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Research Paper

Biophilic Design and IoT Relationships with Micro-Environmental Quality and Elderly Well-Being in Jakarta Urban Farming

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Abstract

Urban farming can improve environmental quality while supporting the activities and well-being of older adults in densely populated residential areas. However, empirical evidence on the relationships among biophilic design, Internet of Things (IoT) technology, micro-environmental quality, and elderly well-being remains limited. This study empirically examines these relationships in urban farming within Jakarta's kampung settlements. A quantitative approach was employed with 75 older adult respondents. The initial instrument comprised 16 statements covering vegetation and natural comfort, technology for environmental monitoring and irrigation, micro-environmental conditions, and physical, psychological, social, and overall well-being. Following an initial measurement evaluation, indicators that did not meet the specified criteria were removed, and the model was re-estimated, resulting in nine indicators in the final model. The findings show that biophilic design has a positive but non-significant relationship with micro-environmental quality ($\beta = 0.219$; $p = 0.084$). IoT technology has a significant but negative relationship with micro-environmental quality ($\beta = -0.269$; $p = 0.023$). Meanwhile, micro-environmental quality has a positive but non-significant relationship with elderly well-being ($\beta = 0.170$; $p = 0.236$). These findings indicate that applying biophilic design and technology does not automatically improve micro-environmental quality or elderly well-being. The study provides empirical evidence that elderly-friendly urban farming requires consideration of design suitability, technology, user experience, and older adults' social and psychological needs.

Keywords: *Urban Farming, Biophilic Design, Internet of Things, Micro-Environmental Quality, Elderly Well-Being, Jakarta Kampung Settlements*

INTRODUCTION

Rapid urban growth creates challenges related to environmental sustainability, spatial quality, food security, and quality of life. Cities can no longer be viewed merely as collections of buildings and infrastructure, but as complex systems in which physical, environmental, social, technological, and economic components interact. From a complexity perspective, sustainable urban development emerges through interactions among multiple subsystems and therefore cannot be addressed through a single approach (Abujder Ochoa et al., 2025).

In this context, urban farming has emerged as an approach that can support food security, utilize limited urban space, and contribute to environmental sustainability. In informal settlements, urban agriculture is also linked to local food systems and resource use, although its implementation is shaped by the area's physical, environmental, and social characteristics (Acevedo De los Ríos & Perrotti, 2024). Research on Jakarta also indicates that urban agriculture can contribute to food supply, productive use of open space, livelihoods, and urban environmental quality, although its sustainability still requires further improvement (Kanosvamhira & Shade, 2025).

These issues are particularly relevant to kampung settlements in Jakarta, which are characterized by high building density, limited open space, and the need to optimize available areas for various community activities. Under such conditions, urban farming can function not only as a space for food production but also as a setting for social and environmental activities. Its success,

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however, depends not only on the presence of plants or technology but also on environmental quality and its ability to respond to users' needs, including those of older adults. Research on green infrastructure and aging populations highlights the importance of accessible and supportive urban environments for physical activity, social interaction, stress reduction, health, and well-being in later life.

One approach for improving environmental quality is Biophilic Design. The concept of Biophilic Cities emphasizes human–nature relationships by integrating vegetation, green spaces, biodiversity, and other natural elements into urban environments (Beatley, 2011). In Indonesia, biophilic principles have been applied to various building and settlement types, including creative-house facilities (Aditya et al., 2022), mental health centers (Puren & Ginting, 2022), settlements and Islamic boarding schools in dense areas (Paramesti, 2021), and vertical housing in East Jakarta (Immanuel et al., 2023). Similar approaches have also been applied to residential and community facilities (Nazihah et al., 2024; Miao et al., 2026; Aziz & Subekti, 2025).

Karera (2021) illustrates the relationship between biophilic design and urban farming by integrating urban living and farming with biophilic design in Begalon public housing in Surakarta. Shafwah and Puspitasari (2025) also examined biophilic architecture in Kampung Bandan, North Jakarta, emphasizing improved quality of life. These studies show that natural elements, green spaces, and biophilic principles can be applied in space-constrained environments.

However, much previous research focuses on architectural design and conceptual development, while empirical testing of the relationship between perceived biophilic design and micro-environmental quality remains limited, particularly among older adults. Elderly users may experience their environment differently depending on comfort, safety, accessibility, ease of activity, and the space's capacity to support everyday needs. Therefore, research is needed not only to examine how biophilic environments are designed but also how elderly users perceive their qualities.

Beyond design approaches, digital technologies offer opportunities to improve urban environmental management. The Internet of Things (IoT) enables environmental monitoring, data collection, device control, and automation. Smart-city technologies can support resource management and urban sustainability (Narain, 2024). Recent research on smart urban agriculture further demonstrates the potential of digital technologies to manage scarce urban resources while emphasizing the importance of organizational and contextual readiness (Christmann et al., 2025). Digital development is also expanding through artificial intelligence and urban digital twins, which enable urban data, scenarios, designs, and three-dimensional models to be managed in increasingly integrated ways (Xu et al., 2024).

Nevertheless, technological implementation does not automatically produce positive outcomes. Systematic research published in Cities shows that smart-city technologies can generate both co-benefits and trade-offs for sustainable development goals (Sharifi et al., 2024). The benefits of technology therefore depend on implementation conditions, governance, and user characteristics. This issue is particularly relevant when elderly people are the primary users. Technologies such as automated irrigation or environmental monitoring may provide technical benefits, but they may not improve users' environmental experience if they are difficult to operate or poorly matched to users' abilities.

Recent research also suggests that biophilic and smart approaches should not necessarily be treated as separate strategies. (Tarek & Ouf, 2021) argue that nature-based and digital approaches can intersect in supporting urban resilience, including through urban ecological networks and urban farming. This perspective provides a basis for examining design and technology together rather than treating them as independent solutions.

Thus, two research tendencies remain relatively separated. Architectural studies commonly

position biophilic design as a spatial and environmental strategy, whereas smart-city studies position IoT as an instrument for monitoring, automation, and efficiency. Although these approaches can complement one another, empirical evidence integrating Biophilic Design, IoT, Micro-Environmental Quality, and Elderly Well-Being remains limited, particularly in urban farming within Jakarta's kampung settlements.

In this study, Micro-Environmental Quality (MEQ) refers to the environmental conditions users directly experience in urban-farming spaces, including lighting, comfort, safety, and other immediate environmental qualities. MEQ is conceptually positioned between design and technological characteristics and users' well-being experiences. However, this conceptual position does not imply statistical mediation, as this study does not test mediation. The research examines only three direct relationships: BD → MEQ, IoT → MEQ, and MEQ → EW.

This study's novelty does not lie in the separate application of biophilic design or IoT, as both approaches have been widely discussed. Rather, its novelty lies in integrating and empirically testing the relationships among Biophilic Design (BD), Internet of Things (IoT), Micro-Environmental Quality (MEQ), and Elderly Well-Being (EW) in the specific context of urban farming in Jakarta's kampung settlements. The study brings together architectural and environmental perspectives, urban technology, and elderly users' experiences.

This approach is consistent with the complexity perspective, which views environmental, technological, human, and activity-related components as interacting elements of urban systems (Abujder Ochoa et al., 2025). The three variables, namely biophilic design, the Internet of Things (IoT), and microenvironmental quality, are important to examine because they are conceptually related to the development of urban farming environments that support older adults' well-being.

Examining these variables is necessary to obtain empirical evidence on each variable's contribution and whether its effect is statistically significant. Thus, the findings not only identify relationships supported by the empirical data but also highlight factors that show no statistically significant effects in this study.

Accordingly, this study empirically examines the relationships among Biophilic Design (BD), Internet of Things (IoT), Micro-Environmental Quality (MEQ), and Elderly Well-Being (EW) in urban farming within Jakarta's kampung settlements. Specifically, it examines three hypothesized relationships: (1) the positive relationship between BD and MEQ; (2) the positive relationship between IoT and MEQ; and (3) the positive relationship between MEQ and EW. The relationships are examined quantitatively using Partial Least Squares–Structural Equation Modeling (PLS-SEM) to provide empirical evidence regarding the connections among design, technology, micro-environmental quality, and elderly well-being.

LITERATURE REVIEW

Urban Farming, Dense Settlements, and Environmental Sustainability

Urban farming is an approach that can respond to limited space, food needs, and sustainability challenges in urban areas. In informal and densely populated settlements, urban farming is not limited to food production but also involves space utilization, environmental quality, and community activities. Acevedo De los Ríos & Perrotti (2024) show that urban agriculture in informal settlements should be understood as part of an urban system connecting food, resources, and environmental characteristics.

This perspective is relevant to urban kampungs, which are characterized by limited land and complex environmental conditions. Abujder Ochoa et al. (2025), through a review of complexity theory and sustainable urban development, cities are described as systems comprising interacting environmental, technological, human, and social components. Urban farming can therefore be viewed as a space where people, nature, the micro-environment, and technology interact.

Spatial quality is also important for elderly users. Sattayakorn et al. (2023), a study of spatial quality and residential satisfaction among low-income older residents highlights the importance of spatial and environmental characteristics for older people. This supports the need to consider elderly users' experiences when examining urban environments.

Biophilic Design and Environmental Quality

Biophilic design is based on the relationship between humans and nature and on integrating natural experiences into the built environment. Beatley (2011), through the concept of Biophilic Cities, it emphasizes the integration of nature into urban life through vegetation, biodiversity, green spaces, and ecological elements.

Biophilic principles have been applied in various contexts. Puren and Ginting (2022) applied them to a mental health center, emphasizing mental health and spatial quality, while Aditya et al. (2022) applied the approach to a creative house facility in Canggu. In dense areas, Paramesti (2021) examined biophilic design in Islamic boarding schools in North Jakarta, while Miao et al. (2026) developed a biophilic settlement concept based on Islamic architecture.

The relationship between biophilic design and urban farming is reflected in Karera (2021), who developed a Living and Farming concept in Surakarta. Biophilic approaches have also been applied to vertical housing. Immanuel et al. (2023) developed a biophilic vertical housing concept in East Jakarta, while Nazihah et al. (2024) examined biophilic architecture in a public housing context in Malang. Shafwah and Puspitasari (2025) linked biophilic architecture with quality of life in Kampung Bandan, North Jakarta. Aziz and Subekti (2025) also positioned biophilic architecture as an approach to strengthening human–nature connections in a youth activity center.

However, most of these studies focus on design application or conceptual development. Empirical research examining the relationship between perceived Biophilic Design (BD) and Micro-Environmental Quality (MEQ) from the perspective of elderly users in urban farming remains limited. This study addresses this gap by testing the BD → MEQ relationship.

Internet of Things, Smart Cities, and Sustainability.

Digital technologies provide opportunities to improve urban environmental management. Narain (2024) explains that smart city technologies, including the Internet of Things (IoT), can support monitoring, automation, information management, resource efficiency, and data-based decision-making. In urban farming, IoT can monitor environmental conditions and support plant management.

These technologies are increasingly integrated into urban systems. Xu et al. (2024) discuss the use of generative artificial intelligence for urban digital twins, including data development, scenario generation, design, and three-dimensional modeling in smart cities. (Xiao, 2023) also highlights the growing use of artificial intelligence in green buildings, demonstrating the increasingly close relationship between digital technologies and building and environmental management.

However, technology does not automatically generate positive outcomes. Sharifi et al. (2024), through a systematic review in Cities, identify both co-benefits and trade-offs between smart-city technologies and sustainable development goals. These findings indicate that technological benefits depend on implementation conditions, user characteristics, and context.

This issue is particularly relevant when elderly people are the users. Ziosi et al. (2024) emphasize the need to balance humanity, technology, and sustainability in smart-city development. Therefore, this study does not assume that IoT automatically improves environmental quality. Instead, it empirically tests the IoT → MEQ relationship from the perspective of elderly users.

Micro-Environmental Quality

Micro-Environmental Quality refers to environmental conditions at the spatial scale users directly experience during urban-farming activities. It includes thermal conditions, air quality, lighting, safety, and comfort.

Studies on green buildings emphasize the importance of environmental quality in creating comfortable spaces. Yee et al. (2020) identifies various barriers to green-building implementation, indicating that sustainability depends not only on design concepts but also on implementation conditions. Yuliani et al. (2020) highlights the role of communities in green roofs as part of green-space provision and sustainable development.

Environmental comfort is also related to ergonomics. Kusuma (2023) developed a green ergonomic building assessment model emphasizing comfort and environmental quality. Chatzis et al. (2022) examined technology-based ergonomic risk assessment, while Rahmat et al. (2023) linked green-ergonomic awareness with user performance. These studies indicate that environmental quality should be considered together with comfort, activity, and user capability.

For elderly users, environmental quality is not determined solely by physical conditions. Sattayakorn et al. (2023) demonstrates the importance of spatial quality and residential satisfaction among older people in low-income housing. Accordingly, the relationship between MEQ and Elderly Well-Being (EW) needs empirical examination in the specific context of urban farming.

Elderly Well-Being

Elderly well-being is multidimensional, involving physical, psychological, and social conditions as well as comfort, safety, and perceived quality of life. Supportive environments can give older people opportunities to remain physically active, comfortable, and socially connected.

Beatley (2011) place human–nature relationships among the important elements of healthy and livable cities. Puren and Ginting (2022) demonstrate the relevance of biophilic environments to mental-health contexts, while Shafwah and Puspitasari (2025) connect biophilic approaches with quality of life in dense residential areas.

Nevertheless, elderly well-being cannot be assumed to be determined only by physical environmental quality. Social factors, activities, individual conditions, safety, and accessibility may also contribute. Therefore, this study positions EW as a construct that may be associated with micro-environmental quality rather than as an automatic outcome of biophilic design or technological implementation.

Literature Synthesis and Research Gap

The literature indicates three research areas that have largely developed separately. First, biophilic-design research focuses on buildings, housing, settlements, community facilities, and human–nature relationships (Beatley, 2011; Karera, 2021; Puren & Ginting, 2022; Immanuel et al., 2023; Shafwah & Puspitasari, 2025). Second, smart-city and IoT research emphasize technology, monitoring, automation, and sustainability (Narain, 2024; Sharifi et al., 2024; Xu et al., 2024). Third, urban-farming research emphasizes food, resources, and sustainability in urban and informal-settlement contexts (Acevedo De los Ríos & Perrotti, 2024).

Research on green buildings, ergonomics, green roofs, spatial quality, and elderly users further broadens this perspective. Green-building literacy (Cole, 2019) barriers to green-building implementation (Yee et al., 2020); green roofs (Yuliani et al., 2020); ergonomics (Chatzis et al., 2022; Kusuma, 2023); and spatial quality among elderly residents (Sattayakorn et al., 2023) demonstrate that sustainability requires consideration of the relationships among environment, technology, activities, and users.

Nevertheless, empirical studies integrating Biophilic Design, IoT, Micro-Environmental

Quality, and Elderly Well-Being within a single model of urban farming in Jakarta's kampung settlements remain limited. Moreover, smart-city research indicates that technological benefits are not necessarily linear and may involve trade-offs. This gap provides the basis for testing three direct relationships: BD → MEQ, IoT → MEQ, and MEQ → EW.

Hypothesis Development

H1: Biophilic Design → Micro-Environmental Quality

Integrating natural elements through biophilic design may support environmental quality and user experience (Beatley, 2011). Research on Living and Farming, vertical housing, and dense settlements indicates that biophilic principles can be applied in space-constrained environments (Karera, 2021; Immanuel et al., 2023; Shafwah & Puspitasari, 2025). Therefore, H1: Biophilic Design (BD) is positively related to Micro-Environmental Quality (MEQ).

H2: Internet of Things → Micro-Environmental Quality

IoT can support environmental monitoring, automation, and management (Narain, 2024). However, technological benefits depend on implementation, user characteristics, and environmental context. Sharifi et al., (2024) show that smart-city technologies can generate both co-benefits and trade-offs, while Ziosi et al., (2024) emphasize the need to balance human needs, technology, and sustainability. Therefore, H2: Internet of Things (IoT) is positively related to Micro-Environmental Quality (MEQ).

H3: Micro-Environmental Quality → Elderly Well-Being

Environmental quality and human–nature relationships may support comfort, mental health, and quality of life (Beatley, 2011; Puren & Ginting, 2022; Shafwah & Puspitasari, 2025). However, because elderly well-being is multidimensional, this relationship requires empirical testing. Therefore, H3: Micro-Environmental Quality (MEQ) is positively related to Elderly Well-Being (EW).

Theoretical Position and Research Model

This study integrates three domains that are commonly examined separately—biophilic design, urban technology, and urban farming—through the perspective of elderly users. This approach is consistent with the view of the city as a complex system in which environmental, technological, human, and activity-related components interact.

The research model consists of four constructs: BD, IoT, MEQ, and EW (Figure 1). BD and IoT are positioned as independent constructs, MEQ represents environmental quality, and EW is the dependent construct. MEQ is not tested as a mediator. The model examines only three direct relationships: BD → MEQ (H1), IoT → MEQ (H2), and MEQ → EW (H3).

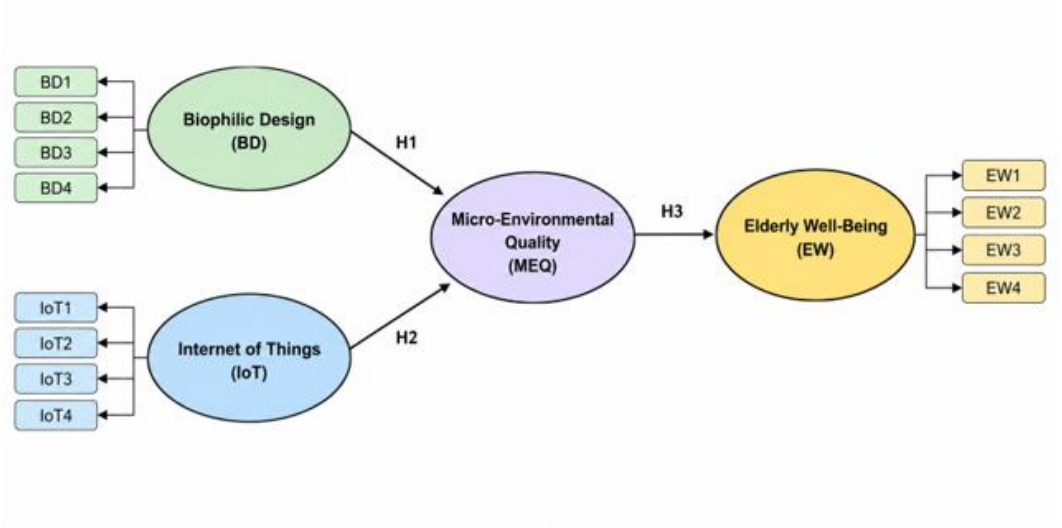


Figure 1: The Research Model

The research therefore contributes by empirically examining the relationships among design, technology, micro-environmental quality, and elderly well-being in the specific context of urban farming in Jakarta's kampung settlements. The model is subsequently tested using PLS-SEM to determine the direction, strength, and significance of the relationships among the constructs.

RESEARCH METHOD

Research Design

This study employed a quantitative approach to empirically examine the relationships among Biophilic Design (BD), Internet of Things (IoT), Micro-Environmental Quality (MEQ), and Elderly Well-Being (EW) in urban farming in Jakarta's kampung settlements. The study focused on elderly users'perceptions and tested three direct relationships: BD → MEQ, IoT → MEQ, and MEQ → EW.

The conceptual model was developed by synthesizing literature on biophilic design, urban farming, smart-city technology, environmental quality, and elderly well-being. BD and IoT were positioned as independent constructs, MEQ as a construct representing user-perceived environmental conditions and conceptually connecting the independent and dependent constructs, and EW as the dependent construct. The study did not test BD → EW or IoT → EW and did not statistically test MEQ as a mediator

Research Context and Respondents

The study was conducted in the context of urban farming in Jakarta's kampung settlements. This context was selected because kampung settlements are generally characterized by high building density, limited open space, and the need to optimize available areas for environmental and community activities. Under these conditions, urban farming functions not only as plant production but also as a space for physical activity, environmental activities, and social interaction.

Criteria for Selecting Elderly Respondents

Respondents were selected based on the following criteria: (1) they were elderly individuals; (2) they lived in or were directly involved with the kampung settlement where the urban-farming activity was located; (3) they had used or interacted with the urban-farming area; and (4) they were able to understand and respond to the questionnaire independently or with appropriate assistance when necessary.

Elderly individuals without direct experience of the urban-farming environment were excluded because they did not have sufficient experience to assess the research constructs. These criteria ensured the data reflected the perceptions of actual users rather than general opinions about urban farming.

Sample Size Adequacy for PLS-SEM Analysis

The respondents consisted of 75 elderly individuals who used or were directly involved in urban-farming activities. This group was selected to obtain assessments from users who directly experienced the environmental conditions, technology, and activities associated with urban farming. A total of 75 respondents participated in this study. According to the 10-times rule, the minimum sample size is determined as ten times the maximum number of structural paths directed at a single endogenous construct (Hair et al., 2022). As three structural paths lead to an endogenous construct in the proposed research model, the minimum sample size based on this rule is 30 respondents. Therefore, the sample of 75 respondents exceeds the minimum threshold suggested by this guideline

Research Instrument and Construct Operationalization

Data were collected using a structured questionnaire developed from the conceptual definitions and dimensions identified in the literature review. The study operationalized four latent constructs: BD, IoT, MEQ, and EW. Initially, each construct had four indicators, for a total of 16 indicators.

BD was measured through indicators concerning vegetation integration and accessibility, adequacy of natural lighting, natural air circulation, and sensory comfort involving visual, thermal, and natural experiences. IoT was measured through environmental sensor accuracy, ease of automated irrigation, ease of remote monitoring, and the ease of operating the IoT interface for elderly users.

MEQ was measured through thermal comfort, air quality, natural lighting that supports activities, and safety and comfort for elderly users. EW was measured through increased physical activity, psychological calmness and comfort, increased social interaction, and overall perceived improvement in well-being. All indicators employed a five-point Likert scale based on respondents' level of agreement.

Data Collection Procedure

The questionnaire was administered directly to respondents in the research setting. Before completing the questionnaire, respondents received an explanation of the research objectives and the meaning of each statement. The collected data represented respondents' perceptions of the physical characteristics of the urban-farming environment, IoT use, micro-environmental conditions, and perceived well-being.

Responses were coded according to indicators BD1–BD4, IoT1–IoT4, MEQ1–MEQ4, and EW1–EW4. The resulting dataset was then prepared for PLS-SEM analysis.

Data Analysis Using PLS-SEM

Data analysis employed Partial Least Squares Structural Equation Modeling (PLS-SEM) using SmartPLS. PLS-SEM analyzed relationships among latent constructs represented by multiple indicators and evaluated both the measurement and structural models. The methodological procedures followed the principles of PLS-SEM discussed by Hair et al. (2022).

The first stage involved evaluating the measurement model (outer model) to assess whether the indicators adequately represented their respective constructs. The evaluation included outer

loadings, convergent validity (Average Variance Extracted [AVE]), discriminant validity, and Composite Reliability. The assessment followed the principles of PLS-SEM described in the cited methodological literature.

The initial instrument contained 16 indicators. If an indicator failed to meet the established measurement criteria, it was removed based on the evaluation results, and the model was re-estimated using the retained indicators. The indicator-removal process and the final measurement results are reported in the Results and Discussion section, rather than in the Research Method section.

After the measurement model had been evaluated, the structural model (inner model) was assessed. The evaluation included R^2, f^2, VIF, and other relevant measures. Hypothesis testing used bootstrapping to obtain path coefficients (β), t-statistics, and p-values. A significance level of 5% (α = 0.05) was applied. These procedures follow the PLS-SEM principles described by Hair et al. (2022).

The three hypotheses were formulated as follows:

H1: Biophilic Design (BD) is positively related to Micro-Environmental Quality (MEQ).

H2: Internet of Things (IoT) is positively related to Micro-Environmental Quality (MEQ).

H3: Micro-Environmental Quality (MEQ) is positively related to Elderly Well-Being (EW).

This study tested only these three direct relationships. Although MEQ is positioned between BD/IoT and EW in the conceptual framework, this study did not conduct an indirect-effect or mediation analysis. Therefore, MEQ is not statistically defined as a mediator.

Research Analysis Stages

The analysis consisted of four main stages. First, the 16 initial indicators were evaluated through the measurement model. Second, indicators that did not meet the required criteria were removed, and the model was re-estimated. Third, the final measurement model was assessed for construct validity and reliability. Fourth, the structural model and the three hypothesized relationships were evaluated using PLS-SEM and bootstrapping.

At this methodological stage, SmartPLS results are not presented. The outer-loading values, removed indicators, validity and reliability results, R^2, f^2, VIF, path coefficients, t-statistics, p-values, and decisions regarding H1–H3 are presented and interpreted in the Results and Discussion section.

FINDINGS AND DISCUSSION

Respondent Demographic Characteristics

This study involved 75 older adult respondents living in Jakarta's urban villages (kampung kota). By gender, 43 respondents (57.3%) were female, and 32 (42.7%) were male. Regarding age, the majority were aged 60–69 years, comprising 45 respondents (60.0%), followed by 23 respondents (30.7%) aged 70–79 years and 7 respondents (9.3%) aged 80 years and above.

In terms of educational attainment, 43 respondents (57.3%) had completed elementary to junior high school, 25 (33.3%) had completed senior high school, and 7 (9.4%) had attained tertiary education. These data provide an overview of the respondents' demographic characteristics and contextualize the analysis of the relationships among biophilic design, the Internet of Things (IoT), microenvironmental quality, and older adults' well-being in the context of urban farming in Jakarta's urban villages. (Table 1)

Table 1. Demographic Characteristics of Respondents (n = 75)

Variable	Category	Number (n =75)	Percentage (%)
Gender	Male	32	42.7

	Female	43	57.3
Age	60–69 years	45	60.0
	70–79 years	23	30.7
	≥ 80 years	7	9.3
Education	Elementary to junior high school	43	57.3
	Senior high school	25	33.3
	Tertiary education	7	9.4

Model Characteristics and Indicator Evaluation

This study examined the relationships among Biophilic Design (BD), Internet of Things (IoT), Micro-Environmental Quality (MEQ), and Elderly Well-Being (EW) in urban farming within Jakarta's urban kampung. Data were collected from 75 elderly respondents and analyzed using Partial Least Squares–Structural Equation Modeling (PLS-SEM) in SmartPLS v.4.1.1.8. The initial model included four constructs, each measured by four indicators, for a total of 16 indicators.

BD initially measured vegetation integration and accessibility, natural lighting, natural air circulation, and sensory comfort. IoT covered environmental sensors, automated irrigation, remote monitoring, and interface usability for elderly users. MEQ included thermal comfort, air quality, natural lighting, safety, and comfort, while EW included physical activity, psychological comfort, social interaction, and overall well-being.

The first-stage measurement model evaluation showed that several indicators did not meet the measurement criteria and were subsequently removed. Table 2 presents the initial results.

Table 2. Outer Loading Results of the Stage 1 Convergent Validity Test

Variable	Biophilic Design (BD)	Elderly Well-Being (EW)	Internet Of Things (IoT)	Micro Elderly Quality (MEQ)
BD1	0.217			
BD2	-0.821			
BD3	-0.626			
BD4	0.130			
EW1		-0.170		
EW2		0.611		
EW3		0.415		
EW4		0.853		
IoT1			-0.188	
IoT2			0.398	
IoT3			0.797	
IoT4			0.830	
MEQ1				-0.147
MEQ2				-0.184
MEQ3				0.801
MEQ4				0.768

After indicator elimination and model re-estimation, the final model retained nine indicators: BD2 and BD3; IoT2, IoT3, and IoT4; MEQ3 and MEQ4; and EW2 and EW4.

Table 3 presents the final outer loading values: BD2 = 0.888; BD3 = 0.754; EW2 = 0.656; EW4 = 0.878; IoT2 = 0.706; IoT3 = 0.806; IoT4 = 0.834; MEQ3 = 0.767; and MEQ4 = 0.836. Thus, all

retained indicators were used in the subsequent analysis. Changes in outer loading values compared with the first-stage estimation result from re-estimating the model after changing the indicator composition. Therefore, the findings are interpreted based on the final model.

Table 3. Outer Loading Results of the Final Stage 2 Convergent Validity Test

Variable	Biophilic Design	Elderly Well-Being	Internet Of Things	Micro Elderly Quality
BD2	0.888			
BD3	0.754			
EW2		0.656		
EW4		0.878		
IoT2			0.706	
IoT3			0.806	
IoT4			0.834	
MEQ3				0.767
MEQ4				0.836

Convergent Validity

Convergent validity was evaluated using outer loadings and Average Variance Extracted (AVE). As shown in Table 4, the AVE values for BD, EW, IoT, and MEQ were 0.678, 0.601, 0.614, and 0.644, respectively. All values exceeded 0.50, indicating adequate convergent validity for the four constructs.

Table 4. AVE Results of the Convergent Validity Test

Variable	Average variance extracted (AVE)	Notes
Biophilic Design	0.678	Valid
Elderly Well-Being	0.601	Valid
Internet Of Things	0.614	Valid
Micro Elderly Quality	0.644	Valid

Nevertheless, the elimination of seven indicators indicates that not all conceptually defined dimensions of biophilic design, technology, micro-environmental quality, and elderly well-being had the same measurement strength in the studied urban farming context. This finding is important because broad theoretical constructs may be represented more narrowly when assessed through the experiences of specific users.

Discriminant Validity

Discriminant validity was assessed using cross-loadings and the Fornell–Larcker criterion. Based on Table 5, each indicator had its highest loading on its intended construct. BD2 had a loading of 0.888 on BD, while its loadings on EW, IoT, and MEQ were only 0.124, 0.192, and 0.185, respectively. IoT4 had its highest loading on IoT (0.834), while MEQ4 had its highest loading on MEQ (0.836).

Table 5. Cross-Loading Results of the Discriminant Validity Test

Variable	Biophilic Design	Elderly Well-Being	Internet Of Things	Micro Elderly Quality	Notes
BD2	**0.888**	0.124	0.192	0.185	Valid
BD3	**0.754**	0.036	-0.100	0.130	Valid
EW2	-0.051	**0.656**	0.017	0.100	Valid
EW4	0.169	**0.878**	0.030	0.157	Valid
IoT2	-0.103	-0.067	**0.706**	-0.172	Valid
IoT3	0.038	0.028	**0.806**	-0.165	Valid
IoT4	0.212	0.089	**0.834**	-0.238	Valid
MEQ3	0.156	0.118	**-0.180**	**0.767**	Valid
MEQ4	0.158	0.154	-0.220	**0.836**	Valid

The Fornell–Larcker results in Tables 6 and 7 also indicated adequate construct separation. The square roots of AVE were 0.823 for BD, 0.775 for EW, 0.784 for IoT, and 0.802 for MEQ, and these values were higher than the corresponding correlations with other constructs. Construct reliability in Table 8 was also adequate, with Composite Reliability values of 0.807 for BD, 0.747 for EW, 0.826 for IoT, and 0.783 for MEQ. Thus, the measurement model demonstrated adequate reliability and validity for evaluating the structural model.

Table 6. Latent Variable Correlations, AVE, and Square Root of AVE

Variable	Biophilic Design	Elderly Well-Being	Internet Of Things	Micro Elderly Quality	Kuadrat AVE	Notes
Biophilic Design	1	0.106	0.086	0.195	**0.823**	Valid
Elderly Well-Being	0.106	1	0.031	0.170	**0.775**	Valid
Internet Of Things	0.086	0.031	1	-0.250	**0.784**	Valid
Micro Elderly Quality	0.195	0.170	-0.250	1	**0.802**	Valid

Table 7. Discriminant Validity Based on the Fornell–Larcker Criterion

Variable	Biophilic Design	Elderly Well-Being	Internet Of Things	Micro Elderly Quality
Biophilic Design	**0.823**			
Elderly Well-Being	0.106	**0.775**		
Internet of Things	0.086	0.031	**0.784**	
Micro Elderly Quality	0.195	0.170	-0.25	**0.802**

Table 8. Composite Reliability Values

Variable	Composite reliability (rho_c)	Notes
Biophilic Design	0.807	Reliable
Elderly Well-Being	0.747	Reliable
Internet of Things	0.826	Reliable

Micro Elderly Quality	0.783	Reliable

Structural Model Evaluation

After the measurement model met the required criteria, the study evaluated the structural model. The study examined three direct relationships: BD → MEQ, IoT → MEQ, and MEQ → EW. The structural model results indicate that the three relationships did not fully correspond to the hypothesized directions.

As shown in Table 9, the R^2 value for MEQ was 0.110, and the adjusted R^2 was 0.085. Thus, BD and IoT jointly explained 11.0% of the variance in MEQ. Meanwhile, EW had an R^2 of 0.029 and an adjusted R^2 of 0.016, indicating that MEQ explained approximately 2.9% of the variance in EW. In PLS-SEM, R^2 represents the proportion of variance in an endogenous construct explained by its predictors.

Table 9. R-Square (R^2) Test Results

Variable Dependent	R-square	R-square adjusted
Elderly Well-Being	0.029	0.016
Micro Elderly Quality	0.110	0.085

The effect sizes reported in Table 10 were also relatively small: f^2 = 0.053 for BD → MEQ, 0.081 for IoT → MEQ, and 0.030 for MEQ → EW. These findings indicate that the individual direct relationships contributed relatively little to the endogenous constructs.

Table 10. Effect Size (f^2) Test Results

Variable	Biophilic Design	Elderly Well-Being	Internet Of Things	Micro Elderly Quality
Biophilic Design				0.053
Elderly Well-Being				
Internet of Things				0.081
Micro Elderly Quality		0.030		

Table 11 presents the model fit evaluation. The SRMR was 0.127, the NFI was −0.093, and the GoF was 0.209953. These results should be interpreted cautiously. PLS-SEM assessment should not rely solely on global model-fit indices; it should also consider the structural model's explanatory and predictive performance. The relatively low R^2 values, particularly for EW, indicate that the model does not capture all factors contributing to micro-environmental quality and elderly well-being.

Table 11. Model Fit Test Results

Parameters	Rule Of Thumb	Parameter Values	Notes
SRMR	SRMR value < 0.10	0.127	No Fit
Chi Square	χ^2 statistic ≥ χ^2 critical value (Chi-Square table) for DF ≤ 3		
NFI	NFI value approaching 1. Ideally ≥ 0.90 (good), 0.80–0.90 (acceptable), and < 0.80 (poor fit)	-0.093	No Fit
GoF	0.10 (small GoF)	0.209953	GoF

	0.25 (moderate GoF) 0.36 (large GoF)	Moderat

Hypothesis Testing

Table 12 presents the bootstrapping direct-effect results, and Figure 2 (Path Coefficients Model) illustrates them. The results revealed three main findings: BD → MEQ was positive but not significant; IoT → MEQ was significant but negative; and MEQ → EW was positive but not significant. Bootstrapping is appropriate for evaluating the statistical significance of PLS-SEM path coefficients because it provides standard errors, t-values, and confidence intervals through repeated resampling.

Table 12. Bootstrapping Results of Path Coefficients for Direct Effects

Path Coefficients	Original sample	T statistics	P values	Notes
Biophilic Design -> Micro Elderly Quality	0.219	1.726	0.084	Not Supported
Internet Of Things -> Micro Elderly Quality	-0.269	2.271	0.023	Supported
Micro Elderly Quality -> Elderly Well-Being	0.170	1.186	0.236	Not Supported

Biophilic Design → Micro-Environmental Quality

The BD → MEQ relationship produced β = 0.219, t = 1.726, and p = 0.084. Because p > 0.05, the evidence did not support H1. Although the coefficient was positive, the empirical evidence was insufficient to demonstrate a statistically significant relationship between perceived biophilic design and micro-environmental quality in the study sample.

This finding differs from previous research emphasizing the potential of biophilic design to improve environmental quality and user experience. Beatley (2011) emphasizes integrating nature into urban environments, while research on green infrastructure and aging populations indicates that the quality, accessibility, and proximity of natural environments may be associated with health and well-being. Previous studies by (Karera, 2021; Immanuel et al., 2023; Shafwah & Puspitasari, 2025) also demonstrate the application of biophilic principles in residential and urban contexts.

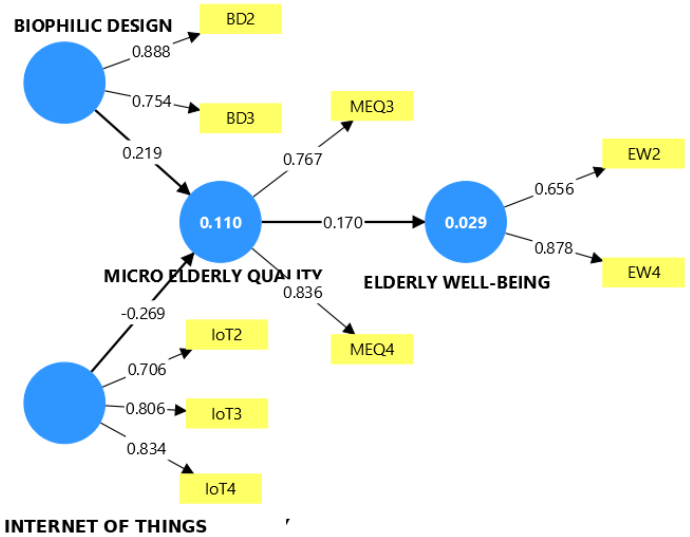


Figure 2. Path Coefficients of the Research Model

However, many previous studies have focused on architectural design, spatial application, or the conceptual benefits of biophilic principles. In contrast, this study evaluates the relationship based on elderly users' perceptions of urban farming. Therefore, the non-significant result suggests that the theoretically proposed benefits of biophilic design may not emerge with the same strength across different users and environmental contexts.

The indicator results provide additional insight. Of the four initial BD indicators, only BD2, concerning adequate natural lighting, and BD3, concerning natural air circulation, remained in the final model (Table 2). BD1, concerning vegetation integration and accessibility, and BD4, concerning sensory comfort, were eliminated. Consequently, BD in the final model primarily represents directly perceived environmental aspects rather than the full range of biophilic design dimensions.

Internet of Things → Micro-Environmental Quality

The IoT → MEQ relationship produced $\beta = -0.269$, $t = 2.271$, and $p = 0.023$. The p-value indicates a statistically significant relationship; however, the coefficient was negative. Because H2 was formulated as a positive relationship, H2 was not supported in the hypothesized direction.

This finding differs from the general expectation that digital technologies can improve efficiency, monitoring, automation, and sustainability. Narain (2024) positions smart city technologies as instruments for urban sustainability, while Xu et al. (2024) highlight the development of urban digital twins and artificial intelligence for integrated urban data management. However, research published in Cities emphasizes that smart-city technologies can generate both co-benefits and trade-offs depending on implementation context, governance, and user characteristics (Sharifi et al., 2024).

Therefore, the negative relationship identified in this study should not be interpreted as evidence that IoT generally reduces environmental quality. Rather, the result indicates that, within this particular study context, higher perceptions of the measured IoT aspects were associated with lower perceptions of MEQ.

In the final model, IoT was represented primarily by IoT2 (convenience of automated irrigation), IoT3 (ease of remote monitoring), and IoT4 (usability of the technology interface for elderly users). IoT1, concerning environmental sensor accuracy, was eliminated (Table 3). Thus, the final IoT construct primarily represents automation, remote monitoring, and usability.

One possible interpretation is that technically useful technologies do not necessarily improve elderly users' perceptions of environmental quality. However, this study did not measure digital literacy, technology burden, technology acceptance, or users' actual difficulties in operating the system. Therefore, these factors cannot be identified as causes of the negative relationship and should instead be regarded as possibilities requiring further investigation. This interpretation is consistent with smart-city research emphasizing the importance of human factors alongside technological capabilities.

Micro-Environmental Quality → Elderly Well-Being

The MEQ → EW relationship produced $\beta = 0.170$, $t = 1.186$, and $p = 0.236$. Although the positive coefficient indicates a directional tendency, $p > 0.05$ indicates that the relationship was not statistically significant. Therefore, H3 was not supported.

In the final model, MEQ was represented only by MEQ3, concerning natural lighting that supports activities, and MEQ4, concerning safety and comfort for elderly users. MEQ1, concerning thermal comfort, and MEQ2, concerning air quality, were eliminated (Table 3). Consequently, the final MEQ construct represents lighting, safety, and comfort more strongly than the broader concept of micro-environmental quality.

This finding differs from the assumption that a more comfortable environment automatically produces higher well-being. Research on green infrastructure, aging, health, and well-being emphasizes that multiple social and ecological determinants shape relationships between environmental conditions and elderly well-being. Similarly, studies of urban environments for older people indicate that safety, accessibility, physical activity, social interaction, environmental quality, and personal characteristics may jointly influence different dimensions of well-being.

The low R^2 value for EW of 0.029 (Table 9) reinforces this interpretation. MEQ explained only a very small proportion of the variance in elderly well-being. Therefore, multiple factors beyond the micro-environmental conditions measured in this study likely influence elderly well-being. Since these factors were not collected and tested, their individual contributions cannot be determined.

Synthesis of Findings and Comparison with Previous Studies

Overall, the study produced three main findings. First, BD had a positive but non-significant relationship with MEQ. Second, IoT had a statistically significant relationship with MEQ, but the direction was negative and contrary to the hypothesized positive relationship. Third, MEQ had a positive but non-significant relationship with EW. Therefore, none of the hypotheses was fully supported in the hypothesized direction.

Although two of the three hypotheses did not show significant effects, biophilic design, Internet of Things (IoT), and microenvironmental quality remain important for understanding the factors associated with older adults' well-being in urban farming environments. The non-significant findings do not necessarily mean these variables are irrelevant; rather, they suggest their effects may depend on the study's specific context and conditions. Therefore, examining all three variables provides a more comprehensive empirical understanding of their respective roles and helps identify which factors have stronger explanatory relevance within the context of this study

These findings differ from some previous studies that generally position biophilic design and smart technologies as potential strategies for improving environmental quality and quality of life. This difference does not imply that previous findings are incorrect; rather, it indicates that the relationships are context-dependent.

This study uses elderly users as the unit of analysis within urban farming in Jakarta's urban kampung, whereas many previous studies have focused on architectural design, buildings, technologies, or urban systems. Acevedo De los Ríos & Perrotti (2024) emphasize the importance of social and environmental contexts in urban agriculture in informal settlements, while Abujder Ochoa et al. (2025) conceptualize sustainable urban development as a complex system involving interacting components.

Accordingly, the findings suggest that developing elderly-friendly urban farming requires more than simply adding biophilic elements or IoT technologies. Greater attention should be given to how well these elements fit environmental conditions, activity requirements, technological capabilities, and elderly users' actual experiences.

Implications of the Findings

Theoretically, this study provides empirical evidence that relationships among design, technology, micro-environmental quality, and elderly well-being are not automatic. Biophilic design did not show a significant relationship with MEQ, whereas IoT showed a significant but negative relationship. These findings reinforce the importance of empirically testing theoretical assumptions within specific environmental and user contexts.

Practically, biophilic design in urban farming should emphasize environmental elements users directly perceive, particularly natural lighting and natural air circulation, which remained as

the BD indicators in the final model. IoT implementation should place greater emphasis on compatibility with elderly users' capabilities and experiences, particularly for automated irrigation, remote monitoring, and user interfaces. Meanwhile, improving elderly well-being cannot rely solely on improving micro-environmental quality because its contribution to EW in the present model remains limited.

Overall, this study extends previous research by providing user-based empirical evidence from elderly users in the context of urban farming in Jakarta's urban kampung. Its main contribution is not to show that biophilic design or IoT always improves environmental quality and well-being, but to show that these relationships may be non-significant or even run opposite to theoretical expectations. These findings provide a basis for developing urban farming environments that are more contextual, adaptive, user-oriented, and responsive to the needs of elderly populations.

CONCLUSIONS

Purpose and overall findings. This study empirically examined the relationships among biophilic design, Internet of Things (IoT), micro-environmental quality, and elderly well-being in urban farming within Jakarta's kampung kota. Based on PLS-SEM analysis of 75 elderly respondents, the findings show that the tested relationships did not fully support the hypothesized positive directions.

Biophilic design and micro-environmental quality. Biophilic design showed a positive but statistically non-significant relationship with micro-environmental quality ($\beta = 0.219$; $p = 0.084$); therefore, H1 was not supported. The retained indicators, particularly natural lighting and natural air circulation, did not show a sufficiently strong relationship with micro-environmental quality. This finding adds empirical evidence to previous studies that have predominantly emphasized the benefits of biophilic design conceptually or through design approaches.

IoT and micro-environmental quality. IoT showed a statistically significant but negative relationship with micro-environmental quality ($\beta = -0.269$; $p = 0.023$); therefore, H2 was not supported in the hypothesized positive direction. The findings indicate that automated irrigation, remote monitoring, and technology interfaces do not automatically produce better perceptions of micro-environmental quality. This highlights the importance of matching technology with the characteristics and experiences of elderly users.

Micro-environmental quality and elderly well-being. Micro-environmental quality showed a positive but non-significant relationship with elderly well-being ($\beta = 0.170$; $p = 0.236$); therefore, H3 was not supported. The R^2 values for MEQ (0.110) and EW (0.029) indicate that the model explains only a small proportion of variance. Elderly well-being may also be influenced by social, physical activity, psychological, accessibility, safety, and personal factors not included in the model.

Research contribution. This study provides empirical evidence based on elderly perceptions that biophilic design and technology do not automatically improve environmental quality or well-being. Elderly-friendly urban farming therefore requires an integrated approach combining environmental quality, technology suitability, user experience, and elderly social-psychological needs.

LIMITATION & FURTHER RESEARCH

Context and generalizability. This quantitative study involved 75 elderly respondents from urban farming in Jakarta's kampung kota. The site, respondent characteristics, and socio-environmental context limit generalization to areas or urban farming settings with different characteristics.

Research indicators. The initial instrument consisted of 16 indicators. Several indicators that

did not meet the measurement criteria were removed during the first-stage evaluation, followed by model re-estimation. The final model retained nine indicators; therefore, interpretation is limited to the aspects they represent.

Explanatory power. Biophilic design and IoT explained 11.0% of the variance in micro-environmental quality (R^2 = 0.110), while micro-environmental quality explained 2.9% of the variance in elderly well-being (R^2 = 0.029). Important factors outside the model may therefore contribute to elderly well-being.

Negative IoT relationship. IoT showed a significant but negative relationship with micro-environmental quality (β = −0.269; p = 0.023). The study did not examine technology suitability, ease of use, user experience, or technology acceptance; therefore, technology mismatch remains a research gap rather than a causal conclusion.

Further research. Future studies should examine the causes of the non-significant biophilic design relationship, the negative IoT relationship, and stronger determinants of elderly well-being. Larger samples, multiple locations, and longitudinal or mixed-method approaches are recommended.

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