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Biophilic Design 4.0 in Smart Buildings: A Conceptual Review of AI, IoT, and Neuroarchitecture

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Abstract

The integration of biophilic design with artificial intelligence (AI), the Internet of Things (IoT), and neuroarchitecture has created an opportunity to rethink smart buildings as environments that can support both operational performance and occupant well-being. Conventional biophilic design has emphasized natural materials, vegetation, daylight, water, views, biomorphic forms, and spatial qualities that evoke nature. However, many applications remain static, visually driven, or checklist-based, and are rarely evaluated through comparable measures of exposure, human response, and long-term building performance. This narrative review synthesizes literature on biophilic design, smart buildings, digital nature, indoor environmental quality, AI-supported assessment, IoT-enabled sensing, and neuroarchitectural evaluation. It argues that Biophilic Design 4.0 is not simply a digital extension of earlier biophilic practice, but a governance-aware framework in which natural stimuli are measured, interpreted, adapted, and validated through human-centered evidence. The review is organized around four transitions: from static natural features to measurable nature dose; from passive exposure to adaptive multisensory intervention; from subjective evaluation to psychophysiological triangulation; and from energy-centered smart buildings to human-centered smart environments. Evidence from nature-dose studies, VR and EEG experiments, AI-supported curation, and tropical smart-building case studies suggests that adaptive biophilic systems may improve perceived restoration, comfort, affect, attention, and energy-performance trade-offs. Yet the evidence remains fragmented, often short-term, and difficult to compare across methods, cultures, climates, and building types. The article proposes an integrative framework and research agenda emphasizing standardized metrics, longitudinal field validation, privacy-preserving AI, equity, and climate-sensitive implementation.

Keywords: Artificial intelligence, biophilic design smart buildings, digital biophilia, Internet of Things, neuroarchitecture, nature dose, occupant well-being

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Introduction

Rapid urbanization, extended indoor living, hybrid work, post-pandemic health concerns, and the digitalization of everyday life have intensified the need to reconsider the relationship between people, buildings, and nature. Contemporary buildings are increasingly optimized for density, safety, energy use, and operational efficiency, yet many interiors remain insufficiently responsive to occupants' psychological, physiological, and emotional needs. This problem is pronounced in offices, schools, healthcare facilities, high-density housing, and urban workspaces where occupants may have limited access to daylight, vegetation, fresh air, natural views, and restorative spatial conditions (Awada et al. 2023; Javid Khan and Lucas 2025; Zheng et al. 2025).

Biophilic design has emerged as one response to this condition by translating human affinity for nature into architectural and interior-design strategies. Its established vocabulary includes direct experiences of nature, indirect representations of nature, and spatial experiences associated with natural settings. Previous studies link biophilic features with perceived restoration, stress reduction, positive affect, satisfaction, attention recovery, and improved indoor environmental experience (Zhong, Schröder, and Bekkering 2022; Tekin et al. 2025; Afamefuna, Schweiker, and Harmsen 2026). However, the field has also faced criticism. In practice, biophilic design can be reduced to decorative greenery, symbolic natural motifs, or checklist compliance rather than being treated as an evidence-informed environmental intervention (Afara et al. 2024; Haidamous 2022; Berto, Barbiero, and Salingaros 2023).

At the same time, smart-building research has advanced through sensor networks, building automation, digital twins, predictive control, AI-supported assessment, and real-time occupant feedback. This technological trajectory has improved the capacity to monitor and control indoor environmental quality. Yet many smart-building systems still prioritize energy management and operational optimization over restoration, affective experience, place attachment, or psychological health. Human-centered building studies therefore call for a stronger integration of building performance with lived experience, especially in workplaces, healthcare settings, schools, and tropical climates (Karimi et al. 2023; Hasama et al. 2026; Heidari et al. 2024).

The central claim of this review is that the next stage of biophilic design requires more than adding sensors or digital nature to existing design patterns. Biophilic Design 4.0 is defined here as an adaptive, data-informed, ethically governed, and human-centered design framework that connects biophilic principles with AI, IoT, neuroarchitecture, and smart-building systems. The framework is distinguished by four capabilities: it makes nature exposure measurable, links exposure to adaptive multisensory response, validates experience through multiple human-response measures, and balances well-being with energy, privacy, equity, and climate performance. Figure 1 summarizes this closed-loop logic, in which biophilic inputs, sensing, intelligence, adaptive response, and

occupant outcomes are treated as interdependent components rather than isolated design features.

Accordingly, the novelty of this article lies not in introducing a new decorative style, but in reframing biophilic design as a measurable and governable building-performance domain. Earlier biophilic frameworks explain why nature matters and how natural patterns can be translated into architecture. Emerging work on nature-dose measurement, digital biophilia, neuroarchitecture, and human-centered smart buildings provides the technical and empirical basis for adaptive implementation. Biophilic Design 4.0 integrates these strands into a single conceptual map and identifies what must be validated before adaptive smart-biophilic environments can be adopted responsibly.

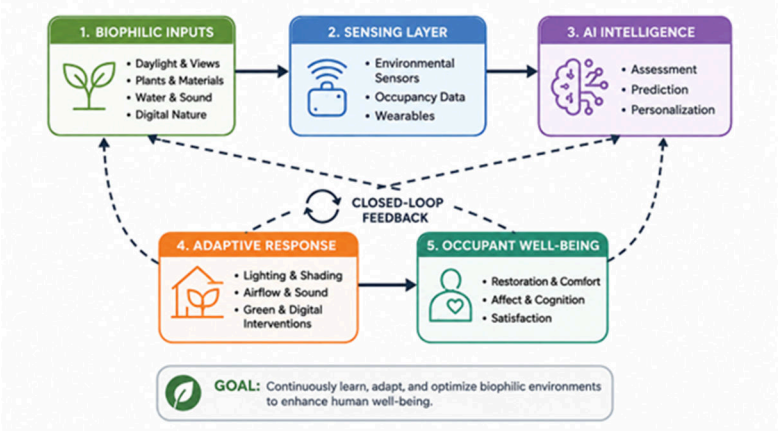


Figure 1
Closed-loop conceptual framework of Biophilic Design 4.0 as a human-centered smart-building system

Methods

Review approach and evidence handling

This study adopts a narrative literature review approach because the topic spans architecture, environmental psychology, smart-building operation, AI, IoT, immersive simulation, digital health, and neuroarchitecture. A purely systematic review would be valuable for a narrower question, such as the effect of indoor plants on stress or the accuracy of EEG classification in virtual environments. The present article instead aims to synthesize conceptual, empirical, and methodological contributions that explain how biophilic environments may become measurable, adaptive, and human-centered.

To improve transparency, the review followed a structured narrative process. Literature was identified through targeted searches in major academic databases and publisher platforms, including Scopus, Web of Science, ScienceDirect, Google Scholar, MDPI, Frontiers, Springer, Taylor & Francis, ACM, ASCE, and IOP sources. Search terms combined biophilic design with smart building, AI, IoT, neuroarchitecture, EEG, VR, indoor environmental quality, nature dose, digital biophilia, occupant well-being, restorative environment, tropical building, and human-centered building. The emphasis was on peer-reviewed studies and indexed conference

proceedings published mainly between 2021 and 2026, while earlier foundational sources were retained when they clarified biophilic theory or conceptual definitions.

Sources were included when they directly addressed at least one of five domains: biophilic design theory and evidence; quantification of nature exposure; AI or digital systems for assessment, curation, or personalization; IoT and smart-building responsiveness; or neuroarchitectural and psychophysiological evaluation of built environments. Sources were excluded when they used biophilia only as a decorative label, lacked relevance to indoor or architectural experience, or did not provide sufficient methodological information for interpretation. Review articles were used to position debates and map field development, whereas original studies, experiments, case studies, and measurement papers were prioritized when discussing quantitative findings.

The final cited corpus contains 50 sources. These were not treated as equal forms of evidence. Controlled experiments, post-occupancy evaluation, physiological studies, and field case studies were used for empirical claims; systematic and scoping reviews were used for coverage and context; conceptual papers were used to clarify vocabulary and identify emerging questions. This hierarchy is important because a visually persuasive digital-nature intervention, a small VR pilot, and a longitudinal occupied-building study do not carry the same evidentiary weight. Table 1 clarifies how evidence was interpreted in the synthesis.

Evidence mapping was performed manually by assigning each cited study to its dominant contribution: AI and digital systems, general biophilic design, health and restoration, indoor environmental quality and workplaces, IoT and smart buildings, nature-dose metrics, or neuroarchitecture and VR. Figure 2 should therefore be read as an interpretive evidence map of the selected corpus, not as a formal bibliometric survey of the entire field. The presence of 2026 studies reflect early-online or proceedings-based sources included in the corpus; these sources should be rechecked before final submission if journal indexing status changes. To make the distribution of the selected evidence more transparent, figure 2 visualizes the reviewed corpus by publication year and dominant thematic contribution. The figure is not intended to represent the full bibliometric structure of biophilic design research; rather, it shows how the selected studies support the conceptual construction of Biophilic Design 4.0 across AI and digital systems, general biophilic design, health and restoration, indoor environmental quality, IoT and smart buildings, nature-dose metrics, and neuroarchitecture.

Table 1
Evidence domains and analytical use in the narrative review

Evidence type	Examples	Analytical role	Primary limitation
Empirical experiments and physiological studies	Controlled VR, EEG, eye-tracking, HRV, EDA, soundscape, plant, and nature-dose studies	Used to infer short-term perceptual, affective, cognitive, or physiological responses	Small samples, artificial settings, short exposure, limited ecological validity
Post-occupancy and field case studies	Occupied offices, museums, hospitals, schools, tropical buildings, and certified healthy-building environments	Used to examine real-building relevance, operational feasibility, comfort, and energy trade-offs	Context-specific design, limited control, possible reporting bias
Measurement and computational methods	Nature View Potential, image-based assessment, computer vision, recommender systems, digital twins	Used to define measurable exposure, assessment layers, and personalization potential	Metric validity, model transferability, opacity, and cultural bias
Reviews and conceptual frameworks	Biophilic design, healthy buildings, multisensory biophilia, smart green buildings, neuroarchitecture	Used to position terminology, controversies, and research agendas	May aggregate heterogeneous evidence and reproduce field assumptions
Ethical and governance-oriented sources	Human-centered design, privacy, data governance, equity, and smart-building implementation literature	Used to define constraints for responsible Biophilic Design 4.0	Often conceptual and requiring translation into operational protocols

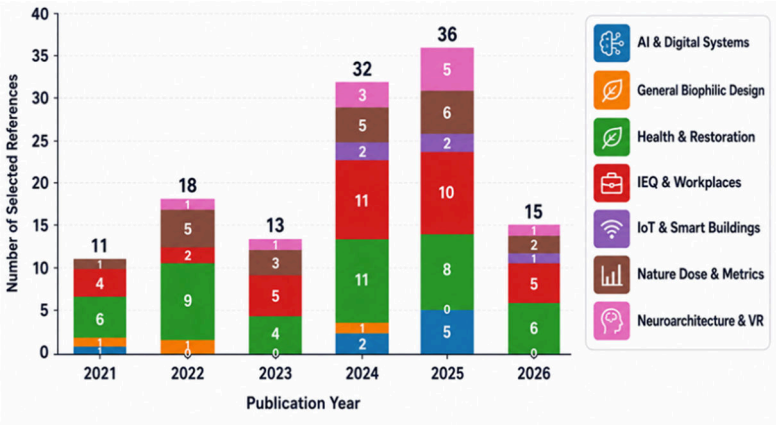


Figure 2
Evidence map of selected literature supporting Biophilic Design 4.0. Categories were manually assigned according to dominant contribution

Conceptual boundary: What Biophilic Design 4.0 Adds

Biophilic design is grounded in the proposition that humans benefit from contact with nature and natural processes. In built environments, this contact can be expressed through direct natural elements, indirect representations, and spatial experiences such as prospect, refuge, complexity, transition, and place-based connection. Established frameworks have helped designers translate broad human–nature affinity into spatial features, including daylight, vegetation, water, natural materials, natural colors, biomorphic forms, views, and naturalistic

complexity (Bolten and Barbiero 2023; Zhong, Schröder, and Bekkering 2022; Wijesooriya, Brambilla, and Markauskaite 2023).

However, a conceptual boundary is needed because not every smart, green, or nature-inspired building qualifies as Biophilic Design 4.0. Established biophilic theory explains the why; pattern-based design explains the what; evidence-based practice explains whether selected features are associated with well-being; smart-building automation explains how environmental conditions can be sensed and adjusted; and neuroarchitecture explains how responses may be measured beyond self-report. Biophilic Design 4.0 adds the integrative question: how can these layers be linked into a responsible feedback system that adapts biophilic exposure while preserving ecological meaning, occupant autonomy, and data rights?

Table 2 positions Biophilic Design 4.0 as a development of previous stages rather than a replacement for them. The progression is not strictly chronological because all stages still coexist in practice. A building with plants and daylight may remain within Biophilic Design 2.0 if features are static and unevaluated. It may approach Biophilic Design 3.0 if post-occupancy evaluation and indoor environmental metrics are used. It becomes a 4.0 system only when measurement, sensing, adaptive response, and human-response validation are intentionally coupled.

Table 2
Evolutionary stages of biophilic design

Stage	Dominant focus	Typical strategies	Main limitation	Contribution
Biophilic Design 1.0	Human–nature affinity	Conceptual and philosophical arguments	Weak operationalization	Clarifies why nature matters in architecture
Biophilic Design 2.0	Pattern-based design	Daylight, plants, views, water, wood, organic form, fractals	Often static, aesthetic, or checklist-driven	Translates biophilia into spatial features
Biophilic Design 3.0	Evidence-based performance	Post-occupancy evaluation, IEQ metrics, surveys, controlled studies	Fragmented methods and short follow-up	Links design features to well-being indicators
Biophilic Design 4.0	Adaptive intelligent biophilia	AI, IoT, VR, EEG, HRV, digital twins, nature-dose metrics, responsive cues	Privacy, validity, equity, maintenance, and ecological-substitution risks	Connects measurement, adaptation, governance, and human-centered validation

Following this conceptual distinction, figure 3 translates Biophilic Design 4.0 into a technology stack that connects biophilic assets, IoT monitoring, AI analytics, neuroarchitectural evidence, and occupant experience as interdependent layers of an adaptive smart-building system

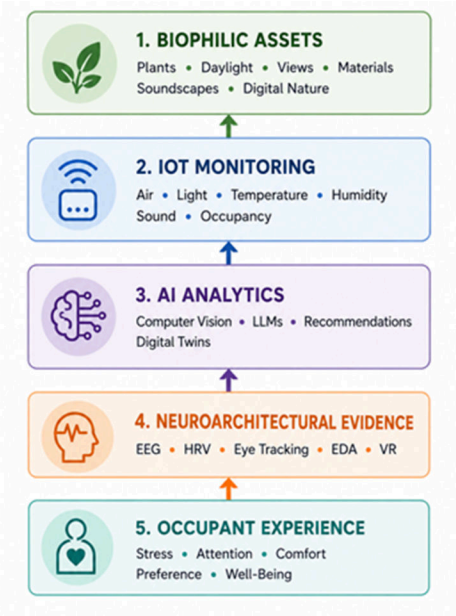


Figure 3
Human-centered technology stack for adaptive biophilic smart buildings. The stack differentiates biophilic assets, sensing, AI analytics, neuroarchitectural evidence, and occupant experience

Transition 1: From static natural features to measurable nature dose
Conventional biophilic design often assumes that the presence of natural elements is beneficial, yet this assumption is insufficient for adaptive smart-building implementation. Designers and facility managers need to know not only whether nature is present, but how much nature is perceived, through which sensory channels it is experienced, and under what spatial or cultural conditions it becomes restorative. The transition from static features to measurable nature dose is therefore a central foundation of Biophilic Design 4.0.

Recent nature-dose research challenges the simple idea that more nature is always better. In virtual office-like environments, Bianchi and Billington (2025) reported that 20% greenery could be optimal for several well-being outcomes, while a 60% combination of greenery and wood may reduce positive arousal, possibly through visual crowding. This finding is important because it suggests that biophilic effectiveness depends on proportion, coherence, and context, not just the quantity of plants or materials. It also indicates that adaptive systems should avoid maximizing greenery mechanically without considering perceptual load and user preference.

Nature View Potential extends this measurement agenda by estimating how much nature can be seen from an interior viewpoint. Bianchi and Billington (2025b) simulated 18,000 environments and generated 288,000 NVP calculations, identifying parameter settings that captured perceived connection to nature effectively. Such metrics can help architects and building operators move from general claims about natural views toward spatially explicit assessment. However, view metrics remain limited because they mainly address visual connection. They do not automatically capture smell, sound, tactile qualities, thermal variability, ecological

authenticity, or cultural meaning.

Visual complexity and fractal qualities further complicate measurement. Studies of facade design and leaf silhouettes suggest that organized complexity, perceptual coherence, and fractal characteristics can influence preference and restorativeness (Berto, Barbiero, and Salingaros 2023; Davison et al. 2025). This means that a room with plants but poor daylight, excessive noise, weak spatial coherence, or uncomfortable thermal conditions may still fail as a restorative environment. Biophilic Design 4.0 should therefore treat nature dose as a multidimensional construct rather than a single percentage of greenery.

The practical implication is that nature-dose metrics should become design hypotheses rather than universal prescriptions. A workplace, classroom, hospital room, and dwelling may require different levels of greenery, daylight, view openness, acoustic stimulation, and sensory richness. Adaptive systems can potentially calibrate these variables over time, but only if measurement is paired with human-response evidence and consent-aware data governance.

Transition 2: From passive exposure to adaptive multisensory intervention

Biophilic environments are often evaluated as static exposures: a room has plants or does not; an office has a natural view or does not; an interior contains wood, water, or biomorphic forms. Biophilic Design 4.0 reframes this logic by asking whether natural stimuli can be adjusted in response to changing environmental conditions, task demands, occupancy patterns, and occupant preferences. This shift does not imply that buildings should constantly manipulate experience. Rather, it suggests that selected biophilic parameters can be responsibly tuned when static conditions are insufficient.

IoT systems provide the sensing infrastructure for such responsiveness. Sensors can monitor illumination, glare, temperature, humidity, CO_2, particulate matter, sound, occupancy, airflow, plant health, water use, and occupant interaction. When connected to building automation, these data can support adaptive lighting, shading, ventilation, irrigation, acoustic masking, airflow modulation, and digital nature interfaces. The multi-layer metrics dashboard in Figure 4 illustrates why environmental, biophilic, physiological, psychological, and operational indicators must be interpreted together. A nature-rich room with poor air quality or thermal discomfort should not be considered successful simply because it contains greenery.

Digital biophilia is one area where adaptive intervention is developing rapidly. Biophilic illusion studies have explored wind-animated shadows, sun-animated lighting, responsive airflow, and location-responsive sounds (Altaf and Billington 2024). A within-subjects experiment with 345 participants indicated that such interventions can influence nature

connectedness, well-being, and acceptance in windowless or confined interiors (Altaf and Billington 2025). AI-based biophilic art curation has also been explored using survey responses and a ResNet50-based categorization system for personalized content delivery (Xing et al. 2024).

These findings support digital and multisensory interventions as useful supplements, especially where real nature is limited. They should not be interpreted as evidence that digital nature is equivalent to ecological contact. Digital biophilia may provide visual, acoustic, or symbolic restoration, but it cannot replace outdoor access, biodiversity, ventilation, microbial exposure, or the social and cultural meanings associated with real landscapes. Therefore, adaptive systems should be designed to supplement, not substitute for, direct nature and healthy indoor environmental quality.

The most difficult design challenge is balancing responsiveness with stability. Occupants may benefit from dynamic lighting, soundscape, or airflow, but excessive automation may feel intrusive or distracting. Participatory design and post-occupancy evaluation are therefore essential. AI or IoT systems should not impose a universal restorative profile; they should provide adjustable environmental support that preserves user control.

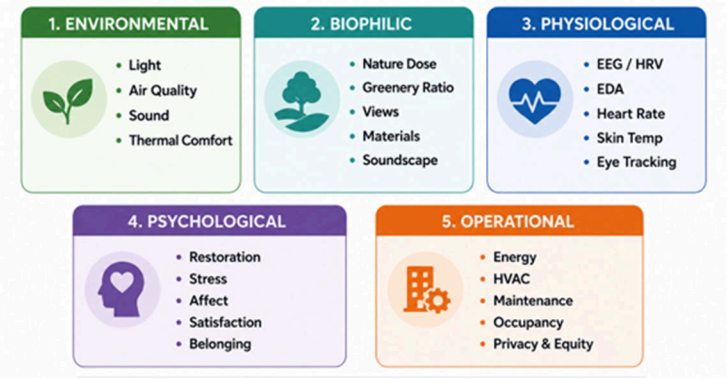


Figure 4
Multi-layer metrics dashboard for Biophilic Design 4.0. The figure emphasizes that biophilic performance must be evaluated through environmental, biophilic, physiological, psychological, and operational indicators

Transition 3: From subjective evaluation to psychophysiological triangulation

Biophilic design has traditionally relied on surveys, interviews, preference ratings, and post-occupancy evaluation. These tools remain essential because well-being is partly subjective, situated, and culturally mediated. However, self-report alone may not capture subconscious attention, physiological arousal, cognitive load, affective regulation, or stress response. Neuroarchitecture and psychophysiology can add an important evidence layer when used carefully.

EEG-based research on biophilic hospital rooms in virtual reality reported machine-learning classification accuracy above 90%, with frontal regions particularly important in distinguishing responses to biophilic conditions (Jung, Kim, and Kim 2023). Other immersive-environment studies using VR, eye tracking, heart rate, and skin conductance suggest that biophilic virtual

environments can influence visual attention, pleasantness, restoration, and physiological arousal (Latini et al. 2024; Sella et al. 2025). These findings indicate that built-environment responses can be measured beyond verbal preference.

Nevertheless, psychophysiological evidence should not be overinterpreted. EEG, HRV, EDA, eye tracking, and heart rate are sensitive to task, novelty, fatigue, movement, individual differences, equipment quality, and analytic choices. A classification model that distinguishes two virtual rooms does not automatically prove long-term well-being benefits in an occupied building. Similarly, physiological arousal can reflect interest, stress, novelty, or effort depending on context. Biophilic Design 4.0 therefore requires triangulation rather than reliance on any single signal.

A robust evaluation strategy should combine self-report, behavioral observation, environmental data, and physiological indicators. Surveys can capture satisfaction, perceived restoration, belonging, and preference. Environmental sensors can capture exposure conditions. Physiological measures can capture short-term regulation and arousal. Behavioral indicators can capture space use, dwell time, productivity, and maintenance interactions. The value of neuroarchitecture lies in this triangulated evidence structure, not in replacing design judgment with biometric scores.

This transition also raises ethical questions. Physiological sensing can become surveillance if used without explicit consent, transparent purpose, minimal data retention, and meaningful opt-out options. In offices, schools, healthcare facilities, and residential buildings, biometric data should be treated as sensitive information. The goal should be to evaluate and improve environments, not to monitor individuals continuously.

Transition 4: From Energy-Centered smart buildings to Human-Centered, Governance-Aware environments

Smart-building research has often prioritized energy efficiency, automation, and operational optimization. These goals are important, but they do not guarantee restorative experience. A building may be energy efficient while still being visually monotonous, acoustically stressful, poorly ventilated, socially isolating, or psychologically unrewarding. Biophilic Design 4.0 therefore extends human-centered design by placing occupant well-being, environmental performance, and ethical governance in the same decision space.

An important example comes from tropical smart-building work. The GEAR case study in Singapore combined radiant cooling, solar shading, biophilic design, natural ventilation, ceiling-fan control, and green-integrated photovoltaic systems, reporting approximately 40% lower energy use than standard office buildings in Singapore while monitoring comfort and well-being (Hasama et al. 2026). The case is valuable because it shows that human-centered strategies need not be separated from energy

performance. However, it remains context-specific and should not be generalized without further field validation across climates, building types, and occupant groups.

Governance is equally central. AI-assisted assessment can help identify visible biophilic attributes, and one study reported up to 88% alignment between GPT-4o-based assessment and expert evaluation after prompt refinement (Alemrajabi et al. 2025). Yet the same result also shows the limits of automation: visible features such as natural light are easier to assess than abstract experiences such as prospect, refuge, mystery, emotional attachment, or cultural meaning. Large language models and computer vision can assist design review, but they cannot replace expert interpretation, user participation, or post-occupancy validation.

Personalization also creates risks. Adaptive systems may use occupancy data, preferences, physiological indicators, or wearable data. Without safeguards, such systems may introduce biometric surveillance, algorithmic bias, unequal access, maintenance burden, or technological greenwashing. A building should not claim to be restorative simply because it contains sensors and AI interfaces. Responsible Biophilic Design 4.0 requires consent-by-design, local data processing where possible, minimal data retention, explainable recommendations, independent audit, and non-digital alternatives for users who do not want to be tracked.

These concerns are especially relevant in tropical and low-resource contexts, including Indonesia. Hot-humid climates create challenges related to solar radiation, humidity, air pollution, overheating, and maintenance, but they also offer opportunities for natural ventilation, shaded transitional spaces, vegetation, water-sensitive design, courtyards, local materials, and indoor–outdoor continuity. Indonesian and Southeast Asian studies indicate that climate-specific design is essential rather than optional (Atthakorn 2022; Aldjaidi, Bobby Saragih, and Sakina 2021; Ristianti et al. 2024). For such contexts, Biophilic Design 4.0 should not be imported as a high-cost technology package. It should begin with passive design, culturally meaningful natural elements, low-cost sensing, maintainable vegetation, and participatory evaluation.

Quantitative evidence and its limits

Table 3 consolidates quantitative findings that support the argument for measurable, adaptive, and human-centered biophilic systems. The table is not intended to prove a single causal pathway. Rather, it shows that several strands of evidence are converging: nature exposure can be quantified; digital and multisensory interventions can be evaluated experimentally; physiological responses can be measured; and smart-building operation can potentially align comfort with energy performance.

The same evidence also shows why caution is necessary. Sample sizes vary widely, many studies are short-term, several are based on virtual or simulated environments, and metrics are not yet standardized. Findings from a VR office, a hospital simulation, a museum workplace, or a tropical

smart-building case study cannot be merged as if they measured the same outcome. Biophilic Design 4.0 should therefore be treated as a research framework requiring validation, not as a mature design recipe.

Table 3
Quantitative evidence informing Biophilic Design 4.0 and its interpretation

Domain	Study focus	Key quantitative finding	Interpretive value and limitation	Source
AI assessment	GPT-4o evaluation of biophilic attributes in five LEED-certified buildings	Up to 88% alignment with expert evaluation after prompt refinement	Suggests AI can support preliminary assessment of visible attributes, but abstract spatial qualities remain difficult to evaluate	Alemrajabi et al. 2025
Digital biophilia	AI-based biophilic art curation and recommendation	Survey of 200 participants; ResNet50 used for automated categorization	Supports personalized digital content, but does not establish equivalence with real nature	Xing et al. 2024
Indoor nature dose	Virtual office-like environments with varied greenery and wood doses	412 participants; 20% greenery suggested as beneficial; 60% greenery/wood may visually crowd the scene	Challenges the assumption that more nature is always better	Bianchi and Billington 2025a
Nature-view metric	Nature View Potential with grid segmentation and ray casting	18,000 simulated environments and 288,000 NVP generations	Provides measurable visual exposure, but does not capture multisensory or cultural dimensions	Bianchi and Billington 2025b
Biophilic illusions	Wind-animated shadows, sun-animated lighting, and location-responsive sounds	345 participants; acceptance related to expectancy, social influence, and hedonic motivation	Useful for constrained interiors, but should supplement rather than replace real nature	Altaf and Billington 2025

Domain	Study focus	Key quantitative finding	Interpretive value and limitation	Source
Neuroarchitecture	Machine-learning EEG analysis of biophilic hospital rooms in VR	Classification accuracy above 90%; frontal regions were salient	Shows measurable neural differentiation, but field validity requires caution	Jung, Kim, and Kim 2023
VR soundscape	Audio-visual biophilic interventions in office environments	198 participants; nature-based soundscapes improved perceived pleasantness and eventfulness	Supports multisensory design, but exposure was controlled and short-term	Latini et al. 2024
Virtual biophilic office	Eye-tracking pilot in immersive biophilic workplace model	25 participants; attention varied with green-feature location and proximity	Useful for design testing, but sample size limits generalization	Latini et al. 2024
IEQ case study	Biophilic strategies in a museum workplace	Physical environment satisfaction M=6.29; work performance M=5.89; overall health M=5.35	Connects design with perceived outcomes, but contextual factors remain important	Asojo and Hazazi 2025
Indoor plants	Between-subjects open-plan office study in India	Improved decoration, visual comfort, and positive emotions; possible >8% cooling energy reduction	Suggests comfort and energy co-benefits, but effects depend on climate and maintenance	Budaniya et al. 2025
Domestic interiors	Greenery in living-room and bedroom images	331 adults; greenery increased perceived restorativeness and positive affective qualities	Supports residential relevance, but image-based studies differ from lived environments	Bellini et al. 2025
Tropical smart building	Human-centric office building in Singapore	Approximately 40% energy-use reduction compared with standard offices while monitoring comfort and well-being	Demonstrates integration potential, but evidence remains case-specific	Hasama et al. 2026

Integrative framework for research and practice

Based on the reviewed evidence, this article proposes a five-layer framework: biophilic input, sensing infrastructure, intelligence layer, adaptive response, and well-being outcome. The framework is shown conceptually in figure 1 and operationalized in table 4. Its primary contribution is to translate the idea of Biophilic Design 4.0 into a sequence of testable design and evaluation decisions.

The first layer consists of physical and digital biophilic inputs. Physical inputs include daylight, vegetation, green walls, natural materials, water, views, natural ventilation, organic forms, fractal patterns, and restorative spatial configurations. Digital inputs include AI-curated biophilic art, simulated natural soundscapes, responsive lighting, animated shadows, immersive virtual environments, and adaptive digital nature interfaces. These inputs should be selected according to climate, culture, building type, maintenance capacity, and ecological integrity.

The second layer consists of sensing infrastructure. Environmental sensors may track light, glare, temperature, humidity, CO_2, particulate matter, VOCs, sound, airflow, occupancy, and plant health. Human-response tools may include voluntary surveys, preference interfaces, wearables, eye tracking, HRV, EDA, or EEG in research contexts. Because human-response data can be sensitive, this layer must be governed by clear consent, limited retention, and transparent purpose.

The third layer consists of computational interpretation. AI, machine learning, rule-based analytics, digital twins, and recommender systems can identify patterns, detect trade-offs, and suggest adjustments. The fourth layer translates analysis into environmental response, such as shading, lighting, airflow, irrigation, acoustic masking, digital content, or restorative-zone prompts. The fifth layer evaluates whether the intervention improves restoration, comfort, affect, attention, satisfaction, belonging, productivity, or health-related perception. The framework is therefore circular rather than linear: evaluation should reshape future design decisions.

Table 4
Conceptual framework of Biophilic Design 4.0

Layer	Core components	Example variables	Expected contribution	Critical design constraint
Biophilic input	Physical and digital natural stimuli	Daylight, plants, views, wood, water, digital nature, soundscape	Provides restorative sensory and spatial material	Avoid tokenistic or faux biophilia; prioritize ecological and cultural meaning
Sensing infrastructure	Environmental and human-response monitoring	Lux, glare, CO_2, VOC, PM, sound, temperature, occupancy, HRV, EDA, surveys	Captures conditions that shape user experience	Use consent, data minimization, and opt-out pathways

Layer	Core components	Example variables	Expected contribution	Critical design constraint
Intelligence layer	Computational interpretation and trade-off management	Computer vision, machine learning, LLM assessment, digital twins, recommender systems	Identifies patterns and suggests adaptive responses	Validate models; avoid opaque or biased personalization
Adaptive response	Environmental adjustment and user-support actions	Lighting, shading, airflow, soundscape, media walls, plant irrigation, green-zone prompts	Personalizes or calibrates biophilic exposure	Maintain user control and prevent intrusive automation
Well-being outcome	Human-centered building performance	Restoration, comfort, affect, attention, satisfaction, belonging, productivity	Evaluates whether the building improves experience	Use multiple metrics and long-term field validation

Research agenda

The field now requires an agenda that is more specific than calling for more research. Figure 5 summarizes a staged pathway from conceptual biophilia to validated adaptive systems. The first priority is metric development. Nature dose, Nature View Potential, sensory richness, spatial complexity, daylight quality, acoustic quality, and physiological restoration need comparable protocols that can be tested across laboratories and building types.

The second priority is longitudinal field validation. Many current studies use short-term exposure, VR simulation, or image-based assessment. These methods are useful for isolating variables, but they cannot determine whether adaptive biophilic environments produce durable well-being benefits in real buildings. Longitudinal studies should combine post-occupancy evaluation, environmental sensing, maintenance data, energy use, and repeated psychological or physiological measures.

The third priority is governance. If adaptive biophilic systems depend on AI and occupant data, then privacy, consent, equity, and algorithmic accountability are not secondary issues. They are preconditions for responsible implementation. The fourth priority is climate-sensitive and culturally situated implementation. Tropical contexts such as Indonesia can contribute original knowledge by testing passive design, low-cost sensing, shaded greenery, local materials, and indoor–outdoor spatial continuity in relation to comfort and energy use.

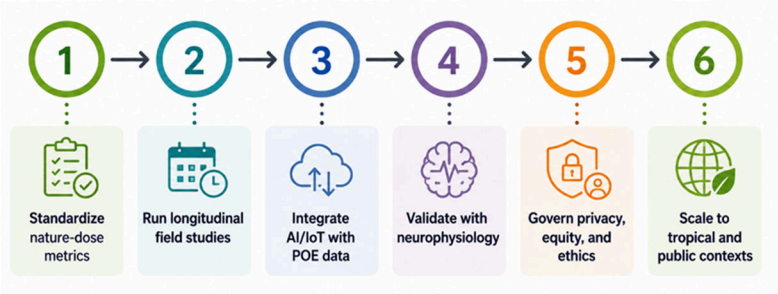


Figure 5
Research agenda for moving from conceptual biophilia to validated adaptive systems

Table 5
Future research agenda for Biophilic Design 4.0

Domain	Key question	Recommended approach	Expected output	Illustrative source
Metrics	How should nature dose, NVP, and multisensory exposure be standardized?	Cross-lab benchmarking with shared visual, acoustic, environmental, and physiological protocols	A validated minimum metric set usable across offices, homes, schools, and healthcare interiors	Bianchi and Billington 2025b
Causality	Which features produce causal well-being effects and under what conditions?	Longitudinal field trials combined with controlled VR experiments and post-occupancy evaluation	Evidence separating short-term preference from durable restoration or health-related benefit	Jung, Kim, and Kim 2023
Human diversity	How do age, culture, climate, disability, and nature connectedness alter responses?	Mixed-method studies in homes, schools, healthcare, workplaces, and public buildings	Design guidance that avoids universal assumptions about nature preference	Bellini et al. 2025
AI governance	How can personalization avoid surveillance and algorithmic bias?	Consent-by-design, minimal retention, explainable models, local processing, and independent audit	Trustworthy adaptive systems that protect autonomy and data rights	Javid Khan and Lucas 2025
Tropical adoption	How can smart-biophilic systems work in hot-humid and low-resource contexts?	Passive design plus low-cost IoT monitoring, maintainable planting, shading, and natural ventilation	Climate-sensitive design models relevant to Indonesia and other tropical countries	Hasama et al. 2026

Conclusion

This narrative review has proposed Biophilic Design 4.0 as a framework for integrating biophilic design, AI, IoT, neuroarchitecture, and smart-building systems in support of occupant well-being. The concept is useful only if it is understood as an evidence and governance framework, not as a technological slogan. Its contribution is to make biophilic exposure measurable, adaptive, and accountable while keeping human experience and ecological meaning at the center of smart-building discourse.

The review identifies four decisive transitions. First, biophilic features must move from static decoration toward measurable nature dose and multisensory exposure. Second, buildings should move from passive natural features toward adaptive interventions that can respond to environmental conditions and user needs without becoming intrusive. Third, evaluation should move beyond self-report alone toward psychophysiological triangulation, while recognizing the limits of biometric interpretation. Fourth, smart buildings should move beyond energy-centered automation toward human-centered and governance-aware environments that integrate privacy, equity, maintenance, and climate responsiveness.

Future progress depends on three near-term steps: standardized measurement protocols for nature exposure and human response; longitudinal field studies in occupied buildings; and privacy-preserving adaptive systems tested in diverse cultural and climatic contexts. Digital nature and intelligent systems should supplement, not replace, real nature, healthy indoor environmental quality, and meaningful outdoor access. When developed with restraint, evidence, and ethical governance, Biophilic Design 4.0 may help shift smart buildings from efficient machines toward environments that are also restorative, inclusive, and humane.

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