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Meta-Analysis of Green Roof Performance Parameters and Policy Readiness in Tropical Indonesia

Meta-Analisis Parameter Kinerja Atap Hijau dan Kesiapan Kebijakan di Daerah Tropis Indonesia

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ABSTRAK

Urbanisasi pesat di Indonesia memperburuk urban heat island (UHI) dan degradasi lingkungan perkotaan. Penelitian ini mengevaluasi efektivitas atap hijau sebagai instrumen kebijakan pembangunan perkotaan berkelanjutan di wilayah tropis, sekaligus menjadi acuan regulasi seperti di Singapura. Pendekatan integratif multitahap digunakan melalui systematic literature review (SLR) berbasis PRISMA 2020 (2020–2025), meta-analisis kuantitatif 20 parameter operasional, dan analisis siklus kebijakan, dengan data ditriangulasi dari Scopus, ScienceDirect, dan Google Scholar untuk memetakan korelasi kinerja teknis dan kesiapan regulasi. Hasil menunjukkan atap hijau menawarkan keunggulan ganda, meningkatkan ketahanan lingkungan dan efisiensi biaya jangka panjang dibanding sistem fotovoltaik surya. Evaluasi difokuskan pada kinerja termal (penurunan suhu ruang hingga 13,14°C; pengurangan beban pendinginan ±40%), mitigasi hidrologi (retensi air hujan 85,7%), serta fungsi sosial-spasial melalui pertanian perkotaan dan ketahanan pangan. Implementasi di Indonesia masih terfragmentasi akibat ketiadaan standar bangunan wajib dan minim insentif finansial. Transformasi pedoman teknis menjadi regulasi nasional yang mengikat, didukung pemetaan berbasis SIG, menjadi prasyarat strategis untuk transisi kota tangguh iklim dan pengambilan kebijakan perkotaan berkelanjutan.

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ABSTRACT

In Indonesia, rapid urban growth has worsened the urban heat island effect and led to more environmental degradation from urban areas. This study evaluates how green roofs are a sustainable urban development policy instrument in tropical regions while also providing a regulatory benchmark for comparison against Singaporean green roof practices. An integrative multi-phase approach was taken using a PRISMA 2020-based systematic literature review (2020-2025), quantitative meta-analysis of twenty operational parameters, and policy cycle analysis. The data sources were triangulated between Scopus, Science Direct, and Google Scholar to identify correlations between technical performance and regulatory readiness for green roofs. Findings for green roofs suggest that they provide dual benefits via improved environmental resilience and much greater long-term cost effectiveness compared to photovoltaic solar panels. The evaluation reviews three areas of impact: thermal performance (reduction of indoor temperatures up to 13.14°C and cooling loads by approximately 40%), hydrological mitigation (rainwater retention up to 85.7%), and socio-spatial benefits through urban agriculture and food security. However, implementation of green roofs in Indonesia remains fragmented due to a lack of mandatory building codes and an absence of significant financial incentives to promote widespread adoption. Transforming technical guidelines into binding national regulations, supported by GIS-based spatial mapping, constitutes a strategic prerequisite for advancing climate-resilient cities and evidence-based sustainable urban policymaking.

1. INTRODUCTION

1.1 Background

In Indonesia, the rapid pace of urbanization puts increasing pressure on a wide variety of environmental issues, such as increased energy consumption in buildings, decreased air quality, land use degradation, thermal discomfort, flood hazard, deficits of green space, and vulnerability of mental health in urban areas (Baig et al., 2020; Haya et al., 2025). Major air pollutants, including carbon monoxide (CO), carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), methane (CH_4), chlorofluorocarbons (CFCs), ozone (O_3), particulate matter (PM), lead (Pb), and biological toxins, contribute to climate change and pose health risks and can be measured by emissions inventories, measured concentrations of PM, and toxicological measures (Siburian, 2020; Taha et al., 2025; Palacio et al., 2023). While Indonesia is ranked as the 16th largest economy in the world based on GDP, it is one of the top four GHG-producing countries in the world, necessitating immediate development of nature-based mitigation strategies (Dodman et al., 2022; Atianta et al., 2025). The contradictory nature of this environmental situation has led the government of Indonesia to establish the urban greening policy and ministerial regulation to improve green open space (Kementerian ATR/BPN, 2022).

Although green architecture has been implemented as a strategy for achieving sustainability, the practice of green architecture has not been strongly institutionalized and is poorly correlated with measurable performance indicators for energy efficiency, thermal control, hydrologic control, land-use efficiency, and the social livability of urban communities (Baig et al., 2020; Bashir et al., 2023; Budhiyanto & Tampubolon, 2025). Research shows that green roofs and green open spaces are a source of environmental benefits, particularly thermal benefits that improve energy performance and reduce the need for additional energy to cool the building (kWh/m²/year), better stormwater retention, and reduced greenhouse gas emissions as demonstrated through various performance indicators such as ΔT, energy intensity (kWh/m²/year), runoff reduction (%), and CO_2 emission savings (Arbiatun & Ayuningtyas, 2025; Berardi et al., 2017; Efendi & Indriyani, 2023). However, the provision of horizontal green open spaces is being limited due to land supply constraints and urbanization/densification pressures, which create a wide gap between actual numbers and what is allowable according to statute (Noveri et al., 2020; Maudina & Kencono, 2022).

In these circumstances, green roofs can help provide a more efficient and productive vertical approach to the provision of urban green space in terms of spatial efficiency, technical performance, synergy with other forms of renewable energy, and their socio-environmental functions such as housing quality, urban agroforestry, and mental health benefits (Amelia et al., 2025; Cakar et al., 2022; Cidell, 2017). The implementation of green roofs into urban planning has been limited due to the absence of performance indicators associated with regulatory standards, such as emission reductions, sustainable transportation, public education, public access to green open space, and adoption of renewable sources of energy (Zubaydah et al., 2024).

Green roof systems can reduce indoor temperatures by 1-2 degrees Celsius and the relative humidity indoors by 17% (Ouldboukhitine et al., 2024; Tseng et al., 2022). In addition, these systems can reduce the use of energy by about 10% through improved heat retention and by providing for the control of soil pH in the substrate layer (Alam et al., 2025; Farah et al., 2024; Saleh et al., 2025).

Moreover, the green roof systems reduce the impact of urban heat island effect and provide an optimized ability to regulate water and ecosystems (Sharifi, 2021; Dodman et. al., 2022; Marando et al., 2022; Reyhani et al., 2023; Ren et al., 2023; Herath & Bai, 2024). In terms of substrate systems currently used in contemporary architecture, research has shown that substrates with a depth of 20 cm provide the maximum amount of soil organic carbon storage and the highest volume of carbon sequestered over time, aligning with bioclimatic standards for net carbon benefits in terms of building design in the United States (Halim et al., 2022; Singh et al., 2025; Fiorentin et al., 2024; Saqib et al., 2024; Alam et al., 2025). Lastly, many studies show that child-friendly parks provide ergonomic play areas, but they are still limited in both the total number of parks and the quality of existing parks, highlighting barriers that still exist in providing equitable access to urban green infrastructure (Kementerian ATR/BPN, 2022; Noveri et al., 2020; Maudina & Kencono, 2022; Saqib et al., 2024).

Green roofs serve as a highly effective urban environmental solution, with multiple advantages including CO_2 reduction, temperature regulation, improved air quality, increased rainwater management, support of local economies via agricultural production, job creation, and related industries (Berardi et al., 2017). However, the overall effectiveness of these urban green systems is primarily based on the four performance indicators of area coverage, amount of water stored, energy efficiency, and crop yield, each of which can be optimized through well-established regulations. Poland, for example, combines SEZ policies and subsidies (My Water 80% & Family Allotment Gardens 30%) to achieve optimal economic and ecological results (Cervantes-Nájera et al., 2024; Sysoiev, 2022), while in Portugal, the government links results to financial incentives and nature-based solutions through the Circular Economy Action Plan (Pineda-Martos & Calheiros, 2021; Calheiros, Castiglione, & Palha, 2022). China has implemented more than 1,083 separate policies, subsidies, and city regulations for monitoring resources, waste, and life cycles, leading to energy savings, reduction in urban heat, and improved human well-being (He et al., 2023; Dong et al., 2020; Feng & Lam, 2021).

Food security, support for community income, and assistance with adaptation to the economy are also benefits of regulated green roofs (Kementerian ATR/BPN, 2022; Unegbu et al., 2025). Climate-appropriate technological improvements will strengthen their effectiveness, as Indonesia's humid tropical climate has the highest potential for vegetation-based green designs (Budhiyanto & Tampubolon, 2025; Saleh et al., 2025). Rooftop gardens serve as a key component of a green infrastructure; they reduce urban heat and help mitigate the shortage of green open spaces (GOS) (Atianta et al., 2025; Latif et al., 2021; Saqib et al., 2024). The equatorial climate of Indonesia contains sufficient sunlight; thus, green architecture based on energy-efficient technology will be efficient (Budhiyanto & Tampubolon, 2025; Ouldboukhitine et al., 2024; Saleh et al., 2025).

Green roofs accomplish the reduction of energy consumption through enhanced insulation capabilities, lower indoor/surface temperatures, improved rainwater retention, and increased biodiversity (Berardi, La Roche, & Almodovar, 2017; Budhiyanto & Tampubolon, 2025; Baig et al., 2020). Specifics in the empirical literature demonstrate that green roofs have rainwater retention equal to 85.7% and a reduction of peak runoff equal to 93% (Arbiatun & Ayuningtyas, 2025), as well as a surface temperature reduction of approximately 7.3°C (Baig et al., 2020).

The execution of sustainable urban solutions encompasses IoT-enabled energy monitoring (Tseng et al., 2022), strategies for enhancing building coverage ratio (Efendi & Indriyani, 2023; Latif et al., 2021; Amelia et al., 2025), and GIS-based prioritization (Marando et al., 2022; Soto-Navarro et al., 2020) for the optimal placement of green infrastructure and improved thermal and environmental quality in low-cost housing (Bashir et al., 2023; Cakar et al., 2022).

1.2 Research Argumentation

Rapid urbanization has led to higher energy use, more air pollution, land degradation, and urban heat stress in cities (Atianta et al., 2025; Marando et al., 2022; Mihalakakou et al., 2023). Green architecture, energy-efficient, and resource-efficient building design are crucial for sustainable residential development and climate adaptation, assessed through key metrics such as energy efficiency, natural lighting, thermal control, renewable energy utilization, and adaptive building systems. However, implementation in Indonesia is still limited and fragmented (Atianta et al., 2025; Latif et al., 2021; Saleh et al., 2025).

One of the main advantages of green roofs is their ability to reduce indoor temperatures by up to 2 degrees, support the improvement of urban agriculture and environmental quality, and mitigate climate change while adapting urban habitats. Green roofs can lower energy demand by up to 10%, absorb CO_2, retain up to 85% of rainwater, and provide urban food security (Berardi et al., 2017; Tseng et al., 2022; Arbiatun & Ayuningtyas, 2025).

Apart from providing a number of environmental benefits, the implementation of green roofing will generate employment in supporting industries such as growing media production, organic fertilizer production, installation and maintenance of irrigation systems, and providing maintenance services (Berardi et al., 2017). Green roofs can provide significant support for developing tropical cities like Indonesia. However, due to the lack of standardized variable-based regulatory frameworks that integrate environmental, economic, and social objectives, the adoption of green roofs is currently fragmented (He et al., 2023).

To bridge this regulatory gap, this study proposes a regulatory framework for climate adaptation supported by empirical evidence that integrates building insulation performance, growing media performance, rainwater retention capacity, and sustainable energy monitoring to improve green roof policy and design (He et al., 2023; Feng & Lam, 2021).

2. METHODS

This study employs a multi-stage integrative approach combining systematic literature review (SLR), meta-analysis, and policy analysis to provide a holistic evaluation of green roof implementation in Indonesia.

2.1 Systematic Literature Review (SLR) and Parameter Identification

In order to conduct the systematic literature review (SLR) according to the PRISMA 2020 guidelines, the researchers followed transparent methods (Halaman et al., 2021). This study synthesized literature from Scopus, ScienceDirect, and Google Scholar for the years 2020-2025 and used targeted keywords such as 'green roof', 'climate-based design', and 'roof maintenance in Indonesia' to identify gaps in the literature and research trends (Atianta et al., 2025; Saqib et al., 2024).

The specific parameters and indicators that were assessed in this research study, including thermal performance, hydrological impact, and environmental policy metrics, are categorized systematically in Table 1 according to each identifier (ID). The analysis of the operational performance of green roof systems is conducted via twenty operational parameter IDs as follows: Thermal and energy performance, represented by IDs 1, 7, 8, 9, and 12 in Table 1, includes technical and empirical validation measures such as ambient temperature difference (ΔT) and cooling load reduction metrics. The identified empirical literature sources required to measure energy performance metrics include studies by Budhiyanto & Tampubolon (2025), Efendi & Indriyani (2023), Ouldboukhitine et al. (2024), and other sources provided in Table 1. Similarly, hydrological mitigation, represented by IDs 2 and 4 in Table 1, includes quantitative approaches related to the structural development of roof systems and stormwater retention analysis. References from Arbiatun & Ayuningtyas (2025) and Yan et al. (2024) also outline quantitative methodologies for developing stormwater retention standards.

Beyond technical performance, this study incorporates urban spatial planning and social standards (SDGs 3, 5, 6, 13, and 16–19) to evaluate land-use efficiency and urban habitability, positioning green roofs within housing equity and spatial governance frameworks (Amelia et al., 2025; Bashir et al., 2023). Empirical evidence from Indonesia confirms the relevance of green roofs to environmental policy, public health, and renewable energy goals (Haya et al., 2025; Atianta et al., 2025; Budhiyanto & Tampubolon, 2025; Latif et al., 2021). However, unlike countries with established regulatory frameworks such as Pakistan (Baig et al., 2020), Singapore (Arbiatun & Wulandari, 2024), North America (Alam et al., 2025), and Europe (Marando et al., 2022), which have developed and implemented regulatory schemes regarding the use of green roofs, these countries utilize standardized green roof performance indicators to assess energy performance, hydrological performance, temperature control, environmental performance, and social outcomes within international regulatory frameworks.

On the contrary, within Indonesia, there have been no uniform set of standards or guidelines related to green roofs;

therefore, regulatory requirements are fragmented based on each individual development project without being legally obligated. Thus, this regulatory void hinders the ability to compare, scale, and integrate public policies (see Table 1 as an illustrative framework for how to move toward an integrated regulatory approach by providing quantifiable performance indicators to the aforementioned countries in accordance with the plan and intent).

This research utilizes empirical evidence collected in Indonesia (Amelia et al., 2025; Atianta et al., 2025; Budhiyanto & Tampubolon, 2025; Latif et al., 2021; Haya et al., 2025) in a well-defined methodology to assess performance based on 20 technical criteria, organized into five performance categories: energy performance, hydrological performance, thermal performance, environmental performance, and social performance. Each of the identified performance criteria was compiled from the results of peer-reviewed research on green roofs in Indonesia and elsewhere. For example, regarding hydrological performance specifically, the following studies were reviewed: Pakistan (Baig et al., 2020), Singapore (Arbiatun & Wulandari, 2024; Arbiatun & Ayuningtyas, 2025), Turkey (Cakar et al., 2022), North America (Alam et al., 2025; Cidell, 2017), and Europe (Marando et al., 2022; Pineda-Martos & Calheiros, 2021).

With the 20 technical parameters providing a multifactorial and quantifiable framework to assess the performance of green roofs, the lack of technical regulations based on these parameters hinders the consistent implementation of green roofs in Indonesia. These 20 parameters presented in Table 1 will thus provide a framework for creating standardized and indicator-based guidelines for green roofs within the disciplines of environmental engineering and urban policy.

2.2 Quantitative Meta-Analysis

A meta-analysis was performed to determine if there is a statistically significant relationship between different environmental conditions and how well roofs perform. A meta-analysis allows researchers to quantify how consistent results are across studies (Berardi et al., 2017; Mihalakakou et al., 2023; Unegbu et al., 2025) and minimize the impact of individual research biases. It specifically estimates the average effect size of vegetation types and structural designs on energy efficiency. The results presented in Table 2 are a summary of the empirical and theoretical data collected across a range of locations, including Indonesia, Singapore, China, Pakistan, Nepal, and the United States, and how they may be applied strategically.

2.3 Policy Analysis Framework and Triangulation

The regulatory assessment was completed using the policy cycle framework that spans from the policy formulation to policy evaluation (He et al., 2023; Chapman et al., 2024). This phase focuses on technical regulations and coordination among stakeholders (Maudina & Kencono, 2022; Noveri et al., 2020). To ensure data credibility, the data were rigorously triangulated, referring to both the empirical results and administrative documents (Kementerian ATR/BPN, 2022). This process has a systematic flow from technical results to formal policy instruments and is shown below in the conceptual framework (see Figure 1).

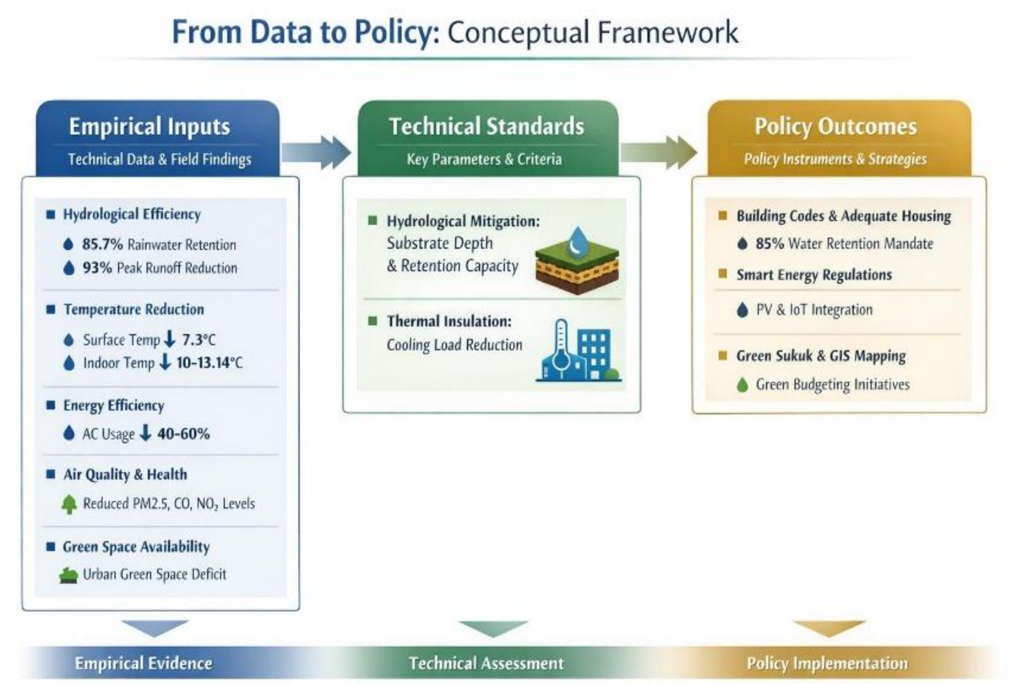

Figure 1. Conceptual Framework for Translating Empirical Evidence into Green Roof Policy Standards (Arbiatun & Ayuningtyas, 2025; Amelia et al., 2025)

2.4 Novelty, Sustainability, and Significance (Critical Review)

This study is noteworthy for urban sustainability efforts because it provides a localized framework for adaptive green infrastructure that is generally absent from international models of sustainability (Chapman et al., 2024; Saqib et al., 2024). The focus on Indonesia's tropical context makes it unique compared to prior investigations, which typically emphasize only the technical or social aspect (He et al., 2023; Yuan, 2024; Unegbu et al., 2025). It seeks to fill the gap between scientific achievement and government readiness (Atianta et al., 2025; Kementerian ATR/BPN, 2022).

3. RESULTS AND DISCUSSION

The increase in anthropogenic levels of greenhouse gas emissions, primarily due to CO_2 (76%), CH_4 (16%), and N_2O (2%), has significantly accelerated the rate of climate change, resulting in temperature increases of between 1.1 °C and 6.4 °C for ocean surface temperatures by the end of the century (Shivanna, 2022; Dodman et al., 2022). The sharp rise in temperatures over the last two decades has resulted in an almost eightfold increase in the rate of change and has had dire consequences for ecological balance and human health. Changes in climate will alter the mechanisms of microbial activity associated with biogeochemical cycles and contribute to the ongoing development of air quality problems, which, in turn, will drive the prevalence of respiratory disease and mortality (Odri et al., 2025; Manisalidis, 2020, as cited in Shivanna, 2022). Additionally, climate change may further facilitate the transmission of pandemics like COVID-19 by facilitating changes in host-pathogen relationships (Weinbauer as cited in Shivanna, 2022).

There has been extensive research on various nature-based solutions to mitigate these impacts across a range of countries, including Singapore (Arbiatun & Wulandari, 2024); China (Dong et al., 2020; He et al., 2023); Pakistan (Baig et al., 2020); Nepal (Rawal & Thapa, 2022); Portugal (Pineda-Martos & Calheiros, 2021); Poland (Sysoiev, 2022); the United States (Alam et al., 2025; Cidell, 2017); and Indonesia (Atianta et al., 2025; Budhiyanto & Tampubolon, 2025), with a detailed summary of the research available in Table 1.

Table 1. Operational Parameters and Performance Metrics for Urban Green Roof Systems

No.	Parameter	Key Indicators	Unit/ Measurement Method	Source(s)
1	Energy & thermal performance	Total building energy consumption; zonal energy efficiency	Kwh/m² per year; temperature differential (ΔT)	Baig et al. (2020); Mihalakakou et al. (2023); Saleh et al. (2025)
2	Hydrological mitigation	Stormwater retention; peak runoff reduction; lag time	Percentage (%); minutes (min)	Arbiatun & Ayuningtyas (2025); Yan et al. (2024); Marando et al. (2022)
3	Urban spatial planning	Green space ratio (GSR); building coverage efficiency	Percentage (%) of green roof area vs total roof area	Amelia et al. (2025); Chapman et al. (2024); Atianta et al. (2025)
4	Technical & structural specification	Substrate depth (growing media); roof inclination	Centimeters (cm); degrees (°)	Arbiatun & Ayuningtyas (2025); Cakar et al. (2022); Farah et al. (2024)
5	Social & habitability standards	Thermal comfort; adequate housing criteria	Sensor-based indoor temperature monitoring (°C)	Baig et al. (2020); Herath & Bai (2024); Semeraro et al. (2021)
6	Affordable & adequate housing	Share of households in adequate and affordable housing	Housing statistics (%, cost–income ratio, access to basic services)	Bashir et al. (2023); Saqib et al. (2024)
7	Indoor thermal comfort	Indoor air temperature reduction (ΔT)	Field temperature measurement (°C)	Berardi et al. (2017); Tseng et al. (2022)
8	Building thermal performance	Indoor temperature decrease	Energyplus simulation (°C)	Budhiyanto & Tampubolon (2025); Fiorentin et al. (2024)
9	Green roof growing media performance Soil temperature measurement (°C)	Growing media temperature (5 cm depth)	Soil temperature measurement (°C)	Cakar et al. (2022); Farah et al. (2024); Halim et al. (2022)
10	Renewable energy performance	PV electricity output on green roof	Inverter/energy meter monitoring (kwh)	Cidell (2017); Cervantes-Nájera et al. (2024)
11	Greenhouse gas emission reduction	CO_2 emission reduction	Energy saving to CO_2 conversion (t CO_2/year)	Alam et al. (2025); Halim et al. (2022); Fiorentin et al. (2024)
12	Building thermal insulation with green roof	Cooling load reduction / indoor temperature decrease.	Indoor–outdoor temperature measurement or AC load calculation (°C, %).	Efendi & Indriyani (2023); Saleh et al. (2025)
13	Residential agroforestry functionality Observation of ~90 yards, land area, dominant function.	Utilization of yard space for plant Production, outdoor activity	Observation of ~90 yards, land area, dominant function	Rawal & Thapa (2022); Latif et al. (2021); Pratama et al. (2023)
14	Air pollution & health	PM 2.5, CO, NO_2, O_3, respiratory, cardiovascular, mental disorders	Literature review (journals, WHO)	Odri et al. (2025); Ren et al. (2023); Shivanna (2022)

No.	Parameter	Key Indicators	Unit/ Measurement Method	Source(s)
15	Local environmental policy	Control programs, budget, coordination	Document analysis, APBD, interviews	He et al. (2023); Maudina & Kencono (2022); Dodman et al. (2022)
16	Urban green space management	Public green space area, ratio to total city area	Ha, %; spatial and functional analysis	Noveri et al. (2020); Maudina & Kencono (2022); Semeraro et al. (2021)
17	Urban green space area & quality	% of green open space and ecological functions (water absorption, clean air)	City statistics, GIS/spatial mapping, surveys	Marando et al. (2022); Yuan (2024); Soto-Navarro et al. (2020)
18	Green open space fulfillment	Gap between ideal and actual green space (ha)	Comparison of existing vs planned area	Atianta et al. (2025); Maudina & Kencono (2022); Kementerian ATR/BPN (2022)
19	Green open space coverage	% of GOS vs total area	Quantitative calculation from BPS or relevant agency	Maudina & Kencono (2022); Noveri et al. (2020); Chapman et al. (2024)
20	Mental health / urban stress levels	Stress, depression, anxiety	Surveys or secondary health data	Herath & Bai (2024); Shivanna (2022); Mori et al. (2021)

Data compiled from various sources (2017-2025). A complete list of references is available in the References.

The rise of green building developments (Mihalakakou et al. 2023; Sharifi 2021) has been viewed as a climate change mitigation strategy. Urban agriculture through urban farming (including green roofs) is cited as a viable technique for cooling (Baig et al. 2020; Budhiyanto & Tampubolon 2025), and its thermal performance and cooling load reduction have been used as urban climatic cold indicators (Efendi & Indriyani 2023; Saleh et al. 2025). Empirical results indicate that ecological social indicators and transformed residual space parameters show its effectiveness for density (Amelia et al. 2025; Kencono & Maudina 2022). This model utilizes new ways of optimizing limited spaces and restores environmental function while securing possible food production options in areas of land constraint in urban regions (Arbiatun & Wulandari 2024; see Table 2 No. 13). The systemic relationship is illustrated in Figure 2.

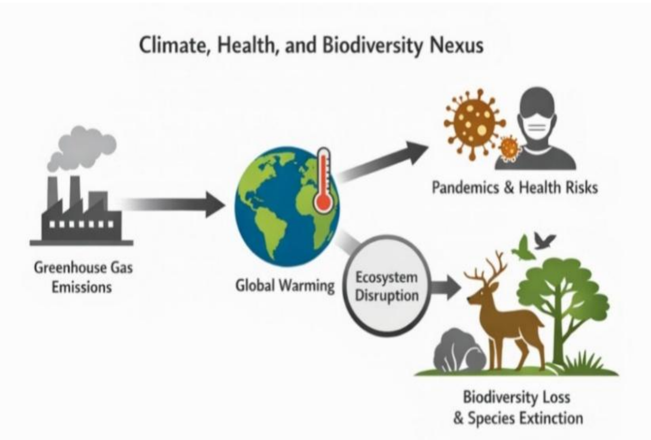

Figure 2. Pathways Linking Ecosystem Degradation to the Emergence of Pandemics (Author, 2026)

Integrated responses are necessary for the interconnected crises of global warming and loss of biodiversity (Mori et al. 2021; Soto-Navarro et al. 2020). Maudina and Kencono (2022) stress the role of green open spaces (GOS), which are crucial to providing a comfortable and healthy urban environment, as being particularly limited in Bantul Regency's city parks, as GOS only account for 13.65% of the total area (Maudina & Kencono, 2022), far less than the minimum requirement of 30%. Publicly funded GOS accounts for only 10.76% of the total area and face a deficit of 9.24% due to significant management issues (Noveri, Najib, & Yusuf, 2020).

An ecological perspective should be included when determining the provision of GOS, as well as the importance of water absorption, economic development of the site, sociocultural values, appearance, and disaster management (Arbiatun & Ayuningtyas, 2025; Chapman et al., 2024; Semeraro et al., 2021). According to Soto-Navarro et al. (2020), climate change is expected to result in a warming of at least 2 °C globally, which would reduce the fraction of remaining species (FRS) by 14% and the fraction of remaining area (FRA) by 35% (Figure 3). In summary, Figure 3 shows the direct relationship between an increase in global temperature, habitat loss, and species extinction due to an increase in global temperature of 3 °C; 17% of local species would be threatened, and 50% loss of the habitat area could occur, thereby potentially causing a global extinction event (Soto-Navarro et al., 2020; Shivanna, 2022).

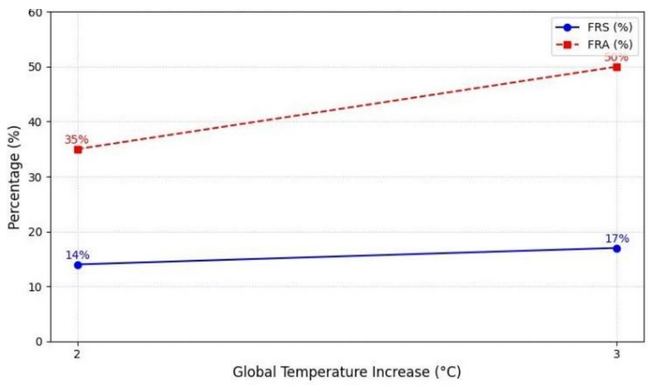

Figure 3. Projected Decline in Fraction of Remaining Species (FRS) and Remaining Area (FRA) Relative to Temperature Increase (Author, 2026; Shivanna, 2022; Mori et al., 2021; Soto-Navarro et al., 2020)

Diverse plant communities are important in terms of biomass and carbon sequestration (Mori et al., 2021; Singh et al., 2025); however, a warming of two degrees Celsius could result in a 17% decline in local species diversity and a decrease in areas that are suitable for climate change conditions of 50%

(Figure 3). Within urban settings, green roofs provide an effective way to address climate change by mitigating climate change's impacts through preserving biodiversity and adapting to climate change (Mihalakakou et al., 2023; Saqib et al., 2024). By absorbing rainfall and preventing runoff through systems that provide retention capabilities, they can also provide an effective means of reducing flooding (85.7% retention rates) by using the surface of green roofs to store water (Saleh et al., 2025; Arbiatun & Ayuningtyas, 2025).

Green roof performance is optimized through drought-tolerant vegetation and efficient drip irrigation (Pratama et al., 2023). Green architecture reduces energy use by at least 60% according to Budhiyanto & Tampubolon (2025), improves air quality (Haya et al., 2025), and provides biophilic pathways for mental well-being (see Table 2, No. 20).

Table 2. Empirical Findings and Strategic Policy Implications for Green Roof Implementation

No.	Author (Year)	Primary Parameter	Key Empirical Findings	Implications for Green Roof Policy	Technical Implications for Policy
1	Arbiatun & Ayuningtyas (2025); Dong et al. (2020); Yan et al. (2024); Marando et al. (2022)	Hydrological & thermal	Rainwater retention up to 85.7%; peak runoff reduction up to 93%.	Critical for flood mitigation and urban drainage management.	Mandate 85% rainwater retention standards in building codes for urban flood mitigation.
2	Baig et al. (2020); Bashir et al. (2023); Herath & Bai (2024); Semeraro et al. (2021)	Social-environmental	Surface temperature reduction of ±7.3°C; ambient air drops of +0.5°C.	Enhances "Adequate Housing" standards in high-density urban slums.	Standardize green roofs in high-density housing to reduce ambient temperatures and improve habitability.
3	Tseng et al. (2022); Fiorentin et al. (2024); Saleh et al. (2025)	Energy efficiency	Real-time energy monitoring via loT; identification of peak load hotspots.	Provides a basis for smart building energy management systems.	Integrate IoT-based energy monitoring in smart building regulations for real-time thermal load management.
4	Amelia et al. (2025); Atianta et al. (2025); Latif et al. (2021); Pratama et al. (2023)	Land use optimization	Increased building coverage ratio (BCR) efficiency through green roof integration.	Offers a solution for limited green open space (GOS) in metropolitan areas.	Incentivize green roofs as a legal substitute for horizontal green open space (GOS) in dense zones.
5	Marando et al. (2022); Soto-Navarro et al. (2020); Chapman et al. (2024)	Geospatial Analysis	Regional mapping of green space distribution (GIS-based).	Identifies priority zones for mandatory green roof implementation.	Use GIS mapping to enforce mandatory green roof zones in areas with critical green space deficits.
6	Bashir et al. (2023); Herath & Bai (2024); Calheiros et al. (2022)	Affordable & adequate housing	~30% urban households live in inadequate housing; green roofs improve thermal and environmental quality.	Integrate green roofs into affordable housing standards.	Incorporate green roofing into affordable housing standards to ensure environmental and thermal equity.
7	Berardi et al. (2017); Mihalakakou et al. (2023); Ouldboukhitine et al. (2024); Saleh et al. (2025)	Indoor thermal comfort	Green roof + evaporative cooling reduces indoor temperature up to 10°C.	Promote hybrid cooling green roof systems in hot climates.	Regulate hybrid cooling-vegetation systems to optimize indoor comfort in tropical urban climates.
8	Budhiyanto & Tampubolon (2025); Efendi & Indriyani (2023); Tseng et al. (2022); Ouldboukhitine et al. (2024)	Building thermal performance	Green roofs reduce indoor temperature by 13.14°C and energy use by ~60%.	Prioritize green roofs in tropical building energy codes.	Embed green roofs into energy codes as a primary passive cooling strategy to cut HVAC demand.
9	Cakar et al. (2022); Farah et al. (2024); Halim et al. (2022); Fiorentin et al. (2024)	Growing media thermal performance	Substrate with geotextile stabilizes and lowers roof temperature.	Regulate substrate layers for optimal thermal insulation.	Standardize substrate and geotextile specifications for optimal structural thermal insulation.
10	Cidell (2017); Ouldboukhitine et al. (2024); Mihalakakou et al. (2023); Sharifi (2021)	Renewable energy performance	Green roofs improve PV efficiency by lowering module temperature.	Encourage green roof PV integration.	Develop "Biosolar" policies to boost PV efficiency through rooftop vegetation-induced cooling.

No.	Author (Year)	Primary Parameter	Key Empirical Findings	Implications for Green Roof Policy	Technical Implications for Policy
11	Alam et al. (2025); Halim et al. (2022); Singh et al. (2025)	GHG emission reduction	Energy savings from green roofs reduce CO_2 emissions.	Include green roofs in low-carbon building policies.	Include green roof carbon sequestration in building-sector Net-Zero Emission (NZE) roadmaps.
12	Efendi & Indriyani (2023); Budhiyanto & Tampubolon (2025); Saleh et al. (2025)	Building thermal insulation performance	Green roof lowers indoor temperature by ±3.4°C and reduces cooling load by ±40%	Vegetation and growing media act as natural insulation, improving thermal comfort and energy efficiency.	Mandate green roofs as natural insulation to lower cooling loads in commercial building standards.
13	Rawal & Thapa (2022); Pineda-Martos & Calheiros (2021)	Functionality of yards as small-scale agroforestry	Limited land can still be utilized; production function prioritized over aesthetics	Green roofs can serve as vertical productive spaces, enhancing urban environmental quality and biodiversity.	Legalize rooftop agroforestry to support urban food security and localized biodiversity.
14	Ren et al. (2023); Herath & Bai (2024); Yuan (2024)	Air pollution & health	Exposure to PM2.5, CO, NO_2, O_3 increases risk of respiratory, cardiovascular, mental health issues	Green roofs contribute to urban air quality mitigation and complement policies for emission reduction and green infrastructure.	Link green infrastructure to public health policies for air pollution (PM2.5) mitigation.
15	He et al. (2023); Dodman et al. (2022); Atianta et al. (2025)	Local government environmental policy	Porong river pollution from industry; weak government coordination; green budgeting implemented	Green roofs can be integrated into urban planning as green infrastructure to mitigate waste, heat, and support sustainable governance.	Align "Green Budgeting" with infrastructure planning to fund heat and pollution-mitigating roofs.
16	Noveri et al. (2020); Maudina & Kencono (2022); Latif et al. (2021); Pratama et al. (2023)	Urban green open space management (Jambi)	Population growth increased pressure on GOS; availability ±10.76% vs 30% target; coordination and participation challenges	Green roofs act as vertical GOS, supporting ecological and social urban functions and requiring multi-level collaboration.	Adopt multi-level governance to leverage vertical greening toward national 30% GOS targets.
17	Marando et al. (2022); Herath & Bai (2024); Semeraro et al. (2021)	Urban green space area & Quality	Jambi city public green space = 779.02 ha (21.53%), below ideal; reduced ecological and social functions	Green roofs increase vertical green space, enhance stormwater absorption, reduce flooding, and improve urban air quality.	Prioritize vertical greening in urban resilience plans to enhance stormwater absorption.
18	Soto-Navarro et al. (2020); Calheiros et al. (2022); Pratama et al. (2023)	Green open space fulfillment	Deficit in Jambi city = 784.27 ha; current GOS far below 30% target	Green roofs supplement vertical green space, reducing the gap between ideal and existing GOS, supporting ecological, aesthetic, and social functions.	Redefine GOS regulations to credit vertical greening against ecological land-use quotas.
19	Maudina & Kencono (2022); Noveri et al. (2020); Latif et al. (2021); Chapman et al. (2024)	Green open space coverage	Bantul regency GOS = 13.65%, below 20% ideal to deficit 6.35%	Green roofs can increase urban vertical green space, improve ecological functions, and provide public access in dense areas.	Mandate public-access green roofs on government buildings to address communal space deficits.
20	Herath & Bai (2024); Semeraro et al. (2021); Mori et al. (2021)	Urban population mental health / stress levels	Access to GOS reduces stress, depression, anxiety in urban residents	Green roofs provide vertical "therapeutic green space," supporting mental health where horizontal GOS is limited.	Integrate therapeutic rooftop spaces into urban planning for population mental health resilience.

Data compiled from various sources (2017-2025). A complete list of references is available in the References.

In addition to their ecological functions, it has been well documented over numerous studies that green roofs serve as efficient hydrological devices that can retain up to 85.7% of precipitation (Arbiatun & Wulandari, 2024; see Table 2, ID 1). The efficiency of rainwater retention, compared to international benchmarks (50-90%, depending on climatic zone), demonstrates a significant level of efficiency in tropical climates (Figure 4). Core studies show that green roof installations reduce the indoor surface temperature of buildings between 3 and 13.14 °C, and reduce building cooling loads by 40–60% (Berardi et al., 2017; Budhiyanto & Tampubolon, 2025; Efendi & Indriyani, 2023; see Table 2, IDs 7, 8, 12), whilst contributing to urban resilience through improved PV efficiency, decreased CO_2 emissions, and the provision of therapeutic vertical spaces to mitigate urban stress (Cidell, 2017; see Table 2, IDs 10, 11, 20).

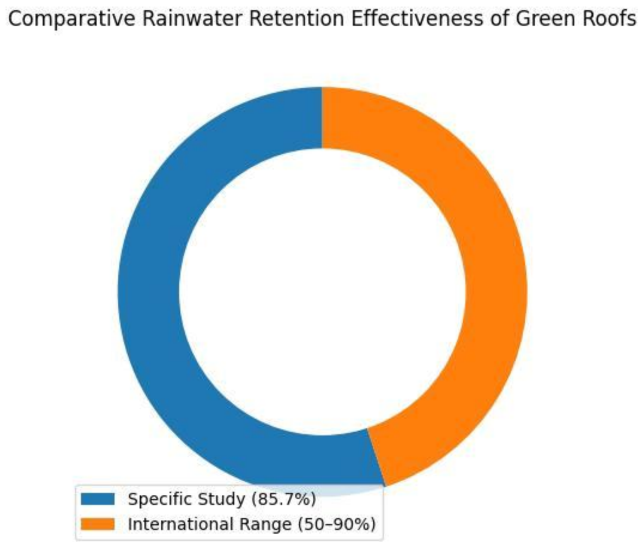

Figure 4. Comparison of Rainwater Retention Performance: Local Empirical Study (85.7%) vs. International Benchmarks (50–90%) (based on Arbiatun & Ayuningtyas, 2025; Dong et al., 2020; Yan et al., 2024; Farah et al., 2024)

Building codes, energy rules, and urban green space policies in Indonesia need to include technical, ecological, and socio-economic factors so that they are properly implemented with positive outcomes, which can be measured (Kementerian ATR/BPN, 2022). The previously discussed outcomes, along with the significant gains from integrating highly efficient hydrology and renewable energy (for example, up to 85.7% (Arbiatun & Wulandari, 2024) retention of rainwater and increased efficiency of PV panels (Cidell, 2017)), support the use of biosolar and sponge city standards. As seen in Figure 5, all of these studies show the same reduction in temperature (Baig et al., 2020; Berardi et al., 2017; Budhiyanto & Tampubolon, 2025; Efendi & Indriyani, 2023).

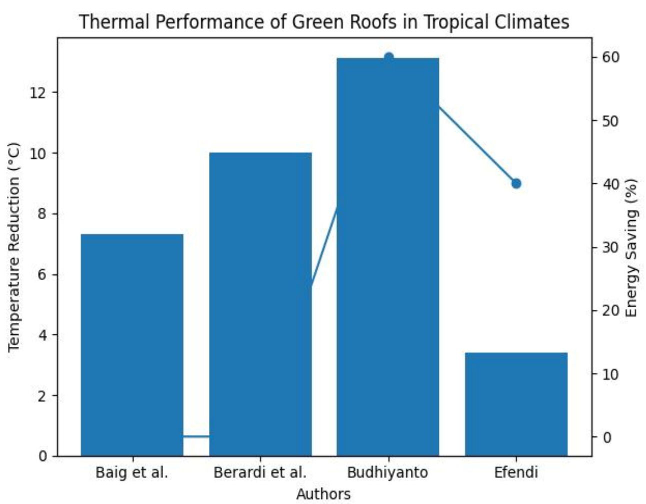

Figure 5. Thermal performance and energy savings of tropical green roofs (based on data from Baig et al., 2020; Berardi et al., 2017; Budhiyanto, 2025; Efendi, 2023)

In addition, there is a clear relationship demonstrated by the meta-analysis regarding the contribution of green roofs to urban spatial and social resilience. Research in multiple regions of Indonesia, demonstrates a very negative lack of horizontal green open space (H-GOS), including in areas such as Bantul (Maudina & Kencono, 2022) and Jambi (Noveri et al., 2020), therefore it would be possible to recommend that Vertical Greening could be considered as a legal substitute to achieve the national requirement of 30% coverage. The optimisation of these areas also leads to direct improvements in public health and mental resilience by reducing the effects of air pollution (Ren et al., 2023) and urban stress (Herath & Bai, 2024). Finally, the application of empirical findings to developing regulatory frameworks requires the geographic information system (GIS)-based mapping and green budgeting to create the necessary governance framework for continued sustainability (Chapman et al., 2024; Kementerian ATR/BPN, 2022).

A thorough analysis of these empirical findings and their associated policy implications can be found in Table 2, indexed by ID. To implement residential-scale green roofs in Indonesia, adaptation is needed for both the tropical climate and high population density (Atianta, Mumtaz & Geminastiti, 2025; Latif et al., 2021). Energy efficiency and urban ecosystem services have increased through optimization of passive design strategies and selection of appropriate plant species (Baig et al., 2020; Budhiyanto & Tampubolon, 2025; Efendi & Indriyani, 2023). However, accelerating this technology will require intervention by policymakers. Green incentives are being implemented worldwide (Cervantes-Nájera et al., 2024; Mihalakakou et al., 2023), and the Minister of Public Works and Public Housing Regulation 21/2021 is one example of a regulation that supports their use (Kementerian ATR/BPN, 2022), but these have had little success in low-income housing (Bashir et al., 2023). Thus, in order to shift developers' thoughts towards sustainable building, it is important to enhance public education along with concrete regulatory tools (Chapman et al., 2024; Saqib et al., 2024).

The mandate for 30% open green space – 20% public and 10% private – is one of several targets for cities under Spatial Planning Law No. 26/2007 (Noveri et al., 2020; Maudina & Kencono, 2022). The synergy between policies and individual actions is also critical in creating sustainable green initiatives (Cidell, 2017). Green open space regulation must be integrated with financial incentives to fill planning gaps such as individual actions in Jambi City and Jakarta (Noveri & al., 2020; Haya & al., 2025) because the combination is necessary to translate the ecological benefits of energy efficiency and thermal comfort created by green space into competitive economic value for properties (Efendi & Indriyani, 2023).

Even though the Directorate General of Human Settlements, Ministry of Public Works and Public Housing, has established design classifications for open green space use (limited, semi-limited, and unlimited) and basic components for construction of such spaces (Kementerian ATR/BPN, 2022; Saqib et al., 2024), it is still not widely accepted. To facilitate widespread acceptance of this technology, it will be necessary to establish rigorous national regulations that convert PUPR technical guidelines into national building codes and standards for all buildings to achieve the systematic integrity and function of the buildings.

The sponge city concept is a treatment for urban flooding and for solving urban heat island effects through integrating green-blue infrastructure into the city (Arbiatun & Wulandari, 2024) (Saqib et al., 2024). Adopting green roofs in Indonesia has not been uniform, and the implementation of these structures has been blocked by financial and technical constraints (Latif et al., 2021; Maudina & Kencono, 2022). With greater household energy consumption (Bashir et al., 2023), green affordable housing (GAH) could be a 15.7 trillion USD investment opportunity worldwide.

The body of research into extensive and intensive green roofs has shown how they enhance building performance (up to 78% greater), as well as how they contribute to the development of 10.3% additional green open space (Amelia et al., 2025; Budhiyanto & Tampubolon, 2025). However, in Indonesia, the adoption of extensive green roofs has been inconsistent and primarily limited to individual residential constructions (Latif et al., 2021).

In the case of high-density urban areas, there are many efforts to mitigate the heat island effect of urban areas (due to loss of vegetation, vehicular emissions, and limited areas of green space) using interventions such as the use of green roofs/walls, high-albedo materials, and sustainable urban design (Atianta et al., 2025; Noveri et al., 2020). While there are not many examples of this intervention, it is prudent to note that green roofs provide a cooling effect by offering shading, evapotranspiration, air movement, and energy efficiency, while also incorporating green, blue, and grey infrastructure with considerations for urban density, land use, and energy use (ATR/BPN, 2022; Atianta et al., 2025; Berardi et al., 2017).

Rainwater management is supported by green roofs, as are decentralized waste systems and a growing focus on vertical green space policies (Kementerian ATR/BPN, 2022; Yan et al., 2024). Integrated regulations and green financing instruments such as green sukuks and green bonds are essential for government intervention (Bashir et al., 2023; Cidell, 2017). Urban green space (GOS) has been poorly implemented despite Law No. 26/2007 giving authority for spatial management. For example, there is a large deficit of GOS in the city of Jambi. The GOS area currently falls well short of the 30% national target (Noveri et al., 2020). Certain regulations are encouraging private green building adoption, but technical and coordination challenges hindered this (Maudina & Kencono, 2022). Multifunctional roof gardens are an effective strategy for improving biodiversity and significantly reducing building energy consumption; research shows that indoor temperatures can be reduced by as much as 13.14 °C (Budhiyanto & Tampubolon, 2025; Semeraro et al., 2021; Sabila et al., 2025).

Rainwater management also has up to 85.7% retention efficiency and combines lightweight materials with photovoltaics (Arbiatun & Wulandari, 2024; Cakar et al., 2022; Cidell, 2017). Sufficient adaptive management for carbon sink efficiency is essential to ensure proper depth of substrate layers and to account for plant growth dynamics (Alam et al., 2025; Pratama et al., 2023).

The implementation of environmental policies at a regional level is often constrained by limited resources, as well as by inconsistent regulatory frameworks between local and central governments (Noveri et al., 2020; Maudina & Kencono, 2022). However, in the context of urban areas, ATR/BPN Ministerial Regulation No. 14/2022 provides the primary legal framework for classifying roof gardens as green open spaces (Kementerian ATR/BPN, 2022), allowing their development in accordance with eco-design principles and expert-driven criteria to support climate resilience and long-term functionality (Rawal & Thapa, 2022; Sabila et al., 2025).

Strong policy implementation should be the major driver for achieving long-term compliance with environmental regulations (Haya et al., 2025; Ministry of ATR/BPN, 2022). The utilization of green roofs is a practical way for Indonesia to maximize the use of restricted urban land and address the urban heat island effect and flooding (Atianta et al., 2025; Yuan, 2024). Analysis of the available local empirical data indicates that the rainwater retention efficiency for local areas is 85.7% (Figure 4), which exceeds international benchmarks and could lead to a reduction in indoor temperature of up to 13°C and a significant decrease in cooling energy loads (Arbiatun & Wulandari, 2024; Budhiyanto & Tampubolon, 2025; Figure 5).

The solution to Indonesia's country-wide shortfall of public green spaces (Maudina & Kencono, 2022; Noveri et al., 2020) requires transitioning away from simply encouraging the use of green spaces by regulating their creation and incorporating financial incentives and IoT technology as part of the process (see Tables 1 & 2; Tseng et al., 2022). Two primary components of this transition include standardization of substrate materials and selection of tropical vegetation to ensure integrity and performance of the structures being established (Cakar et al., 2022). Beyond providing physical benefits, this green infrastructure has the ability to contribute towards a circular economy through carbon sequestration while also providing space for therapeutic uses to improve public mental health (Cervantes-Nájera et al., 2024; Singh et al., 2025; see Figure 1).

Failure to invest in the creation of green infrastructure increases the likelihood of continued degradation of ecosystems, which ultimately leads to the extinction of numerous species and presents considerable risk for global pandemics (see Figures 2 & 3; Shivanna, 2022; Soto-Navarro et al., 2020). Green roofs will be transformed from an afterthought into a crucial component of resilient, sustainable, and inclusive urbanism in Indonesia when building codes become synergized with adaptive standards of policy with respect to multiple functions, including agroforestry and biosolar systems (Cidell, 2017; Yan et al., 2024; Calheiros et al., 2022; Mihalakakou et al., 2023; Pratama et al., 2023).

4. CONCLUSION

The importance of green architecture as an urgent and strategic response to protecting the environment in Indonesia, which suffers from the impacts of rapid urbanization and the urban heat island (UHI) effect, is underscored by the significant increase in greenhouse gas emissions associated with the UHI. This study utilized an integrative approach, which included a systematic literature review (SLR) employing PRISMA 2020 standards, a quantitative meta-analysis of 20 operational parameters, and policy cycle analysis, all of which enabled the study to bridge the gap between the technical performance of green infrastructure (GI) and the readiness of the regulatory environment for tropics in helping to achieve GI implementation.

The key findings reveal that green roofs are a viable physical alternative to traditional rainwater management systems and provide highly effective thermal management benefits. In particular, based on the empirical data compiled in this research (Tables 1 and 2), green roof systems yield up to 85.7% rainwater retention rates and provide the potential to decrease indoor ambient temperatures by up to 13.14°C, thus significantly reducing HVAC cooling loads and total energy use in buildings. In addition to their biophysical benefits, green roofs that incorporate urban agriculture into their design have demonstrated the potential to enhance local food security and create new economic opportunities for communities through the development of industries that support the production of growing media and irrigation.

While green roofs have demonstrated significantly higher ecological performance and efficiency levels than photovoltaic solar systems in humid tropical climates, implementation of green roofs across Indonesia remains fragmented, resulting in the inability to achieve large-scale adoption due to a lack of mandatory building requirements combined with weak financial incentives. The findings of this research indicate that converting technical guidelines into regulatory standards at a national level, supported by spatially enabled geographic information system (GIS) mapping and a green financing mechanism, is essential for achieving the institutionalization of green infrastructure. Additionally, these findings offer a strategic basis for policymakers to use green roofs as a legally recognised alternative to horizontal green open space (GOS) in order to achieve sustainability goals within Indonesia's metropolitan areas.

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