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Digital Technology as an Enabler for Sustainable Natural Resource Management Policies in Indonesia

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ABSTRACT

This study investigates the role of digital technologies in supporting sustainable natural resource management in Indonesia. The research aims to identify dominant technologies and clarify their contributions to policy-oriented sustainability frameworks. A mixed-methods approach was applied, combining a systematic review of Scopus-indexed journals, thematic coding of sustainability elements, AI-assisted clustering of architectural technology usage, and quantitative frequency mapping. The results highlight the prominence of the Internet of Things (IoT, 45.88%) and Building Information Modelling (BIM, 30.63%) in enabling real-time monitoring and integrated infrastructure planning. Complementary tools such as ArcGIS, Google Earth Engine, Blockchain, and VR/AR further support transparency, spatial analysis, and eco-friendly design. By synthesising these contributions, the study demonstrates how digital technologies enable sustainable resource management strategies in Indonesia and provides a foundation for future research and implementation.

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1. INTRODUCTION

Sustainable development is an integrated effort to meet present needs while minimising the impact of resource use, ensuring that future generations can meet their own needs. This approach emphasises the importance of wise natural resource management by balancing economic growth, social equity, and environmental conservation, commonly known as the three pillars of sustainable development [1], [2]. In this context, the success of development depends not only on economic factors but also on social and ecological elements that sustain ecosystem functions. Major challenges, such as deforestation, global warming, watershed degradation, and uncontrolled population growth, have the potential to exacerbate climate change and reduce the availability of natural resources [3].

Natural resources, both biotic and abiotic, play a crucial role in meeting human needs and supporting well-being. Improper use can cause environmental damage and be detrimental to human life [2]. Therefore, natural resource management should focus not only on environmental aspects but also on the three main areas: economic, social, and environmental. From an economic perspective, management focuses on improving society's capacity to produce competitive, high-quality products that support sustainable economic growth [1]. Social management emphasises fostering good interactions between communities, residents, and visitors, which are necessary to build harmony for sustainable development [1].

On the other hand, environmental management emphasises the optimal utilisation of resources. This includes energy efficiency through building designs that utilise natural lighting, cross-ventilation, and eco-friendly materials. Additionally, water management plays an essential role. Strategies such as rainwater harvesting, eco-friendly waste treatment, and landscape design can help reduce surface water runoff [4]. Water management reforms, including forest rehabilitation, pollution control, water conservation, and community empowerment, are also needed to address poverty, food security, and energy issues while maintaining ecosystem balance [3]. Therefore, an approach that integrates economic, social, and environmental aspects in resource management is critical. This approach includes forest rehabilitation, pollution control, energy efficiency, and the optimisation of natural resources through innovative designs, such as the use of renewable energy and eco-friendly building materials [4].

Digital architecture leverages communication and information technologies throughout the architectural planning and design process. This utilisation is not limited to drawing or presentation tools but is also used for the philosophical processing of information. In architecture, both academically and practically, strong communication networks and the ability to manage architectural data information are essential to support every stage of the design process [5]. Digital technology also significantly impacts speed, resilience, and accuracy, with machines functioning as an "extended brain" that collaborates with humans to create better, more responsible architectural works [5].

Advancements in digital technology, such as artificial intelligence (AI), advanced robotics, the Internet of Things (IoT), 3D printing, and augmented reality/virtual reality (AR/VR), have fostered the creation of a more dynamic life beyond spatial and temporal boundaries. In this context, architecture must adopt a smart, wise approach to balance physical, spiritual, social, and environmental needs [6]. While traditional design methods, such as pencil sketching, are still used—particularly in architectural education—digital technology has advanced rapidly and is widely adopted by architects in the design process. Architecture students also combine these two methods in their learning [7]. Given the importance of sustainable natural resource management, this study aims to observe the use of digital technology in identifying sustainability elements, including materials, water, energy, and ecology, in natural resource management.

2. RESEARCH METHOD

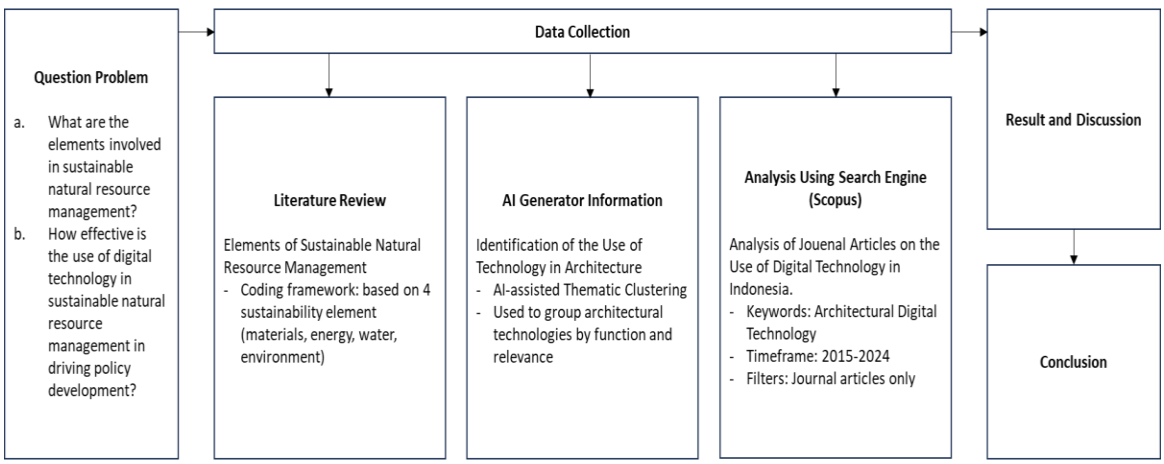

Figure 1. Research Framework

Figure 1 illustrates the mixed-methods research framework integrating qualitative and quantitative approaches. The process begins with two guiding questions on sustainability elements and the effectiveness of digital technologies in policy support. Data collection involves three streams: (1) a literature review identifying sustainability themes through thematic coding; (2) AI-assisted clustering to map architectural technology usage; and (3) a Scopus-based journal analysis using defined keywords, filters, and timeframes. Results are synthesised to highlight dominant technologies and their roles, followed by a contextual discussion linking global findings to Indonesia’s specific challenges. The conclusion reflects on methodological limitations and proposes future integration of local, non-indexed sources.

3. RESULTS AND DISCUSSION

The discussion is divided into several sections, starting with the elements considered in sustainable natural resources, digital technologies used in architecture, and the application of digital technologies to the elements of sustainable natural resources.

3.1. Elements of Sustainable Natural Resources

Advancements in digital technology have simplified human life, including in eco-friendly architecture. Concepts such as Building Information Modelling (BIM), energy simulation, sustainable materials, and the Internet of Things (IoT) used for environmental monitoring are key to achieving efficient and sustainable buildings. Each of these technologies enhances architectural performance, particularly in the context of sustainability. BIM can support collaboration; energy simulation helps analyse building performance; sustainable materials can reduce environmental impacts; and IoT enables real-time monitoring.

A holistic approach utilising digital technology in architecture can integrate functional efficiency with environmental responsibility. Therefore, this discussion will focus on how digital technology supports sustainable natural resource management through four main elements: materials, water, energy, and the environment.

3.1.1. Materials

In digital architecture, the selection of construction materials can be optimised to reduce the carbon footprint. Digital technology enables architects to track the origin and carbon footprint of eco-friendly materials through interactive applications. These applications record all building materials, including their base components, potential hazards, and lifespan. By using a smartphone camera, users can scan materials to assess their carbon footprint and automatically receive notifications when replacements are needed [8].

Other digital technologies, such as ArcGIS and QGIS, facilitate mapping the locations of materials, helping architects identify local material sources and reduce their carbon footprint through efficient distribution [9]. The use of IoT technology with real-time sensors enables monitoring of material conditions throughout a building's lifecycle, providing predictive data on material replacement needs while minimising construction waste [8]. Simulation software such as ENVI-met can analyse the thermal impact of materials on the microenvironment, offering insights into how specific materials affect thermal comfort and local air quality [10]. Meanwhile, other simulation software, such as Dialux and Ecotect, supports lighting optimisation and energy simulation to select energy-efficient materials while maintaining overall performance [11], [12]. Google Earth Engine, with its global satellite database, enables spatial analysis of the environmental impact of materials, including tracking changes in material usage over time [13], [14].

Additionally, interactive applications like VR and AR aid in interactive visualisation to evaluate the aesthetic and functional impact of materials before construction begins. At the same time, Blockchain provides transparency in material supply chains by recording carbon footprints, ensuring the sustainability of the materials used [15]. The use of BIM tools like Autodesk Revit serves as a central hub for material data management, enabling the integration of material lifecycle analysis through plugins such as Tally [8], [9]. By combining these digital technologies, architects can create designs that are more efficient, functional, and environmentally sustainable.

3.1.2. Energy

The primary goal of eco-friendly buildings is to reduce energy consumption. Digital architecture can be optimised to design buildings with better energy efficiency, minimising electricity and gas usage in a controlled manner. Digital technologies enable energy simulations using software such as Ecotect and Dialux, which analyse energy usage and building thermal efficiency [8]. These tools allow architects to model building layouts, natural lighting, and thermal insulation to achieve optimal energy savings. The use of Big Data and Artificial Intelligence (AI) plays a vital role in real-time energy monitoring. This is complemented by IoT sensors that collect data on energy consumption and operating conditions, which are then analysed using AI algorithms to identify consumption patterns and opportunities for energy-efficiency improvements. Additionally, these digital technologies support the integration of renewable energy sources, such as solar panels and wind turbines, tailored to the building's energy needs [16].

The utilisation of BIM allows direct integration of energy data into building designs. This is achieved through HVAC systems and energy simulations, which facilitate the analysis of various parameters such as air circulation, natural lighting, and potential energy savings in the overall building design [9]. Google Earth Engine also enables spatial analysis to identify optimal locations for utilising renewable energy sources, leveraging satellite data to provide insights into the potential for solar and wind energy in specific areas [17].

Other supporting technologies, such as ArcGIS and QGIS, can be used for spatial analysis of site selection for renewable energy through energy-efficiency mapping [9]. Simulation applications like ENVI-met, Ecotect, and Dialux provide simulations that help design buildings adapted to local climates and potential energy savings [10], [11], [12]. Meanwhile, interactive technologies like VR and AR enhance the efficiency of the design process through simulations and visualisations of energy performance and natural lighting. By combining these digital technologies, eco-friendly architecture not only reduces environmental impacts but also creates buildings that are more energy-efficient throughout their lifecycle.

3.1.3. Water

The development of IoT for monitoring water quality and administrative systems in small-scale clean water management enables visual monitoring of water quality through a website, which can be efficiently controlled using wireless media. pH sensors and filters are used to ensure the water is safe for consumption, while monthly utility costs are displayed based on flow-meter data. Each sensor is tested to ensure the equipment's functionality in clean water management. This approach also supports the modernisation of tools and water system management in small-scale Smart Cities, achieving efficiency and sustainability in water management [18].

The integration of ArcGIS and QGIS can also be utilised for mapping clean water distribution geographically and monitoring water quality in various locations in greater detail. This enables the creation of thematic maps that display water quality to support spatial data-driven decision-making [19]. Additionally, Google Earth can be used to visualise the locations of water management systems, enabling monitoring of distribution and the identification of areas requiring attention in water resource management [20].

In managing water systems, BIM can support planning and maintenance of water infrastructure by digitally modelling and analysing piping systems and other supporting structures. As a complement, ENVI-met simulations can assist in modelling the surrounding environment of water management systems, optimising design and maintenance while considering climate factors and environmental quality. By combining these digital technologies, clean water management can support the sustainable utilisation of natural resources through efficient distribution, accurate water-quality measurement, and continuous monitoring, thereby ensuring resource preservation.

3.1.4. Environment

By utilising digital sensors and the IoT, real-time monitoring of the surrounding environment is made possible. This aids in the efficient management of energy and resources, including monitoring air quality, water quality, atmosphere, soil, and even wildlife and their habitats. IoT can also be applied to early-warning systems for disasters such as tsunamis and earthquakes [8]. Remote sensing satellite technologies, such as drones and IoT sensors, enable continuous large-scale environmental data collection, covering air quality, water conditions, soil moisture, and land-use changes [16]. These aspects are crucial for understanding environmental dynamics and taking appropriate actions. Google Earth Engine can provide accurate spatial information to support the identification of environmental changes such as land conversion and the impacts of urbanisation [20], [21]. Additionally, ArcGIS and QGIS can assist with building design by optimising layout and orientation to renewable energy sources, thereby minimising environmental impacts [22].

In the context of carbon footprint transparency, Blockchain plays a crucial role as a tracking tool that verifies and records the production cycle of construction materials, from raw material extraction through manufacturing and distribution. This technology enables transparent, concrete records, allowing architects to consider carbon contributions at every stage while selecting materials with minimal environmental impact. For instance, in the production of eco-friendly concrete, Blockchain can be used to track the mix ratio of recycled materials and the carbon emissions from material transportation [23].

Simulation technologies like ENVI-met can assist in modelling a building's microclimatic impact before construction. Meanwhile, BIM can integrate environmental data management into design processes. By incorporating Blockchain, the generated data can be validated to ensure compliance with environmental sustainability standards. This combination supports data-driven decision-making in selecting more sustainable materials and designs [24].

Other simulation technologies, such as Dialux and Ecotect, supported by VR and AR visualisations, enable analysis of building energy performance and provide an interactive understanding of the resulting environmental impacts. Through this technological collaboration, modern architecture supports environmental sustainability by improving energy efficiency, monitoring carbon footprints, and optimising the use of natural resources. GIS-based data integration and spatial analysis contribute to the design of solutions that help preserve ecosystems while minimising the environmental impact throughout a building's lifecycle [21], [22].

3.2. Architectural Digital Technology

The use of digital technology in architecture has advanced rapidly, creating opportunities to enhance efficiency, accuracy, and sustainability. To provide a clearer understanding, Table 1 summarises the advantages and disadvantages of using digital technology in architecture, which can serve as a reference for professionals to utilise it strategically.

Table 1. Advantages and Disadvantages of Digital Technology in Architecture

Software	Advantages	Disadvantages
ArcGIS, QGIS	▪ Analyze spatial patterns to identify land use; ▪ Assist in managing resources based on local contexts.	▪ Requires accurate and up-to-date spatial data; ▪ Time required for the software learning process.
Internet of Things (IoT)	▪ Monitor and control the use of energy, water, and materials in real-time; ▪ Improve resource efficiency.	▪ High initial implementation costs; ▪ Potential security and privacy issues with data.
ENVImet	▪ Simulates environmental impacts; microclimate effects on the environment. ▪ Simulation can be used before construction/after construction.	▪ Requires high computer specifications. ▪ Limitations on the scale of simulations.
Google Earth Engine	▪ Processes global environmental data quickly. ▪ Helps analyse land changes and deforestation.	▪ Requires a good internet connection (cannot work offline).
VR/AR	▪ Visualises buildings and their impact on the environment before construction. ▪ Reduces the risk of inefficient design.	▪ High hardware cost. ▪ User limitations in VR/AR content development.
Blockchain	▪ Transparency in the supply chain of eco-friendly materials.	▪ Very high energy consumption (depends on blockchain type). ▪ Implementation complexity.
BIM	▪ Integrates data on materials, energy, water, and the environment in one model. ▪ Allows multi-dimensional simulations (4D-7D) for energy efficiency and sustainability before construction. ▪ Increases collaboration between project teams. ▪ Supports building lifecycle management for long-term sustainability.	▪ High initial implementation costs, including licensing and staff training. ▪ Requires high hardware specifications.

HVAC	▪ Optimises heating, ventilation, and cooling systems for energy efficiency. ▪ Reduces excessive energy consumption.	▪ Requires specific training for software users. ▪ Licensing costs are quite high for small organisations.
Dialux, Ecotect	▪ Evaluates lighting design and energy-efficient buildings. ▪ Supports environmental simulation and energy efficiency.	▪ Limitations in large-scale project execution. ▪ Requires technical expertise to operate simulation parameters.

Based on Table 1 above, digital technologies in architecture offer advantages and disadvantages that are crucial to supporting sustainable resource utilisation policies. Software like ArcGIS, QGIS, and Google Earth Engine helps optimise land management at both micro and macro scales, enhance energy efficiency, and minimise environmental impacts through spatial data analysis, energy simulations, and material supply chain transparency. Additionally, technologies such as IoT and Blockchain enable real-time resource management, while VR/AR, ENVImet, BIM, HVAC, Dialux, and Ecotect assist in visualising and simulating the environmental impacts of designs before construction, thereby enhancing building efficiency and effectiveness.

Although these technologies provide significant benefits, their implementation faces challenges such as high costs, the need for adequate device specifications, and training complexity. However, their strengths in promoting efficiency and sustainability make them vital tools for better environmental planning and management.

3.3. Applications of Digital Architecture Technology for Sustainable Natural Resources in Indonesia

The use of digital technology in architecture plays a crucial role in supporting sustainability principles. With these technologies, architects can conduct in-depth analyses to identify the best approaches for utilising natural resources efficiently and responsibly. The integration of digital architectural technology into sustainable natural resources can be observed in detail in Table 2 as follows:

Table 2. Applications of digital architectural technology in sustainable natural resources

Software	Materials	Energy	Water	Environment
ArcGIS, QGIS	✔ Spatial-based material usage pattern analysis	✔ Identification of regional energy potential	✔ Water source monitoring	✔ Geospatial environmental impact analysis
IoT	✔ Material usage monitoring	✔ Real-time energy consumption monitoring	✔ Continuous water quality monitoring	✔ Environmental monitoring sensor-based system
Google Earth Engine	✔ Monitoring land use changes	✔ Identification of renewable energy locations, solar or wind energy	✔ Analysis of water flow pattern changes	✔ Global environmental change analysis and carbon emissions
VR and AR	✔ Simulation of environmentally friendly material usage	✔ Simulation of building design energy efficiency	✘ Does not support water analysis	✔ Evaluation of environmental design impacts
Blockchain	✔ Sustainable material supply chain	✘ Does not support energy analysis	✘ Does not support water analysis	✔ Carbon footprint transparency in production
BIM	✔ Material analysis for sustainable design	✔ Building energy efficiency simulation	✔ Optimisation of water distribution in buildings	✔ Evaluation of building design impact on the environment
HVAC	✔ Optimisation of material use in HVAC	✔ Optimisation of HVAC systems for energy savings	✘ Does not support water analysis	✔ Building environmental efficiency for carbon footprint reduction
Dialux, Ecotect	✔ Material analysis for lighting efficiency	✔ Energy-efficient lighting design simulation	✘ Does not support water analysis	✔ Building energy performance analysis in relation to the environment

Referring to Table 2, the use of digital technology can significantly support sustainable natural resource management by addressing research elements, such as materials, energy, water, and the environment. Material management in natural resource utilisation can leverage software such as BIM and

IoT, which enable monitoring and optimisation of sustainable material use. At the same time, Blockchain ensures transparency in the supply chain of eco-friendly materials. For the energy element, digital technologies such as BIM, HVAC, Dialux, Ecotect, and ENVI-met play a major role in simulating building energy efficiency and directly reducing energy consumption. For water management, tools like IoT and BIM facilitate monitoring and management of water distribution and quality. However, some software, such as Blockchain and Dialux, is less suited to specific water analysis. In sustainable natural resource management involving environmental elements, software such as ArcGIS, Google Earth Engine, and ENVI-met provides benefits for environmental impact analysis through geospatial technology and microclimate simulation, while VR and AR assist in visualising the impact of designs on sustainability before construction. The integration of these technologies demonstrates significant potential to support sustainable architectural design and management in the future.

Journal and article search in Scopus using architectural digital technology keywords reveals the use of digital technology as research data. The analysis results are presented in Table 3 and Figure 2, which provide a comprehensive breakdown of the percentage distribution.

Table 3. Percentage of Research Journals Using Architectural Digital Technology

Software	Number of Journals	Percentage
ArcGIS	3.897	6,22%
QGIS	710	1,13%
IoT	28.758	45,88%
ENVImet	6	0,01%
Google Earth Engine	3.337	5,32%
VR-AR	185	0,30%
Blockchain	3.864	6,16%
BIM	19.200	30,63%
HVAC	1.734	2,77%
Dialux	471	0,75%
Ecotect	516	0,82%
Total	**62.678**	**100%**

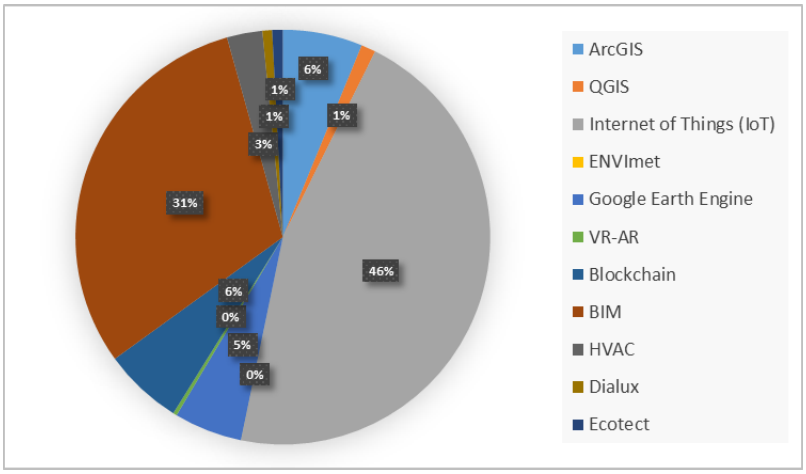

Figure 2. Percentage of Research Journals Using Digital Technology

Table 3 illustrates the application of various digital technologies in sustainable natural resource management policies based on journal identification using the Scopus search engine. The IoT emerges as the most dominant technology, with 28.758 journals (45.88%), highlighting its significant role in real-time resource monitoring and management. Following this, BIM ranks second with 19.200 journals (30.63%), emphasising its focus on sustainable infrastructure planning. Mapping technologies such as ArcGIS (3.897 journals, 6.22%) and Google Earth Engine (3.337 journals, 5.32%) underscore the importance of spatial analysis in decision-making processes. Additionally, Blockchain contributes with 3.864 journals (6.16%), supporting transparency and data tracking in resource management systems.

Other technologies, such as HVAC (2.77%), are utilised for building energy efficiency. Meanwhile, VR-AR (0.30%), Dialux (0.75%), and Ecotect (0.82%) play roles in simulation and environmentally friendly design. QGIS (1.13%) serves as an alternative for geospatial analysis, while ENVI-met shows minimal contribution, with only 6 journals (0.01%). Overall, IoT and BIM dominate research interest as key digital technologies supporting sustainable natural resource management, followed by geospatial and other digital applications.

Moving beyond tool-by-tool descriptions, this study emphasises the need for a strategic framework that aligns digital technologies with specific policy stages in Indonesia, such as planning, monitoring, and reporting. For example, IoT has been applied to strengthen real-time water quality monitoring in the Citarum River [25], and BIM supports integrated planning in urban development, such as Jakarta's Transit-Oriented Development (TOD) projects [26]. At the same time, Blockchain enhances transparency in material supply chains despite its high energy consumption [24]. At the same time, IoT raises concerns regarding data privacy and security [18].

Integrating climate change projections, such as RCP 4.5 scenarios for Indonesia, underscores the urgency of deploying these technologies not only for efficiency but also for resilience in long-term policy planning [13], [17]. By situating its findings within national practices, such as watershed rehabilitation programs and sustainable development strategies, the study clarifies its objectives of supporting adaptive and context-sensitive resource management policies [1], [2], [3]. This synthesis highlights how digital technologies can inform strategies that are both technically robust and contextually grounded, thereby reinforcing Indonesia's trajectory toward sustainable natural resource management.

4. CONCLUSION

Digital technologies are increasingly vital in supporting sustainable natural resource management policies in Indonesia. Core elements such as materials, energy, water, and environmental systems can be optimised through tools that reduce environmental impacts, enable real-time monitoring, and ensure transparency across supply chains. The Internet of Things (IoT, 45.88%) and Building Information Modelling (BIM, 30.63%) emerge as the most prominent technologies, reflecting their capacity to strengthen integrated planning, monitoring, and reporting, thereby improving resource efficiency.

However, Indonesia's diverse geography and socio-economic conditions present challenges, including infrastructure limitations, high implementation costs, and gaps in institutional capacity. Addressing these requires adaptive strategies and capacity building tailored to local contexts, as reflected in initiatives such as watershed rehabilitation and transit-oriented development. Complementary technologies—such as geospatial platforms (ArcGIS, Google Earth Engine, QGIS), Blockchain, HVAC, and VR/AR—can further enhance transparency, spatial analysis, and eco-friendly design when integrated with Indonesia's policy frameworks.

By combining global technological advances with local literature and field data, Indonesia can develop context-sensitive policies that not only improve efficiency and sustainability but also reinforce resilience in critical sectors. These insights help shape national and regional planning frameworks, strengthening the country's pathway toward sustainable natural resource management.

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Christina Esti Wardani	Currently works for the Regional Government of the Special Region of Yogyakarta. She has a strong interest in government policies related to building regulation and environmental management. Her work focuses on applying sustainable design principles and urban planning regulations to enhance the quality of public spaces and housing.