprehensiveness. Key among these was the development of robust data governance frameworks designed to ensure the protection of privacy, secure data handling, and enhance transparency in the collection, usage, and sharing of data. Ethical conduct was rigorously maintained throughout the research process. Permissions were obtained from all participants, who were comprehensively informed about the study's objectives and the use of the data collected. A strong emphasis was placed on the confidentiality and voluntary nature of their participation, with clear assurances that there was no coercion involved. This ethical rigor was further supported by the requirement that all researchers and enumeraries involved in the study complete the Taiwan Academic Research Ethics Education (AREE) program, certificate number P111013124. This program ensured that all involved parties were well-versed in the ethical standards necessary for conducting sensitive research, particularly in the administration of questionnaires and the handling of personal and potentially sensitive data.

3.3. Constructs and indicators

The survey covered several constructs, each with specific indicators designed to measure different community engagement dimensions and willingness to adopt digital twin technology for marine debris management (as detailed in Table 1). The constructs included perception of risk, planning capability, coping ability, interest level, and the primary outcome variable, willingness to adopt digital twins. The perception of risk was assessed through community workshops on marine debris impacts, public awareness events and their attendance, social media campaigns for marine debris awareness, and surveys assessing the perceived risk of marine debris. Planning capability was evaluated based on developing and disseminating action plans, establishing a local marine debris task force, involvement in simulation exercises for marine debris response, and training programs for debris management. Coping ability was measured through access to advanced cleanup technologies, community self-help initiatives, the effectiveness of emergency response protocols, and the provision of basic cleanup tools. Interest level was gauged through cultural engagement activities, the development of a marine waste management initiative, support for policy advocacy, and volunteer rates for marine debris cleanups. Finally, the community's willingness to engage with and support using digital twin technology in marine debris management projects determined the willingness to adopt digital twins.

3.4. Data analysis

The application of Structural Equation Modeling (SEM) in this research was pivotal for dissecting the complex interrelations among constructs such as risk perception, planning capability, coping ability, and interest level, specifically within the context of marine debris management in Bali. SEM's comprehensive capability to model multiple interdependent relationships simultaneously made it the optimal choice for examining how various factors collectively influence the community's readiness to embrace digital twin technology. The SEM analysis encompassed several methodical steps, starting with Confirmatory Factor Analysis (CFA). CFA was crucial for validating the measurement model, confirming that the survey items accurately represented the constructs they were intended to measure. This process was fundamental in verifying the hypothesized factor structure within the theoretical framework, ensuring that each construct was precisely depicted by its indicators. After CFA, the reliability and validity of the constructs were rigorously assessed. Reliability was determined using Cronbach's alpha, which checked for internal consistency, while Composite Reliability (CR) and Average Variance Extracted (AVE) were calculated to evaluate the overall reliability of the constructs and the variance they captured relative to measurement error, respectively. These metrics were instrumental in confirming that the constructs were reliable and robust for further analysis (Cheung et al., 2023; Hair et al., 2020; Melkamu Asaye et al., 2022; Mohd Dzin & Lay, 2021).

The evaluation of the model's goodness of fit was a critical step in assessing the SEM applied in this study. To determine how well the proposed model represented the relationships among the variables, several statistical indices were utilized: the Standardized Root Mean Square Residual (SRMR), Comparative Fit Index (CFI), and Root Mean Square Error of Approximation (RMSEA) (Maydeu-Olivares, 2017; Maydeu-Olivares et al., 2018). These indices provide a comprehensive measure of fit that helps in evaluating whether the model adequately fits the observed data. The SRMR is a measure of the average discrepancy between the observed correlations and the model's predicted correlations, with lower values indicating a better fit. The CFI compares the fit of the target model to an independent model, with values closer to 1.0 suggesting a good fit. The RMSEA assesses fit per degree of freedom in the model, considering the error of approximation in the population, with values less than 0.05 indicating a close fit. Following the evaluation of model fit, path analysis was undertaken to examine the direct and indirect relationships between the constructs within the SEM framework (Rahman, Suhardono, Sofiyah, Sianipar, & Lee, 2025; Ulhasanah et al., 2025; Yang, Lee, & Suryawan, 2024). This component of the analysis calculated path coefficients, which provide a quantification of the strength of the relationships between variables. Additionally, t-values and p-values were computed for these coefficients to assess their statistical significance. This phase of the analysis is fundamental to understanding how constructs such as risk perception and planning capability influence the community's willingness to adopt digital twin technology, both directly and indirectly.

The integration of qualitative insights from interviews with key stakeholders such as community leaders and NGO representatives further enriched the analysis. These qualitative insights provided a deeper understanding of the contextual factors influencing technology adoption, which helped in refining the survey questions and adjusting the theoretical model. This integration ensured that the constructs were appropriately operationalized within the SEM framework, reflecting the complexities of community engagement with technology. By combining detailed qualitative insights with rigorous quantitative analysis through SEM, the study not only validated the structural model but also ensured that the research findings were empirically robust and culturally relevant. This comprehensive approach provided a nuanced understanding of how different factors influence the adoption of digital twin technology in marine debris

Table 1
Specific indicators designed to measure different dimensions of community engagement and willingness to adopt digital twin technology for marine debris management.

Framework	Variables	Question	Example	Type
Risk awareness	Social media campaigns for marine debris awareness	How do workshops on marine debris impacts influence your willingness to support digital twin technology for climate resilience?	Workshops demonstrating digital twins that simulate the accumulation and movement of marine debris in coastal areas.	MET
	Community workshops on marine debris impacts	How does attendance at public awareness events affect your willingness to engage with digital twin technology for marine debris management?	Public events featuring interactive digital twin models that show the impact of marine debris on local ecosystems.	MET
	Surveys assessing perceived risk of marine debris	How effective are social media campaigns in shaping your willingness to adopt digital twin technology for addressing marine debris?	Social media campaigns using digital twin animations to illustrate the long-term effects of marine debris on the environment.	MET
	Public awareness events and their attendance	How do surveys on perceived marine debris risk influence your willingness to support the use of digital twins?	Surveys incorporating digital twin visualizations to help respondents understand the potential future scenarios of marine debris accumulation.	MET
Planning capability	Training programs for debris management	How does developing and disseminating action plans using digital twins enhance your willingness to participate in marine debris management?	Action plans created using digital twin simulations to identify and prioritize areas for intervention.	MET
	Establishment of a local marine debris task force	How important is establishing a local marine debris task force in encouraging the adoption of digital twin technology?	Formation of a task force that utilizes digital twin technology to coordinate marine debris cleanup efforts.	MET
	Development and dissemination of action plans	How does participation in simulation exercises using digital twins affect your willingness to engage in marine debris response planning?	Participation in exercises that use digital twins to model and practice responses to marine debris incidents.	MET
	Involvement in simulation exercises for marine debris response	How valuable are training programs that incorporate digital twin technology for your willingness to support debris management efforts?	Training programs that include hands-on experience with digital twin tools to plan and manage debris cleanup operations.	MET
Coping ability	Provision of basic cleanup tools	How does access to advanced cleanup technologies integrated with digital twins influence your willingness to cope with marine debris?	Access to cleanup technologies that are optimized through digital twin simulations.	MET
	Access to advanced cleanup technologies	How do community self-help initiatives using digital twins affect your willingness to participate in marine debris management?	Community initiatives that leverage digital twins to organize and coordinate cleanup activities.	MET
	Effectiveness of emergency response protocols	How effective are emergency response protocols that leverage digital twin technology in influencing your willingness to cope with marine debris?	Emergency protocols developed with the help of digital twins to enhance preparedness and response.	MET
	Community self-help initiatives	How useful is providing basic cleanup tools, enhanced by digital twin simulations, in your willingness to participate in marine debris management?	Provision of cleanup tools that are selected based on recommendations from digital twin analyses.	MET
Interest level	Cultural engagement activities	How do cultural engagement activities that incorporate digital twin technology enhance your interest in marine debris management?	Cultural events that use digital twin displays to raise awareness about marine debris.	MET
	Development of a marine waste management initiative	How supportive are you of developing new marine waste management initiatives that utilize digital twins?	Support for new initiatives that use digital twin technology to design and implement waste management solutions.	MET
	Volunteer rates for marine debris cleanups	How likely are you to volunteer for marine debris cleanups that utilize digital twin technology for coordination and planning?	Volunteer initiatives that leverage digital twin technology to optimize cleanup efforts and track progress.	MET
	Support for policy advocacy	How important is supporting policy advocacy for implementing digital twin technology in marine debris management?	Advocacy efforts that promote the use of digital twins in policy-making for marine debris management.	MET
Willingness to adopt digital twins	Desire to participate to beach cleanup programs	How willing are you to participate in adopting and implementing digital twin technology for effective marine debris management and climate-resilient urbanization?	Your willingness to engage with and support the use of digital twin technology in marine debris management projects.	0|1

management, offering actionable insights for policymakers, practitioners, and researchers aiming to implement effective environmental management strategies in Bali and potentially other similar settings.

4. Result

Table 2 provides a detailed summary of the descriptive statistics for the variables examined in this study, focusing on community engagement and willingness to adopt digital twin technology for marine debris management. Each variable is associated with specific constructs, including risk awareness, planning capability, coping ability, interest level, and willingness to adopt digital twins. The table includes the mean values, excess kurtosis, and skewness for each variable, offering insights into the responses' central tendencies and distributional characteristics.

Table 2
Summary of the descriptive statistics for the variables examined.

Framework	Variables	Mean	Excess kurtosis	Skewness
Risk awareness	Social media campaigns for marine debris awareness	4.368	0.723	−0.791
	Community workshops on marine debris impacts	4.411	1.147	−1.036
	Surveys assessing perceived risk of marine debris	4.355	0.27	−0.812
	Public awareness events and their attendance	4.371	0.738	−0.894
Planning capability	Training programs for debris management	4.369	0.38	−0.73
	Establishment of a local marine debris task force	4.326	0.551	−0.788
	Development and dissemination of action plans	4.275	−0.126	−0.666
	Involvement in simulation exercises for marine debris response	4.284	0.583	−0.892
Coping ability	Provision of basic cleanup tools	3.958	−0.61	−0.858
	Access to advanced cleanup technologies	3.437	−0.556	0.415
	Effectiveness of emergency response protocols	3.538	−0.77	0.128
	Community self-help initiatives	3.529	−0.609	0.242
Interest level	Cultural engagement activities	3.601	−0.821	0.133
	Development of a marine waste management initiative	3.436	−0.447	0.492
	Volunteer rates for marine debris cleanups	3.567	−0.712	0.37
	Support for policy advocacy	3.493	−0.68	0.203
Willingness to adopt digital twins	Desire to participate to beach cleanup programs	0.535	−1.987	−0.14

Fig. 3 presents the study's SEM results, illustrating the relationships between various constructs and their impact on the community's willingness to adopt digital twin technology for marine debris management. The model examines how different factors, including risk perception, planning capability, coping ability, and interest level, influence the primary outcome willingness to engage with and support the use of digital twin technology. Theis highlights the standardized path coefficients, showing the strength and direction of the relationships between the constructs. Perception of risk, planning capability, coping ability, and interest level are all depicted as

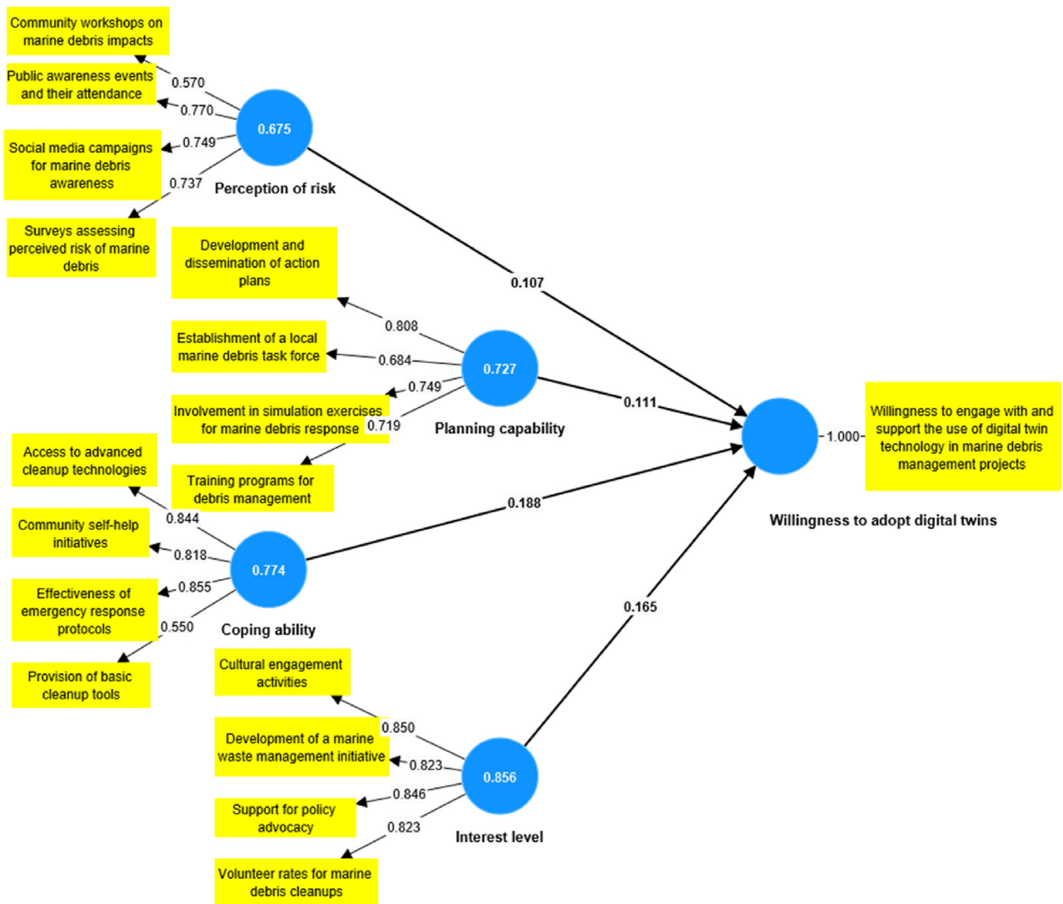

Fig. 3. SEM result illustrating the relationships between various constructs and their impact on the community's willingness to adopt digital twin technology for marine debris management.

influencing the willingness to adopt digital twins. Each construct is measured by several indicators, represented by yellow boxes, which provide detailed insights into community engagement and preparedness. Perception of risk is influenced by community workshops, public awareness events, social media campaigns, and surveys assessing the perceived risk of marine debris. Planning capability encompasses developing and disseminating action plans, establishing local marine debris task forces, and involvement in simulation exercises and training programs. Coping ability includes access to advanced cleanup technologies, community self-help initiatives, effectiveness of emergency response protocols, and provision of basic cleanup tools. Cultural engagement activities, development of marine waste management initiatives, support for policy advocacy, and volunteer rates for marine debris cleanups determine interest level.

Table 3 presents the goodness-of-fit results for the SEM conducted in this study. These fit indices provide crucial information on how well the proposed model fits the observed data, which is essential for validating the hypothesized relationships between the constructs of risk perception, planning capability, coping ability, interest level, and willingness to adopt digital twin technology for marine debris management. The Standardized Root Mean Square Residual (SRMR) value of 0.066 indicates an acceptable fit, as values below 0.08 generally indicate a good fit. The unweighted least squares (d_ULS) and geodesic discrepancy (d_G) values of 0.674 and 0.214 also support the model's adequacy, suggesting minimal discrepancies between the observed and model-implied covariance matrices. Although significant, the Chi-square statistic of 744.32 must be interpreted cautiously due to its sensitivity to sample size. The Normed Fit Index (NFI) value of 0.846 indicates a good fit, approaching the threshold of 0.90 typically used to denote a well-fitting model. The R-square value of 0.623 and the adjusted R-square value of 0.62 reflect the proportion of variance in the outcome variable (willingness to adopt digital twins) explained by the model. These values suggest that the model explains a substantial portion of the variance, underscoring the relevance of the identified constructs in influencing community engagement and technology adoption.

Table 4 provides the Heterotrait-Monotrait Ratio (HTMT) matrix and reliability and validity measures for the constructs used in this study. The HTMT ratio measures discriminant validity, indicating how well a construct is distinct from other constructs within the model. Lower HTMT values suggest better discriminant validity, implying that the constructs are not overly similar and measure distinct concepts. The HTMT matrix displays the relationships between coping ability, interest level, perception of risk, planning capability, and willingness to adopt digital twins. The values show that most relationships between constructs are well below the threshold of 0.85, indicating good discriminant validity. However, it is notable that the HTMT value for the relationship between coping ability and interest level slightly exceeds 1, suggesting some overlap between these constructs. In terms of reliability and validity, this includes CR and AVE for each construct. Composite Reliability values above 0.70 indicate good internal consistency; all constructs meet this criterion. The AVE values indicate the proportion of variance captured by the construct relative to the variance due to measurement error, with values above 0.50 considered acceptable. All constructs except "perception of risk" meet this threshold, indicating that most constructs explain a satisfactory amount of variance in their respective indicators.

Table 5 and Fig. 4 presents the results of the path analysis conducted as part of the SEM process. The path coefficient for risk perception (H1) is 0.107 with a p-value <0.001, indicating that while awareness of marine debris risks is crucial, its impact on technology adoption is relatively modest compared to other factors. Planning capability (H2) shows a path coefficient of 0.111 with a p-value <0.001, highlighting that structured planning processes significantly enhance the community's readiness to integrate digital twins. Coping ability (H3) presents the highest impact with a path coefficient of 0.188 and a p-value <0.001, suggesting that communities with robust mechanisms to handle emergencies and adapt to technological changes are most likely to embrace digital twins. Interest level (H4) also shows a substantial positive influence with a coefficient of 0.165 and a p-value <0.001, indicating that higher

Table 3
The goodness of fit result.

Parameter	Value
SRMR	0.066
d_ULS	0.674
d_G	0.214
Chi-square	744.32
NFI	0.846
R-square	0.623
R-square adjusted	0.62

Table 4
HTMT and rollability and validity.

HTMT-Matrix					Reliability and Validity	
Variables	Coping ability	Interest level	Perception of risk	Planning capability	Composite reliability	Average variance extracted (AVE)
Coping ability					0.856	0.604
Interest level	1.017				0.903	0.699
Perception of risk	0.118	0.087			0.802	0.506
Planning capability	0.121	0.061	1.005		0.829	0.55
Willingness to adopt digital twins	0.728	0.705	0.41	0.458	–	–

Table 5
Path analysis conducted and hypothesis testing as Part of the SEM process.

Variable	Original sample	Sample mean	Standard deviation	t-value	p-value
Perception of risk - > Willingness to adopt digital twins (H1)	0.107	0.107	0.017	6.363	<0.001
Planning capability - > Willingness to adopt digital twins (H2)	0.111	0.111	0.017	6.668	<0.001
Coping ability - > Willingness to adopt digital twins (H3)	0.188	0.188	0.023	8.356	<0.001
Interest level - > Willingness to adopt digital twins (H4)	0.165	0.164	0.023	7.197	<0.001

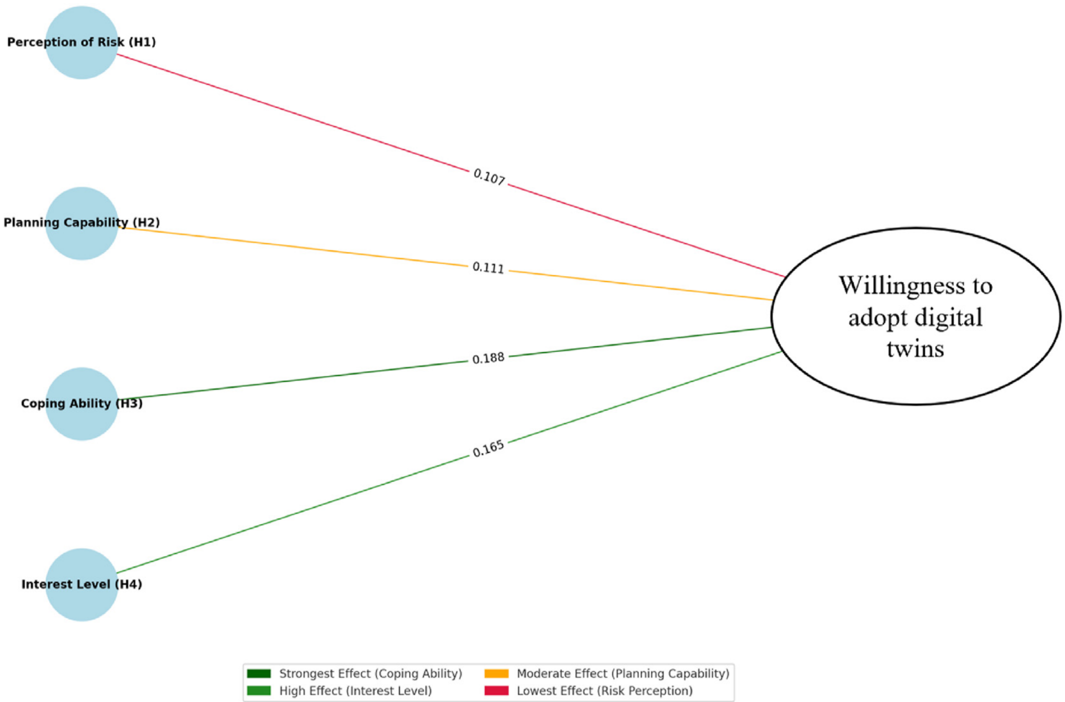

Fig. 4. Visualization of standardized path coefficients in the SEM model, showing the relative influence of each latent variable on the willingness to adopt digital twins for marine debris management.

community engagement and interest in marine debris management significantly boost the adoption of digital twin technology. These findings clarify how different factors variably influence the willingness to adopt digital twin technology. The paramount importance of coping ability suggests that enhancing community resilience and response capabilities should be a focal point in efforts to foster technological adoption. The relatively lower impact of risk perception may necessitate reevaluating and enhancing current awareness-raising strategies to make them more effective in promoting digital twin solutions. This nuanced understanding not only advances the theoretical discourse on technology adoption but also provides actionable insights for policymakers and practitioners aiming to implement digital twin technology in environmental management effectively.

5. Discussion

The perception of risk significantly influences the willingness to adopt digital twin technology (H1; path coefficient = 0.107; $p < 0.001$), emphasizing the need for strong community awareness around marine debris challenges. Risk perception is shaped through targeted interventions such as community workshops, social media campaigns, and public awareness events, which help communicate the environmental and economic threats posed by marine debris (Purba et al., 2023). These initiatives not only raise awareness but also create a sense of urgency, prompting greater public support for advanced management technologies like digital twins. This finding aligns with broader literature highlighting risk awareness as a key driver of pro-environmental behavior (Appolloni et al., 2021; Lewin et al., 2020). Beyond the specific case of marine debris, digital twin technology is increasingly recognized as a transformative tool in broader disaster risk management frameworks, especially within smart city development. For example, digital twins are being used to monitor wind-borne debris on construction sites (Kamari & Ham, 2022), improve the effectiveness of emergency response operations through real-time hazard localization (Kwok et al., 2021), and support intelligent disaster mitigation strategies by integrating multi-source data for informed decision-making (Yu & He, 2022). However, their integration into disaster management systems introduces added technical and governance complexities, requiring coordinated protocols and significant stakeholder capacity (Ariyachandra & Wedawatta, 2023; Zio & Miqueles, 2024). Recent developments in digital twin-based post-disaster risk modeling have shown promising results in improving real-time assessments and enhancing recovery planning efforts (Lagap & Ghaffarian, 2024).

Planning capability also shows a significant positive effect on the willingness to adopt digital twins (H2; path coefficient = 0.111; $p < 0.001$), this indicates that communities with well-developed planning strategies are more inclined to integrate digital twin technologies into their marine debris management practices. Key elements of planning capability include developing and disseminating action plans, establishing local marine debris task forces, involvement in simulation exercises, and comprehensive training programs. These activities enhance the community's preparedness to respond to marine debris issues and demonstrate the practical applications and benefits of digital twin technology. Action plans and task forces that utilize digital twins can identify critical areas for intervention and coordinate effective responses (Pańkowska & Żytniewski, 2024). Simulation exercises, which offer hands-on experience with digital twin tools, further bolster the community's confidence in using these technologies. This finding is consistent with the notion that effective planning and preparedness are essential for successfully implementing innovative solutions in environmental management (Chofreh et al., 2020; Zhang et al., 2020). Additionally, in the realm of waste management, digital twin technology serves as a pivotal planning entity. It significantly enhances route optimization for waste collection organizations by integrating comprehensive performance optimization for waste management systems (Barth et al., 2023). This involves a meticulous consideration of transportation task distribution and path planning, adjusted locally using the time window method to streamline operations effectively (Wu & Li, 2022). Moreover, the integration of digital twins with artificial intelligence in smart cities facilitates environmentally sustainable planning. This synergy is critical in evolving smart city infrastructure to support sustainable development (Bibri et al., 2024). Also, the application of digital twins extends to higher-level management systems, optimizing spare parts management and transportation planning through seamless integration with procurement, warehouse, and transportation management systems, or global enterprise resource planning systems, enhancing organizational efficiency across multiple domains (Preut et al., 2021). Communities with advanced planning capabilities are exceptionally well-positioned to leverage digital twin technology for proactive and efficient debris management, reflecting a broad application of this technology from marine debris management to complex waste management systems and smart city planning.

Coping ability (H3; path coefficient = 0.188; $p < 0.001$) emerges as a significant factor with the highest path coefficient and has a strong positive relationship, highlighting that communities with robust coping mechanisms are more willing to adopt digital twin technology. Coping ability encompasses access to advanced cleanup technologies, community self-help initiatives, the effectiveness of emergency response protocols, and the provision of basic cleanup tools. These components collectively enhance the community's resilience and capability to manage marine debris. When equipped with the necessary tools and resources, communities can effectively utilize digital twin technology to optimize cleanup operations and emergency responses. Advanced cleanup technologies, integrated with digital twin simulations, can provide real-time data and predictive analytics, enhancing the efficiency and effectiveness of waste management efforts (Seyyedi et al., 2024; Suryawan & Lee, 2023; Wu & Li, 2022). Community self-help initiatives and emergency response protocols, supported by digital twins, enable coordinated and rapid responses to debris incidents. This aligns with research indicating that technology-organization-environment availability critical determinants of green innovation adoption (Zhang et al., 2020). The application of digital twins extends beyond traditional waste management. For example, in an urban community in Ghana, West Africa, digital twins are explored for their potential to systematically support sustainable development and poverty alleviation (Cordes et al., 2024). This involves using digital twins to include additional data sets for studying various scenarios of Sustainable Development Goal (SDG) interventions, allowing for virtual modeling of interventions and subsequent monitoring of their physical implementation (Cordes et al., 2024). Moreover, digital twins have been utilized in strategic decisions regarding the location of temporary disposal centers and the transportation of COVID-19 medical waste, taking into account the hierarchical relationships among stakeholders (Cao et al., 2023). Furthermore, digital twin technology, combined with blockchain, is being proposed as an innovative method to optimize waste management by enhancing monitoring capabilities while reducing overall costs (Castiglione et al., 2023). In the context of Waste Electrical and Electronic Equipment (WEEE) remanufacturing, digital twins are being developed to support manufacturing and remanufacturing processes throughout their lifecycle, introducing Industry 4.0 enablers to improve system efficiency (Wang & Wang, 2019).

Interest level significantly influences the willingness to adopt digital twin technologies (H4; path coefficient = 0.165; $p < 0.001$), indicating that community involvement plays a key role in supporting innovative approaches to marine debris management. Community interest is reflected through active participation in cultural events, volunteer cleanup efforts, policy advocacy, and the initiation of local waste management programs. These actions demonstrate not only awareness but also a collective commitment to environmental stewardship. Cultural engagement activities, such as local festivals and educational campaigns, help strengthen community ties and foster a shared sense of responsibility (Suryawan & Lee, 2024), creating a social environment that is more receptive to adopting new technologies. Beyond the marine context, digital twin integration in urban planning also benefits from high levels of public interest and stakeholder collaboration. Government-led initiatives increasingly involve citizens in co-creating smart city solutions through city-scale digital twins, improving both planning strategies and community ownership (Adade & de Vries, 2024). Stakeholder engagement in land-use planning ensures that decisions reflect diverse interests, contributing to more socially equitable and informed urban governance (Adade & de Vries, 2023). Additionally, the adoption of digital twins in cities serves a range of goals from enhancing operational efficiency to advancing social outcomes—depending on institutional priorities (Al-Sehrawy et al., 2023). Further integrating digital twins involves sophisticated multi-agent interactions, artificial intelligence, and coupled natural-physical-social systems to enhance community infrastructure resilience and adaptive planning capabilities (Ye et al., 2022). This holistic approach to urban planning considers the intricate web of decisions, investments, and activities that define urban environments (Lai, 2022), highlighting the importance of institutional designs in influencing organizational performance and planning outcomes (Lin & Lai, 2022).

This study merges qualitative insights from interviews with SEM to provide a nuanced understanding of the community dynamics that influence the adoption of digital twin technology for managing marine debris in Bali. By integrating in-depth stakeholder interviews with rigorous quantitative analysis, the research clarifies how community perceptions and capacities impact their willingness to embrace new technologies. Risk perception (H1; path coefficient = 0.107, $p < 0.001$) emerges as a significant factor, with qualitative interviews underscoring that heightened community awareness significantly raises risk perception associated with marine debris. Stakeholders expressed that initiatives like community workshops and public awareness events substantially increase the community's understanding of the risks posed by marine debris. For instance, a community leader shared during an interview, "The use of digital twins in workshops shows us real-time impacts and what could happen if we don't act—making the threat of marine debris very real and immediate for everyone involved." This aligns with the SEM results, which indicate that higher risk awareness correlates with a greater willingness to adopt digital twin technologies. Coping ability (H3; path coefficient = 0.188, $p < 0.001$) was found to have the strongest positive influence on the adoption of technology, as demonstrated by the highest path coefficient. Interviews with community leaders and NGO representatives revealed that communities that are well-equipped with robust emergency response capabilities and advanced cleanup technologies are more adaptive and open to integrating new technologies like digital twins. "Our community has seen firsthand how technology can aid in crisis situations. Digital twins offer a promising addition to our tools, especially for predictive management of marine debris," noted an NGO representative. This qualitative feedback complements the quantitative findings, emphasizing the importance of readiness in technology adoption. Planning capability (H2; path coefficient = 0.111, $p < 0.001$) also significantly affects technology adoption. The qualitative data highlighted the crucial role of structured planning in facilitating digital twin integration. A government official explained, "With established action plans and task forces, we can seamlessly incorporate digital twin technologies into our operations, enhancing our response to marine debris." This systematic approach ensures that technology integration is not only strategic but also efficient. Interest level (H4; path coefficient = 0.165, $p < 0.001$) reflects the community's enthusiasm and engagement, which is pivotal for adopting new technologies. Interview insights revealed that cultural engagement activities and educational workshops play a vital role in generating interest and support for digital twin technology. "When people see the benefits of digital twins in real-time, especially during cleanups, it sparks a genuine interest and desire to support these technologies," shared a volunteer coordinator.

The findings of this study have significant implications for policymakers, practitioners, and researchers. Enhancing community risk perception through targeted awareness campaigns and educational programs is crucial (Cori et al., 2022; Kuang et al., 2020). Policymakers should invest in initiatives that effectively communicate the risks associated with marine debris and the potential benefits of digital twin technology. This can be achieved through multimedia campaigns, interactive workshops, and public events that showcase real-world applications of digital twins (Menon et al., 2023). Expanding the analysis beyond Bali, comparative case studies and frameworks from various global regions where digital twin technology has been applied demonstrate its broader applicability and contextual relevance. The integration of such comparative analyses underscores the importance and transformative potential of digital twin technology as part of the next industrial revolution, reflected in strategic initiatives like Germany's "Industry 4.0" (Kagermann et al., 2013), the United States' "Advanced Manufacturing" (Yao et al., 2019), Japan's "Society 5.0″, China's "Made in China (2025)", and Europe's "Factory of the Future" (Drath & Horch, 2014). For instance, in Hong Kong, a marine litter smart coastal management framework that leverages unmanned aerial vehicles for data collection, detection, localization, and decision-making has validated the efficacy of digital twins in offering scalable, automated, real-time solutions (Zhang et al., 2024). This approach addresses continuous monitoring challenges that are exacerbated by factors such as beach characteristics and varying weather conditions, thereby highlighting the high costs and necessity for innovative, fully automated approaches in beach waste management as demonstrated in the BIOBLU project (Cicceri et al., 2023). Similarly, in Switzerland, a field study involving 98 waste bins equipped with fill-level sensor modules justified the adoption of digital twin-based decision support systems by showcasing cost savings and improved service quality in affluent societies (Barth et al., 2023). In South Africa, the urban digital twin prototype illustrates the complexity and potential of digital twins in urban waste management, integrating real-time monitoring, citizen participation, and optimized collection routes, although stakeholders' opinions on the urban digital twin usefulness varied based on their backgrounds and skills (Cárdenas-León et al., 2024). Further exploration in Polish cities tested different machine learning models to predict waste generation, integrating these systems with digital twins to refine urban garbage collection systems (Shah et al., 2024). In Sejong City, South Korea, a digital twin system was developed to experiment with and refine the garbage collection schedule, highlighting the rigidities in system management and the potential for simulation to improve operational efficiency (Yun et al., 2023). Moreover, the impact of digital twin technology on smart city development in Malaysia (Waqar et al., 2023), and its potential influence on achieving Sustainable Development Goal 11 in New Zealand underscore the technology's significance (Patel et al., 2024). Challenges such as data integration, cross-sector collaboration, and governance barriers are prominent, with a strong emphasis on knowledge sharing and transfer to effectively translate insights into local actions. Lastly, in Australia, digital twin technology has been employed to visualize potential developments in greenfield land and water resources in key catchments (Branchaud, Seo, & Petheram, 2023). This application aims to bridge gaps through visualization, facilitating informed consensus and benefiting both the environment and communities.

5.1. Policy recommendations

This study highlights actionable strategies for policymakers and practitioners to boost community engagement and encourage the adoption of digital twin technologies in managing marine debris in Bali. By leveraging the capabilities of digital twins, the proposed interventions are specifically tailored to address the island's unique challenges and opportunities. Policymakers are advised to launch multimedia campaigns that utilize digital twin simulations to vividly illustrate the dynamics and impacts of marine debris (**risk awareness)**. These campaigns should involve community workshops where stakeholders can interact with real-time simulations and scenario planning tools, providing a tangible understanding of the severity of marine debris issues. To broaden the reach and impact, digital twin technology should be integrated into school curriculums and public outreach programs, ensuring comprehensive community engagement and education. The study recommends establishing a regulatory framework that mandates the inclusion of digital twin technologies in all marine debris management plans by local governments (**planning capability**). This framework would standardize the use of digital twins, ensuring consistent application across various administrative levels and enhancing the effectiveness of management efforts. Incentives such as tax breaks or funding support should be provided to encourage local governments to adopt these advanced technologies. Guidelines should be developed to facilitate the implementation of these tools within Bali's distinct administrative and ecological contexts. A specialized fund should be created to finance the acquisition of advanced cleanup technologies integrated with digital twins, funded by environmental fees or levies charged to major polluters (**coping ability**). This initiative would equip communities with the necessary tools for real-time monitoring and automated debris collection, significantly boosting their ability to effectively manage both emergency situations and routine debris challenges. The application of these technologies should be tailored to suit the specific coastal dynamics of Bali, ensuring their effectiveness in both urban and rural settings across the island. An innovation challenge fund is proposed to encourage local organizations to develop innovative applications of digital twin technology in debris management (**interest level**). This fund would support pilot projects that demonstrate the practical benefits of digital twins, actively engaging community members in the design and execution of these projects. Such initiatives would serve as practical demonstrations of the technology's effectiveness, fostering community interest and support for digital twin solutions.

To make the policy recommendations more actionable, this study proposes that local governments integrate digital twin technology into official marine debris management plans by establishing regulatory mandates and operational guidelines tailored to Bali's coastal dynamics. This integration should be supported by collaborative partnerships with universities, technology developers, and private sector actors to co-develop training programs, simulate planning scenarios, and build localized decision-support tools. NGOs can further facilitate adoption by organizing community workshops, providing access to open-source digital twin platforms, and leading pilot initiatives in high-risk coastal zones. To incentivize uptake, governments may offer regulatory measures such as tax relief, grant schemes, or priority funding for municipalities and organizations that adopt digital twin solutions. In terms of financing, a blended approach that combines environmental levies on major polluters, corporate social responsibility (CSR) funding, and public-private partnerships could support both the initial deployment and long-term scaling of these technologies. Additionally, the establishment of an innovation challenge fund would stimulate grassroots innovation by supporting community-led pilot projects that demonstrate the practical benefits of digital twins in debris management. These strategies together provide a replicable and sustainable roadmap to accelerate the adoption of digital twin technology in Bali and comparable coastal regions.

As digital twins become more embedded in marine debris governance, attention must also be paid to ethical considerations related to data privacy, equitable access, and inclusive governance. The success of these technologies relies not only on technical implementation but also on the adoption of transparent, community-centered data practices. To ensure responsible use, this study recommends the establishment of community-based data governance frameworks grounded in principles of informed consent, data anonymization, and open-access protocols. Local governments should form oversight committees comprising community members, academic experts, and civil society organizations to monitor how data is collected, shared, and used within digital twin systems. Furthermore, publicly accessible dashboards should be developed to empower residents to interpret real-time data and participate meaningfully in decision-making processes. Bridging the digital divide is also critical, ensuring that marginalized and underserved communities have equitable access to both the technology and the platforms for engagement it enables. These governance mechanisms are essential for building community trust, protecting individual rights, and ensuring that the deployment of digital twin technology in Bali is not only effective but also socially responsible and inclusive.

6. Conclusion

This research provides a comprehensive analysis of the factors influencing communities' willingness in Bali's metropolitan area to adopt digital twin technology for marine debris management. Utilizing Structural Equation Modeling (SEM), the study identifies four critical determinants: risk perception, planning capability, coping ability, and interest level. Each factor plays a significant role in shaping community readiness and support for innovative technological solutions. The findings reveal that a higher risk perception regarding marine debris issues significantly enhances community willingness to adopt digital twin technology. This underscores the importance of effective awareness campaigns and educational programs that clearly communicate the risks and impacts of marine debris and the potential benefits of using digital twin technology for mitigation. The implications of these findings are significant for policymakers, practitioners, and researchers. Enhancing risk perception, strengthening planning capabilities, improving coping mechanisms, and fostering community interest are essential strategies for promoting the adoption of digital twin technology in marine debris management. Policymakers should invest in targeted interventions and supportive policies that address these factors, while practitioners should focus on integrating digital twin technology into existing frameworks and leveraging community engagement.

This research offers insights into the adoption of digital twin technology for marine debris management in Bali, but it comes with certain limitations that may affect the generalizability and application of its findings. Primarily, the unique geographical, cultural, and socioeconomic landscape of Bali makes the results specific to this context. Given Bali's heavy reliance on tourism and its distinct environmental challenges, strategies that prove effective here may not necessarily apply to regions with different economic focuses or environmental conditions. Furthermore, the study's focus was narrowly tailored to specific scenarios within marine debris management, potentially overlooking the versatility of digital twin technology in addressing a broader range of environmental or urban challenges. For future research, it is recommended to extend the application of digital twin technology across diverse geographic and socioeconomic settings. This expansion would help ascertain the adaptability and scalability of the technology under different environmental management scenarios, offering a broader validation of the model's effectiveness. Additionally, integrating digital twin technology with other smart technologies could be explored to develop more comprehensive environmental management solutions, thereby enhancing systemic resilience and adaptability. Another valuable direction would be longitudinal studies tracking the long-term impacts of digital twin technology on marine debris management. Such studies would shed light on the sustainability and evolution of technology adoption over time, helping to identify persistent barriers and facilitators within community settings. Investigating the integration and interaction between digital twin technology and community engagement strategies in various global contexts could also provide deeper insights into the universal applicability and scalability of digital twin solutions in environmental management.

CRediT authorship contribution statement

Sapta Suhardono: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Laili Fitria:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Wisnu Prayogo:** Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Chun-Hung Lee:** Visualization, Supervision, Methodology. **I Wayan Koko Suryawan:** Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, 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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