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Systematic Review

Indoor Biophilic Design for Higher Education Environments: A Systematic Mixed-Methods Review

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Abstract

Indoor biophilic design may support student well-being and learning, yet evidence relevant to higher education interior environments has not undergone systematic synthesis with formal quality appraisal. This systematic mixed-methods review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 and searched Scopus and the Web of Science Core Collection. We screened 1601 unique database records and 59 supplementary records and included 63 empirical studies. We appraised study quality using Mixed Methods Appraisal Tool (MMAT) 2018 and integrated findings through a convergent integrated approach. The evidence base was recent but uneven, with interior design elements forming the largest category; ambient conditions were largely decontextualized, and spatial attributes were dominated by window views. Perceptual outcomes were assessed most often and had the highest positive rate. Physiological and cognitive findings were less consistently positive, while cognition contained the most negative findings. Most studies adopted a restorative paradigm, whereas a protective paradigm appeared in 25% of studies but in two-thirds of those assessing cognition. Current evidence supports cautious use of indoor plants, green walls, and window views of nature in classrooms for perceptual and short-term affective benefits. It does not yet support transferable claims about sustained cognition, non-classroom settings, ambient conditions, or spatial attributes beyond window views.

Keywords: biophilic design; higher education; learning environment; perceptual; psychological; physiological; cognitive

1. Introduction

Most people now spend roughly 90% of their time indoors [1], making interior environments a substantial part of daily health and performance. Biophilic design responds to this condition by integrating natural elements into buildings to support occupant health, well-being, and cognitive function. The approach is grounded in Wilson's biophilia hypothesis and is commonly operationalized through Kellert and Calabrese's three experiential dimensions and Browning et al.'s 14 patterns [2–4]. Evidence has accumulated for natural elements, including plants, daylight, and views, in relation to stress reduction, attention recovery, and mood [5]. Recent syntheses indicate that the wider biophilic design literature now exceeds 400 peer-reviewed studies, with concentrations in workplaces, schools, and healthcare settings [6]. Evidence from higher education interiors remains less clearly synthesized, although these spaces are where young adults sustain cognitive work under chronic academic stress.

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1.1. Health and Cognitive Challenges in Higher Education

Students in higher education face a dual burden of mental health risk and sustained cognitive demand. Rates of depression, anxiety, and stress-related disorders are higher among university students than in the general adult population [7,8]. The World Health Organization (WHO) World Mental Health International College Student Initiative reported a 12-month mental disorder prevalence of 31% among 13,984 first-year students from 19 colleges in eight countries. Depression and anxiety were the most prevalent diagnoses in that cohort [9]. These risks are embedded in the broader pressures of university life. Academic pressure, financial insecurity, uncertainty during the transition to university, identity formation, and social adjustment interact with lectures, examinations, prolonged study, and laboratory or studio work [10]. The rapid uptake of generative artificial intelligence (AI) adds another source of uncertainty, as students reassess productivity, competitive standing, and future employment prospects [11]. Physical learning environments therefore matter because academic work is carried out in settings that can shape attention, mood, and performance [12]. Strategies that can reduce stress while supporting attention and academic performance are especially relevant for higher education environments.

1.2. Theoretical Foundations and the Recovery–Protection Divide

Biophilic design in higher education draws mainly on two environmental psychology theories. Ulrich's stress reduction theory (SRT) posits that natural settings can trigger rapid affective and physiological recovery from stress through evolved appraisal processes [13]. A recent reformulation links SRT to higher-order cognitive performance, including creative problem solving and cognitive flexibility, by preserving executive resources under stress [14]. Kaplan and Kaplan's attention restoration theory (ART) locates nature's benefit in involuntary soft fascination, which allows depleted directed attention resources to recover [15]. Together, SRT and ART explain why plants, daylight, views, and other natural cues may matter in academic settings where students sustain long periods of attention.

These theories are commonly translated into design variables through Kellert and Calabrese's three experiential dimensions and Browning et al.'s 14 patterns [3,4]. This translation has made biophilic design measurable, but it also carries a conceptual bias. SRT and ART primarily treat nature as a recovery resource, activated after stress, fatigue, or attentional depletion. Higher education interiors may require a broader account because classrooms, libraries, studios, and informal study spaces are not only places of recovery. They are also places where academic demand is actively produced and sustained. Salutogenic design and psychosocially supportive design offer a protective or buffering paradigm, asking how environments can sustain health and support coping during demanding work [6,16]. In higher education biophilic design research, this protective paradigm remains underdeveloped. The dominant restorative framing has therefore rarely been tested against the possibility that indoor academic spaces should reduce depletion while work is underway, not only facilitate recovery afterwards. Visual neuroscience offers one possible explanation for how classroom design may support students during ongoing work. Determan et al. proposed that collinear and curvilinear contours and statistical fractal patterns may be processed more fluently by the visual system, thereby reducing extraneous perceptual demand and helping preserve attention during classroom activity [17]. This interpretation remains provisional because these features were included only as part of a bundled classroom intervention, and the study did not directly measure visual processing or cognitive load.

1.3. Research Challenges in Higher Education Biophilic Design

Evidence on indoor biophilic design in higher education is accumulating, but three challenges limit synthesis and application. The first challenge is conceptual. General frameworks, such as Kellert and Calabrese's three experiences and Browning et al.'s 14 patterns, classify broad biophilic experiences, but they do not specify which elements suit particular functions, users, tasks, or intended outcomes [3,4]. Browning and Determan present an outcome-first approach to school design, in which designers first define the outcomes to be supported and then select matching biophilic patterns [18]. Their outcome–pattern matrix makes this decision sequence explicit, but it draws the proposed relationships from a general design guide rather than deriving them through systematic evidence synthesis. The two school cases presented in the article combine multiple biophilic strategies and therefore do not permit the effects of individual patterns to be isolated. The article thus provides a useful decision logic rather than a validated selection framework. Higher education still lacks an evidence map linking spatial functions and academic demands to intended outcomes, candidate elements, response directions, and evidence quality.

The second challenge is spatial. Because campuses often provide abundant outdoor greenery, student-focused restorative research has tended to examine green and blue spaces outside buildings. A recent meta-analysis of college student trials, for example, drew almost entirely on outdoor exposures in forests and parks [19]. This emphasis is useful for understanding campus nature contact, but it leaves a weaker evidence base for classrooms, libraries, studios, and study spaces. These interiors are where students spend much of their academic time and where design guidance is most directly actionable.

The third challenge is paradigmatic. Indoor studies often carry the restorative logic developed for outdoor or recuperative settings into academic interiors, without asking whether restoration fully matches the work performed there. Foyers, corridors, lounges, and dormitories can function as places of respite. In contemporary universities, however, these same spaces often become informal learning environments where students read, prepare, and continue demanding cognitive work. Classrooms and libraries make this demand explicit. Where academic work is underway, biophilic design may need to protect attention and buffer resource depletion, rather than only help students recover afterwards. Current evidence therefore remains unable to specify which elements work in which higher education interiors and under which recovery or protection paradigm.

1.4. Existing Reviews and Persistent Gaps

Peters and D'Penna provide the closest direct point of departure [16]. Their semi-systematic critical review assembled multidisciplinary evidence relevant to stress reduction, psychological well-being, cognitive function, social support and belonging, and physical comfort in university environments. However, the review found that this evidence consisted largely of discrete studies of individual environmental parameters, with few holistic or design-specific investigations of actual university learning spaces. The authors therefore called for more systematic and contextually grounded research. Although the empirical literature has since expanded substantially, indoor biophilic design in higher education has not been synthesized as a distinct evidence domain with formal quality appraisal.

Adjacent reviews leave the same gap from different directions. Fisher's critical synthesis of 47 systematic reviews addresses biophilic design across education as a whole, from early years settings to higher education, but does not isolate higher education interiors [20]. Van den Bogerd et al. focus on students, but center the review on outdoor campus green space across secondary and tertiary education [21]. As a result, classrooms, libraries, studios, and study spaces fall between broad educational syntheses and outdoor campus nature reviews. The broad claim that biophilic design supports student well-being and

learning, therefore, still rests partly on evidence assembled from other settings, populations, and exposure contexts. Designers, facilities planners, and policymakers lack a synthesis grounded in the indoor spaces where higher education students undertake academic work. What remains missing is a review that focuses specifically on indoor biophilic design for higher education environments and formally appraises the quality of the evidence.

1.5. Research Questions

Accordingly, this review addresses two related but non-equivalent dimensions of evidence relevant to biophilic design for higher education environments. The spatial design dimension concerns studies conducted in or explicitly modeling identifiable higher education interiors. These studies provide direct evidence about actual or represented classrooms, libraries, studios, residence halls, and informal learning spaces. The population-response dimension concerns studies of university students exposed to biophilic conditions in generic laboratory, indoor, or virtual settings. These studies provide controlled evidence about student responses but do not directly represent a higher education spatial typology. Both dimensions can inform design, but decontextualized findings require validation in identifiable campus spaces before supporting setting-specific guidance.

This review addresses the gap through a systematic mixed-methods review of 63 primary empirical studies [22]. It applies the Mixed Methods Appraisal Tool (MMAT) 2018 for quality appraisal [23] and convergent integrated synthesis [24], with reporting guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 [25]. The review is guided by four research questions.

- What is the scope and bibliometric profile of empirical research on indoor biophilic design for higher education environments?
- Which biophilic elements, exposure modes, spatial settings, situatedness levels, and measurement instruments characterize the included studies?
- How are biophilic elements associated with perceptual, psychological, physiological, and cognitive responses across the included studies?
- What gaps and limitations constrain the validity and transferability of current conclusions?

2. Materials and Methods

This systematic mixed-methods review integrated qualitative, quantitative, and mixed-methods primary studies using a convergent integrated synthesis approach [22,24]. Reporting followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement [25]. The protocol was registered in the International Prospective Register of Systematic Reviews (PROSPERO), registration number CRD420261409783. Before formal screening, we prepared a written internal protocol that specified the research questions, eligibility criteria, search strategy, coding framework, quality appraisal, and synthesis plan. The protocol and related process documentation are available from the corresponding author upon reasonable request.

2.1. Search Strategy

A systematic search was conducted in Scopus and the Web of Science Core Collection. The final search was run on 18 May 2026. Searches were not restricted by publication year or language.

The main Boolean string combined four concept blocks with AND. These blocks covered higher education context, biophilic or nature-related design features, indoor, educational, or virtual settings, and user-related outcomes. Terms within each block were

combined with OR. Table 1 gives an abbreviated version of the terms used in each block. The complete database-specific syntax is provided in Supplementary Materials S1.

Table 1. Main Boolean search.

Concept	Search Terms
Higher education context	universit* OR college* OR . . . OR "university student*" OR "college student*"
Biophilic or nature-related design features	biophilic OR biophilia OR . . . OR "water sound*" OR "thermal variability" OR airflow
Indoor, educational, or virtual setting	indoor* OR interior* OR . . . OR "virtual reality" OR VR OR "virtual environment*"
User-related outcomes	wellbeing OR "well-being" OR . . . OR productivity OR satisfaction OR comfort

* Indicates the truncation wildcard used in the database searches.

A targeted supplementary search was also conducted because several spatial morphology biophilic concepts were sparsely represented in the main vocabulary. These terms included fractal dimension, biomorphic forms, curvilinearity, spatial complexity, prospect–refuge, spatial openness, and ceiling height. The supplementary search used the same four-block structure, but substituted the feature terms relevant to spatial morphology.

2.2. Eligibility Criteria

Eligibility criteria were specified using the Population, Intervention, Comparison, Outcomes, and Study Design (PICOS) framework [26]. We adapted the framework for a mixed-methods review by treating intervention broadly as exposure to biophilic or nature-related environmental features. The criteria covered population, intervention or exposure, comparator, outcomes, and study design, as shown in Table 2.

Table 2. PICOS eligibility criteria.

Element	Inclusion
P—Population	University students and other users of higher education environments, including university, college, postsecondary, and campus contexts
I—Intervention	Biophilic design or nature-related environmental features linked to user experience
C—Comparison	No specific comparator required; eligible comparators include conventional spaces, baseline conditions, non-biophilic environments, or alternative design scenarios
O—Outcomes	At least one user-centered outcome, whether perceptual, psychological, physiological, or cognitive and behavioral
S—Study Design	Original empirical or evaluative studies of any quantitative, qualitative, or mixed-methods design

Title and abstract screening was conducted independently by two reviewers using a written screening protocol. Disagreements during study selection were resolved through discussion. The protocol operationalized the PICOS criteria rather than adding a separate eligibility system. The first two questions asked whether each record addressed a biophilic or nature-related feature and concerned higher education users. Three further questions assessed setting, scope, and outcome. They asked whether the record was located in an indoor higher education setting, went beyond a purely physical or technical environment, and measured a user-level outcome. Boundary rules were added for recurrent edge cases. Each record was labeled as include, exclude, or maybe. Records clearly outside the review scope were excluded at this stage.

At both screening stages, eligibility decisions followed the study aim, design, outcomes, and interpretive framing rather than isolated keyword matches. Recurrent boundary cases were resolved using the same domain-specific rules. Features such as comfort, day-

light, airflow, thermal variation, natural materials, and plants supported inclusion only when linked to an explicit nature-related exposure and user-level outcome. Studies limited to building certification, energy performance, heating, ventilation and air conditioning, indoor air quality, photometric or thermal indices, material performance, plant maintenance, or pollutant removal were excluded.

Office-style and simulated environments were eligible when higher education users encountered a spatially represented indoor biophilic condition, and researchers measured a user-level response. Corporate offices without a higher education sample or campus context were excluded. Virtual exposures required an indoor room or building referent, while nature photographs or videos shown only as screen content were excluded. Mixed education samples were retained only when higher education participants were identifiable. Studies combining indoor and outdoor settings were retained only when indoor findings could be extracted separately. Supplementary Material S2 provides the complete boundary rules and representative examples of records excluded after full-text assessment.

The main search returned 1363 records from Scopus and 856 from Web of Science. After 618 duplicates were removed in EndNote (version 2025.3.1), 1601 unique records remained for title and abstract screening. The supplementary search returned 38 records from Web of Science and 52 from Scopus. Removal of 23 internal duplicates and 8 records already present in the main library left 59 additional records. In the main search, 126 reports were retained for retrieval. Seven reports could not be obtained, so 119 reports were assessed in full text. In the supplementary search, 10 reports were retained for retrieval. One report could not be obtained, leaving 9 reports for full-text assessment. One reviewer assessed all retrieved full texts for eligibility, and a second reviewer verified the decisions. The process is shown in the PRISMA 2020 flow diagram in Figure 1. Full-text screening retained 59 reports from the main search and 4 from the supplementary search, giving a final set of 63 included studies.

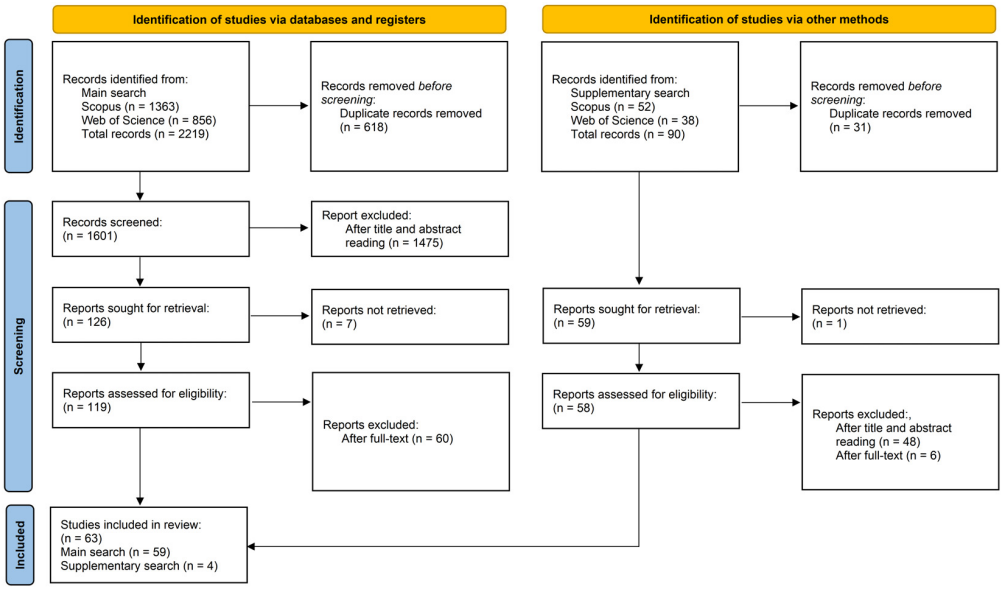


Figure 1. PRISMA flow diagram adapted from the official PRISMA 2020 template [25] under the Creative Commons Attribution 4.0 International license.

2.3. Data Extraction

For each included study, we extracted bibliographic information, country, study design, sample size, participant group, discipline, randomization, and control condition. We also recorded the biophilic elements, exposure modality, sensory channel, and dose. Outcome coding covered perceptual or psychological measures, physiological indicators, cognitive

measures or tasks, effect direction across four outcome domains, a narrative summary of findings, and methodological quality appraisal. The complete coded dataset and coding rules are provided in Supplementary Material S3. Data extraction was performed by one researcher and verified by a second reviewer. Discrepancies were resolved by discussion.

2.4. Evidence Synthesis

Evidence was synthesized using a convergent integrated approach [22,24]. This approach transforms qualitative findings and quantitative results into a common analytical format for synthesis. Findings were organized into four outcome domains, including perceptual, psychological, physiological, and cognitive outcomes. Quantitative outcome directionality was coded as positive, mixed, null, or negative, and was extracted alongside qualitative interpretive themes. Both forms of evidence therefore informed the same analytical categories. No meta-analysis was undertaken. Statistical pooling was precluded by heterogeneity in outcome metrics, including self-report scales, physiological signals, cognitive tasks, and qualitative outcomes. Exposure protocols were also heterogeneous, ranging from 30 s image presentations to 7-day longitudinal designs. A convergent integrated approach was therefore appropriate because the literature was methodologically diverse and conceptually fragmented.

Perceptual and psychological outcomes were distinguished by the referent of each measure, rather than by whether the instrument used self-report. Perceptual outcomes comprised evaluations directed at the environment, including naturalness, comfort, preference, environmental quality, and perceived restorativeness. Psychological outcomes comprised the participant's internal state, including affect, mood, stress, anxiety, mental fatigue, and experienced restoration. Perceived restoration can span both environmental appraisal and psychological response. We therefore coded it according to the construct assessed in each study. Measures of restorative qualities or potential attributed to a setting were coded as perceptual. Measures of restorative change experienced by the participant were coded as psychological. Studies assessing both referents contributed separately to both domains. This operational distinction does not imply that perceived restoration is non-psychological.

The extracted evidence was organized using a higher education evidence mapping framework comprising seven analytical dimensions, including biophilic elements, exposure modality, spatial context, situatedness, study paradigm, outcome domain, and response direction. Together, these dimensions described which biophilic elements were studied, how and where they were encountered, how the exposure related to task demand, and what responses were reported. Within this framework, biophilic elements were classified according to where and how they operated within higher education interiors. Interior design elements included localized objects, surfaces, and representations at the interface between occupants and the interior environment. Ambient conditions comprised distributed sensory and physical conditions. Spatial attributes arose from spatial geometry and organization. A fourth category captured configurations spanning two or more levels without a single dominant level. The four categories and their classification bases are defined in Table 3.

The category assigned to each study followed the biophilic elements that were manipulated or evaluated. Studies combining multiple elements within one architectural level remained in the corresponding single-level category. Studies were classified as cross-level configurations only when the evaluated design combined elements from two or more levels and could not be represented adequately by one level alone.

After the biophilic element category was assigned, the exposure and context dimensions described how and where each element was studied. Exposure modality was coded as a physical environment, virtual reality, two-dimensional media, audio, or no assigned

exposure. Spatial context was coded using higher education setting typologies, including classrooms, libraries, dormitories, informal and public learning spaces, academic offices, and circulation spaces. Situatedness distinguished studies that took place in or explicitly modeled identifiable higher education settings from studies using decontextualized laboratory, generic indoor, or virtual environments that did not represent a specific higher education space.

Table 3. Architectural classification of biophilic elements in higher education interiors.

Dimension	Classification Basis	Elements Represented in the Included Studies
Interior design elements	Localized objects, surfaces, or representations operating at the interface between occupants and the interior environment	Indoor plants, green walls, nature imagery, natural materials, natural color, and biomorphic or fractal representations
Ambient conditions	Distributed sensory or physical conditions experienced within the interior environment	Daylight, natural sounds, plant scents, airflow, and thermal conditions
Spatial attributes	Attributes arising from spatial geometry, openings, enclosure, and organization	Window views, ceiling height, spatial scale, spatial form, and openness or enclosure
Cross-level configurations	Configurations combining elements from two or more of the preceding architectural levels without a single dominant level	Combinations of interior design elements, ambient conditions, and spatial attributes

Study paradigms were classified by the temporal relationship between biophilic exposure and task demand. A restorative paradigm treated biophilic exposure as a post-stressor or between-task recovery condition. A protective paradigm kept the biophilic condition present while participants performed a resource-consuming cognitive task. This classification was introduced during synthesis and was not used as an eligibility criterion.

To assess whether the overall outcome-direction pattern varied between the two dominant experimental exposure modalities, we conducted an exploratory post hoc study-level comparison of immersive VR and real physical environments. For each outcome domain, we calculated direction counts and positive proportions, using the number of studies measuring that domain as the denominator. The smaller two-dimensional media and audio groups, along with studies without an assigned exposure, were excluded from this comparison. Because designs, settings, interventions, and outcome instruments differed between groups, the comparison was descriptive and did not include inferential testing.

2.5. Quality Appraisal

The methodological quality of included studies was appraised using the 2018 version of the Mixed Methods Appraisal Tool (MMAT) [23]. MMAT was selected because it provides design-specific criteria for the study types represented in the included studies. These types were qualitative studies, randomized controlled trials (RCT), non-randomized quantitative studies, descriptive quantitative studies, and mixed-methods studies. One researcher appraised each study against the relevant five MMAT criteria. A second reviewer verified the appraisal, and disagreements were resolved by discussion.

In line with the MMAT developers' guidance [23], no study was excluded because of a low quality rating. The appraisal was used to contextualize confidence in the evidence rather than to apply a pass-or-fail threshold.

Because MMAT discourages a single aggregate score, sensitivity restrictions were defined from item-level judgments rather than a summary rating [23]. The first exploratory post hoc analysis excluded studies with at least two definite "No" judgments across the five design-specific criteria. The second retained studies with "Yes" judgments on at least three of the five criteria. For each restricted set, we calculated the proportion of positive findings among studies assessing each outcome domain and compared the resulting pattern with

that of the full corpus. These restrictions were used only to assess robustness and did not alter study eligibility or constitute a formal certainty-of-evidence rating.

3. Results

A complete tabulation of the 63 included studies, covering first author, year, country, setting, biophilic elements, exposure modality, sample size, measurement approach, and outcome direction, is provided in Supplementary Material S3.

3.1. Bibliometric Overview

3.1.1. Temporal Trajectory

The 63 included studies covered a publication period between 2004 and 2026. Annual output was low and intermittent before 2018, increased modestly from 2021, and accelerated from 2024. Studies published in the three most recent years accounted for 65% of the included studies (Figure 2). The lower count at the end of the series reflects the search window rather than a true decline. The last database search was conducted on 18 May 2026, so the 2026 count covers less than five months. Even within this short window, 11 studies had already been indexed, exceeding the full-year total for any year before 2024.

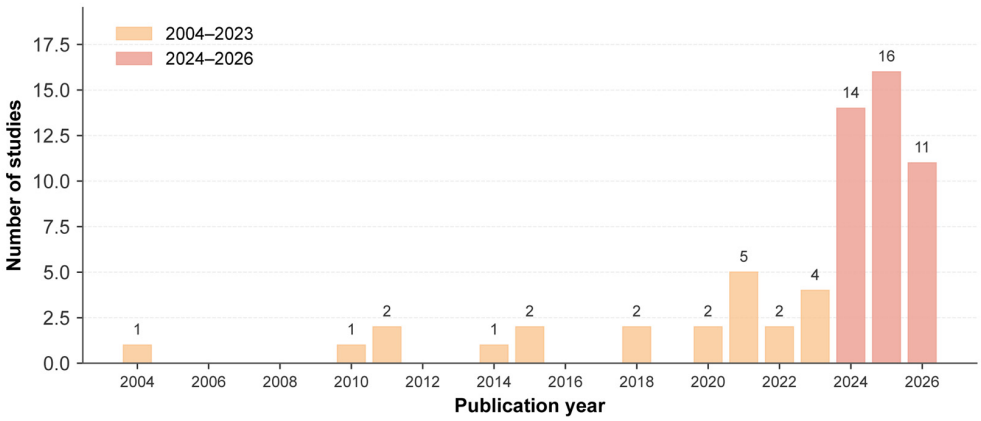


Figure 2. Annual distribution of publications included in the review.

3.1.2. Geographic and Journal Distribution

The included studies were conducted in 18 countries, and two additional studies were coded as multi-country collaborations. East Asia accounted for the largest regional share. China, Korea, and Japan together contributed 55.6% of the included studies, with China alone contributing 36.5%. Outside East Asia, the United States was the largest contributor, followed by the United Kingdom and Italy. The 63 studies appeared in 44 publication sources. *Building and Environment* was the most frequent outlet, followed by *Scientific Reports* and *Buildings* (Figure 3).

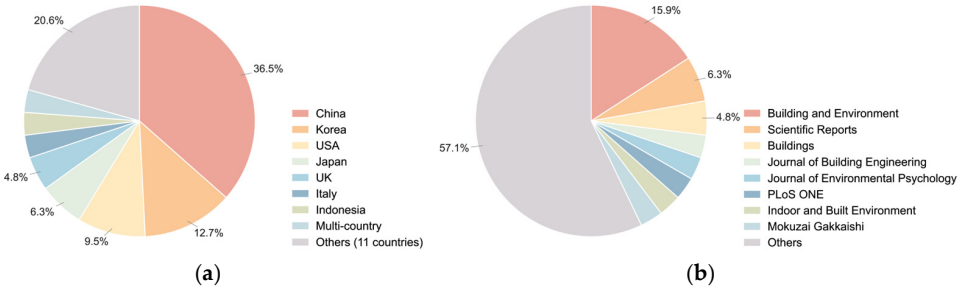


Figure 3. Geographic and journal distribution of included studies. (**a**) Country distribution; (**b**) Journal distribution.

3.1.3. Study Designs and Samples

Most studies used experimental designs, rather than surveys or qualitative methods. Within-subjects crossover designs were most common, with 31 studies in total. Ten studies explicitly balanced condition order through Latin-square allocation, reversed sequences, rotations, or equivalent procedures that assigned both exposure sequences. Sixteen randomized or otherwise varied exposure order without demonstrating balanced allocation. One study described its design as counterbalanced but did not report the implemented sequence, while four provided no usable exposure-order procedure. Washout intervals and controls for task-related fatigue were reported inconsistently across this subgroup. The remaining studies comprised 12 randomized controlled trials, seven quasi-experimental designs, five cross-sectional surveys, four mixed-methods studies, three between-subjects controlled studies, and one qualitative study (Figure 4). Sample sizes varied widely across designs, with most experimental studies enrolling groups of a few dozen participants. The largest samples came from a small number of cross-sectional surveys. The participant pool consisted mainly of undergraduates or mixed student samples. Only one study focused on graduate students, and faculty or staff appeared in only a small number of studies.

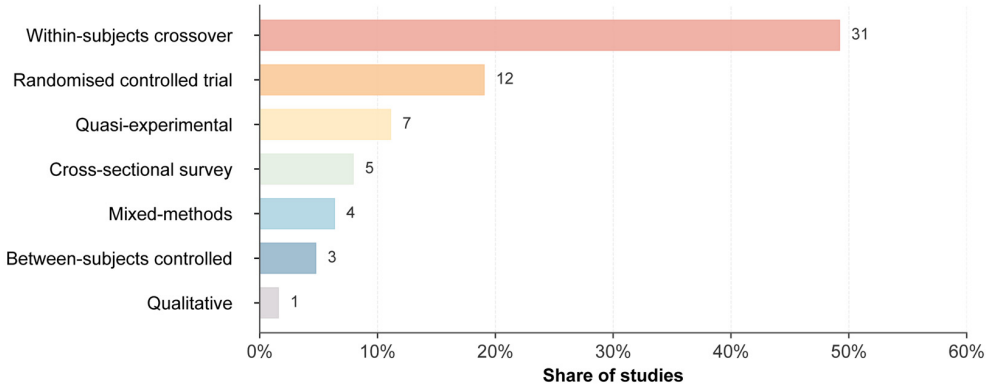


Figure 4. Distribution of study designs.

3.2. Characteristics of Included Studies

3.2.1. Biophilic Elements and Exposure Modalities

Across the four biophilic element categories, interior design elements formed the largest class, accounting for 23 studies. Cross-level configurations followed with 19 studies. Among these, 11 integrated all three architectural levels, four combined interior design elements with spatial attributes, three combined interior design elements with ambient conditions, and one combined ambient conditions with spatial attributes. Spatial attributes accounted for 11 studies and ambient conditions for 10. When charted by publication year, the evidence base was concentrated in interior design elements and cross-level configurations, with fewer studies of ambient conditions and spatial attributes (Figure 5).

Exposure modality was also unevenly distributed, with 54 of the 63 studies administering an experimental biophilic exposure. The remaining nine were observational and assessed students' existing surroundings without manipulating a biophilic condition. Among the 54 experimental studies, real physical environments were the most common medium, with 22 studies across purpose-built and in situ settings. Fully immersive virtual reality (VR) followed closely, with 21 studies, while seven used two-dimensional images or video and four used audio recordings of natural soundscapes. All but one of the 21 VR studies appeared in 2021 or later, peaking in 2024 (Figure 6).

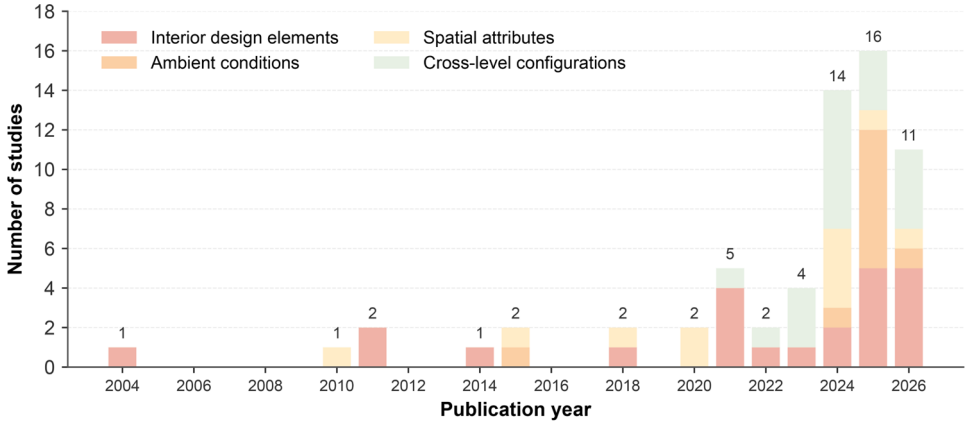


Figure 5. Distribution of biophilic element categories by publication year.

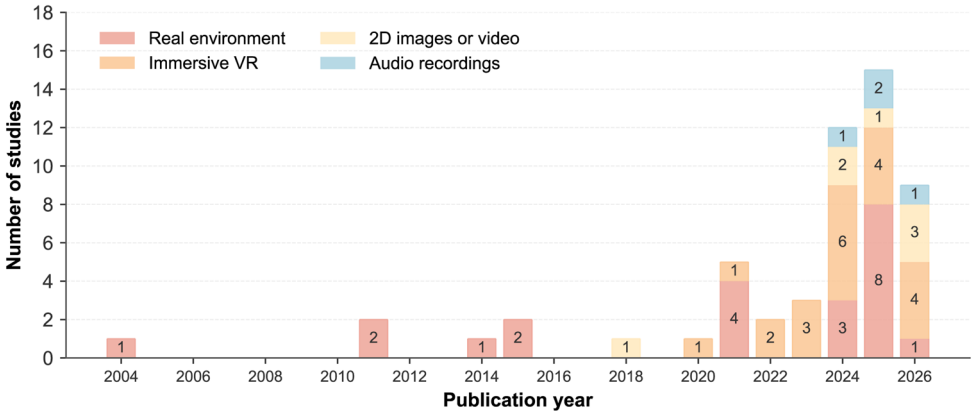


Figure 6. Exposure modality by publication year.

Among the 54 experimental studies, visual exposure predominated. Thirty-four were purely visual and 14 combined two or more channels in multisensory designs. Only four studies were purely auditory, and two were purely olfactory. No study used touch in isolation, although tactile cues appeared as one component of multisensory designs (Figure 7). Multisensory and nonvisual designs remained a minority, but they appeared almost entirely from 2021 onward.

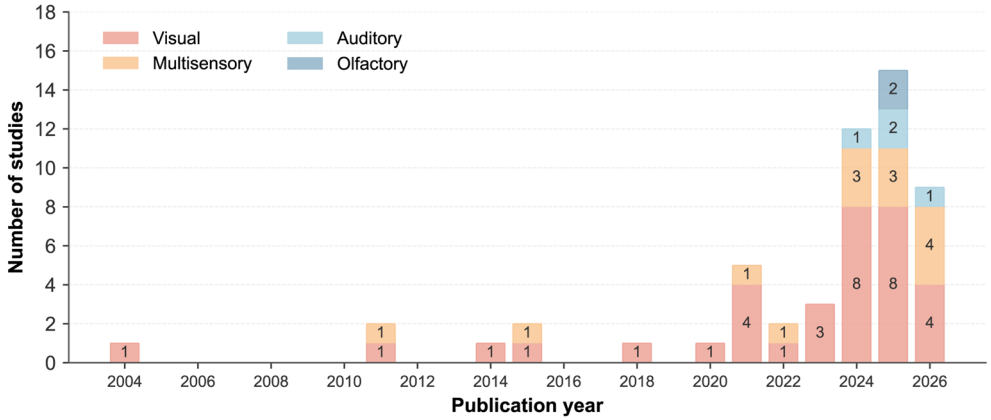


Figure 7. Sensory channel by publication year.

3.2.2. Settings and Situatedness

By spatial setting, the studies fell into situated and decontextualized groups (Figure 8). Situated studies either took place in identifiable spaces within higher education campuses or buildings or explicitly modeled such spaces. Decontextualized studies used laboratories or

generic indoor settings that could belong to almost any building, although their participants were university students. Overall, 62% of studies were situated in recognizable campus spaces. Classrooms and lecture rooms were the largest category, with 17 studies. Public or shared study spaces and academic or research offices each accounted for four studies. Libraries and indoor lounges or breakout spaces each accounted for three. Dormitories, design studios, and multi-setting studies each accounted for two. Study rooms and corridor and stairwell settings were each represented by only one included study. The remaining 38% of studies were decontextualized, comprising 22 simulated indoor laboratory studies that reproduced a generic room and two studies that assessed campus interiors without identifying a specific setting. These 24 studies were retained as population-response evidence because they assessed university students under controlled indoor biophilic exposure, but they were not assigned to a higher education spatial typology. Virtual environments appeared in both groups, with 21 studies using fully immersive virtual reality, most often to reproduce a classroom, library, or lounge.

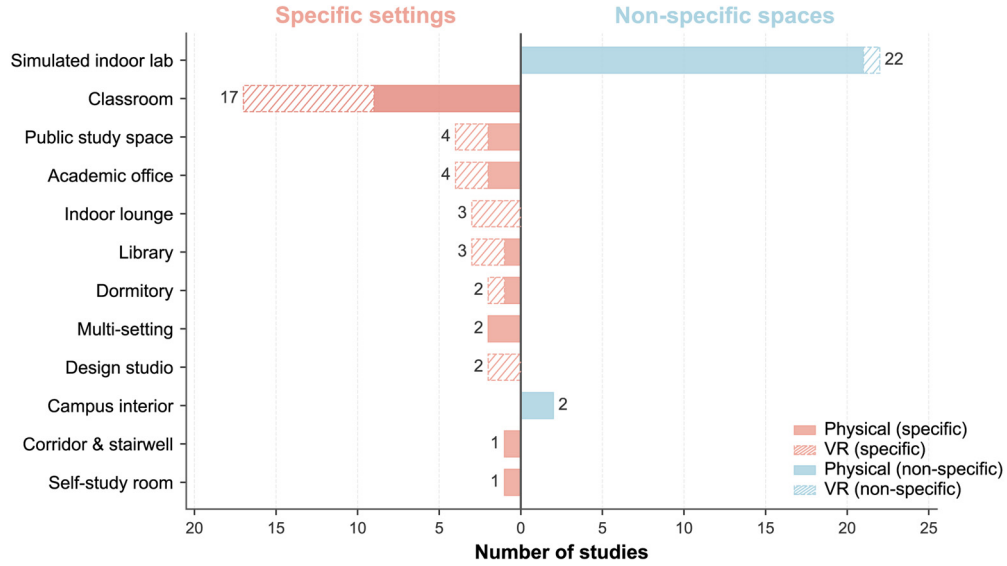


Figure 8. Included studies by higher education setting and situatedness.

The classroom subset comprised eight in situ studies, one image-based study using standardized classroom photographs, and eight immersive VR reconstructions. The in situ studies used diverse designs, from field surveys to randomized trials. They generally used larger or more naturalistic samples, authentic exposures, and installable elements rather than finely controlled visual parameters. Window views were the most studied element, appearing in four classroom studies. These comprised Chang's windowed examination room [27], Benfield et al.'s and Zhang et al.'s view comparisons [28,29], and Wang's image-based campus window survey [30]. Indoor plants or green walls appeared in two studies, Purwaningsih et al. and Li et al. [31,32]. Two-dimensional nature imagery appeared in two studies, Lebasi et al. and Jia et al. [33,34], and natural daylight in 1, Wang et al. [35]. Their outcomes mainly comprised self-report measures and academic outcomes, including mood and stress inventories, course evaluations, examination scores, course grades, and creativity tasks. Seasonal and daylight-related controls varied across the eight in situ studies [27–29,31–35]. Six restricted data collection to a stated season or date range, one generally kept curtains closed, and one reported no corresponding control; none repeated the same comparison across seasons.

The VR classroom studies were small within-subjects experiments with brief, single-session exposures. They manipulated rendered parameters rather than installed elements, and the manipulated features varied across studies. Window view content appeared

in two studies [36,37]. Wall color, spatial scale, and a virtual green wall appeared in 1 study each [38–40]. The remaining three studies combined several dimensions at once [41–43]. VR classroom studies relied more heavily on continuous physiological instruments, including electroencephalography (EEG), eye-tracking, electrodermal activity, and heart rate variability (HRV). These measures were paired with standardized cognitive tasks, such as the Stroop test, digit span tasks, and divergent thinking batteries.

Across 22 physical environment studies and 28 in-person mediated-exposure experiments, none reported heating, ventilation, and air conditioning (HVAC) air-exchange rates. Twelve studies in each group instead documented ventilation, air-conditioning, airflow, carbon dioxide, or related air-quality conditions. Reported temperatures ranged from 20 to 32.7 °C, with 24–25 °C being the most common range used in controlled settings [27,31]. Relative humidity ranged from 37.9% to 70%, with 50–60% being the most common controlled range [40,44]. Background air speeds ranged from 0.010 to less than 0.5 m/s, with 0.05 m/s being the most frequently used setting [40,45]. Reported carbon dioxide values ranged from approximately 350 to 580 ppm, while one study specified a threshold below 800 ppm [27,46]. Background sound was quantified in three physical studies and three mediated experiments, with qualitative control in five additional studies in each group. Reported levels ranged from 11 to 50 dBA, and four of the six numerical reports were no higher than 40 dBA [27,47]. Room lighting was quantified in nine physical studies and four mediated experiments. Two additional physical studies and four mediated experiments controlled it qualitatively. Fixed artificial-light settings ranged from 300 to 750 lx, with 300 lx at 4000 K being the most frequently repeated combination [45,48]. Measured daylight ranged from 118 to 8902 lx [49]. No study used a standardized daylight-glare index. One VR study instead reported unified glare rating (UGR) values of 15, above 26, and 16 under three simulated electric-lighting conditions [40].

3.2.3. Measurement Instruments

The coding scheme classified outcomes into four domains, perceptual, psychological, physiological, and cognitive. Figure 9 summarizes the instruments used in each of these domains. Perceptual evaluation, meaning how students perceived and judged a space, was the most frequently measured outcome. No standardized perceptual instrument was used across the included studies as a whole. Most studies used self-designed scales, including Likert ratings, semantic differential adjective pairs, visual analogue scores, and single-item votes. These measures captured perceived comfort, naturalness, atmosphere, spaciousness, brightness, environmental quality, preference, and satisfaction. Environment-directed measures of perceived restorativeness, including the Perceived Restorativeness Scale, were the only partly standardized instruments in the perceptual domain. Restoration measures directed at the participant's experienced state were classified as psychological. Studies that assessed both environmental appraisal and internal state contributed separately to both domains.

Psychological state was the most frequently assessed of the three domains with established instruments. Unlike environmental appraisal, this domain captured changes in the participant's internal state and relied mainly on validated measures of mood, stress, anxiety, mental fatigue, and experienced restoration. The Profile of Mood States (POMS) appeared in 10 included studies. The Positive and Negative Affect Schedule (PANAS) and the Perceived Stress Scale (PSS) appeared in six studies each. The State–Trait Anxiety Inventory (STAI), Depression Anxiety Stress Scales (DASS), and pleasure–arousal–dominance (PAD) affect model were used less often.

Physiological measurements appeared in 31 studies and were concentrated on a small set of instruments. Electroencephalography (EEG) was the most common instru-

ment and appeared in 20 studies. Cardiovascular indices, including heart rate, heart rate variability, and blood pressure, appeared in 14. Electrodermal activity appeared in five, eye-tracking in four, skin temperature and salivary measures in three, and functional near-infrared spectroscopy (fNIRS) in three. The EEG and fNIRS studies were concentrated from 2024 onward.

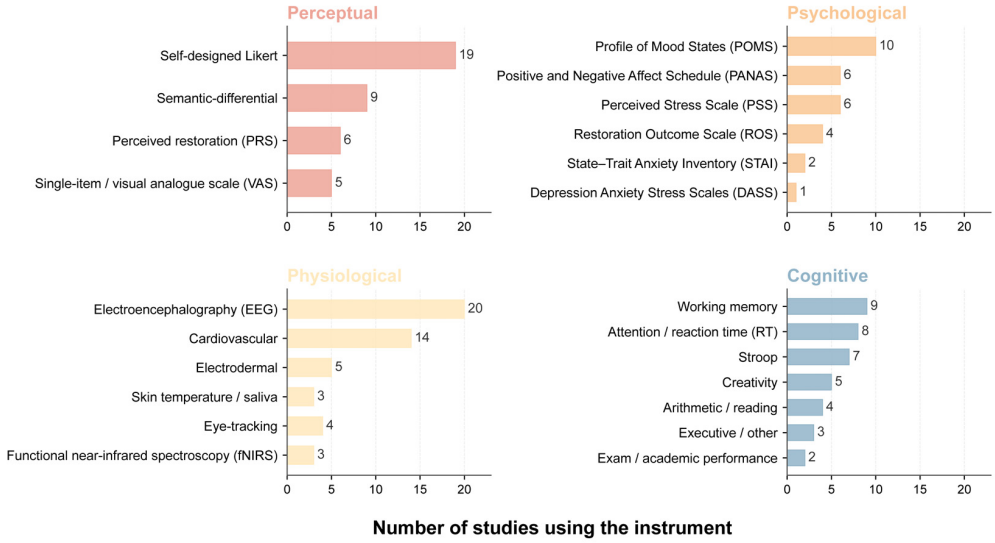


Figure 9. Outcome measurement instruments across domains.

Cognitive performance was measured in 24 studies, the lowest count among the four domains. Most studies in this domain used behavioral task batteries for assessment. Working memory tasks, such as n-back and operation span task (OSPAN), appeared in nine studies, attention and reaction time tasks in eight, and the Stroop task in seven. Creativity tasks appeared in five, arithmetic and reading tasks in four, and executive function tasks in three. Two studies measured real academic performance through examination scores or course grades.

3.3. Methodological Quality

All 63 studies passed the MMAT screening questions, and none was excluded on the basis of quality appraisal. The 41 quantitative non-randomized studies, which formed the largest design group, met a median of four of five criteria. The 12 randomized controlled trials met a median of 2.5 criteria. The five quantitative descriptive studies met three, the four mixed-methods studies met 2.5, and the single qualitative study met all five criteria.

In the randomized controlled trials, unmet criteria mainly reflected incomplete reporting rather than clear negative judgments. Most unmet items were coded as “Can’t tell”, most often because the randomization procedure was not described in sufficient detail. Mixed-methods studies were weakest on the coherence of integration, whereas quantitative descriptive studies were most limited by sample representativeness and nonresponse.

A full per-study appraisal is provided in Figure 10. The appraisal informed interpretation of the evidential strength of the synthesized findings but was not used to exclude studies or formally weight the synthesis.

Using the item-level MMAT judgements, we conducted two sensitivity analyses. The first excluded studies with at least two definite “No” judgements, removing four studies and leaving 59. Positive findings occurred in 30 of 43 perceptual studies, 20 of 38 psychological studies, 11 of 30 physiological studies, and eight of 24 cognitive studies. These values corresponded to 69.8%, 52.6%, 36.7%, and 33.3%, respectively. The stricter restriction retained studies with “Yes” judgements on at least three of the five criteria, leaving 52 of the 63 included studies. Positive findings occurred in 26 of 37 perceptual studies,

17 of 33 psychological studies, eight of 27 physiological studies, and eight of 23 cognitive studies. These values corresponded to 70.3%, 51.5%, 29.6%, and 34.8%, respectively. Both restrictions preserved perceptual and psychological outcomes as the two most consistently positive domains. The stricter restriction reversed the relative order of physiological and cognitive positive proportions.

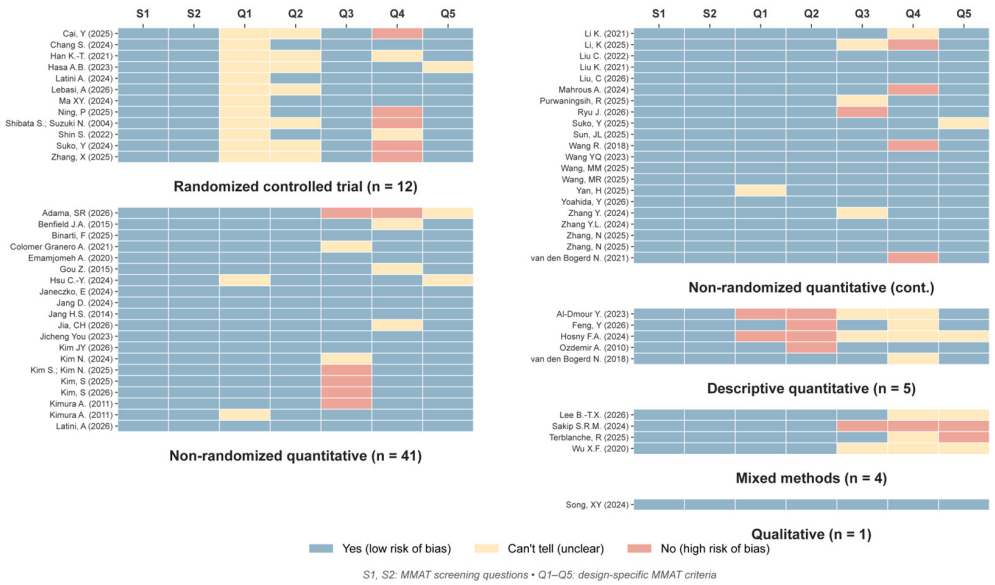


Figure 10. MMAT quality appraisal heatmap for the 63 included studies [27–89].

3.4. Outcome Evidence for Biophilic Design

Outcome evidence was organized by biophilic element category, with findings for specific elements reported across perceptual, psychological, physiological, and cognitive domains. The direction of each finding was classified as positive, mixed, null, or negative. Figure 11 provides an overview of these element–outcome–direction relationships across the included studies.

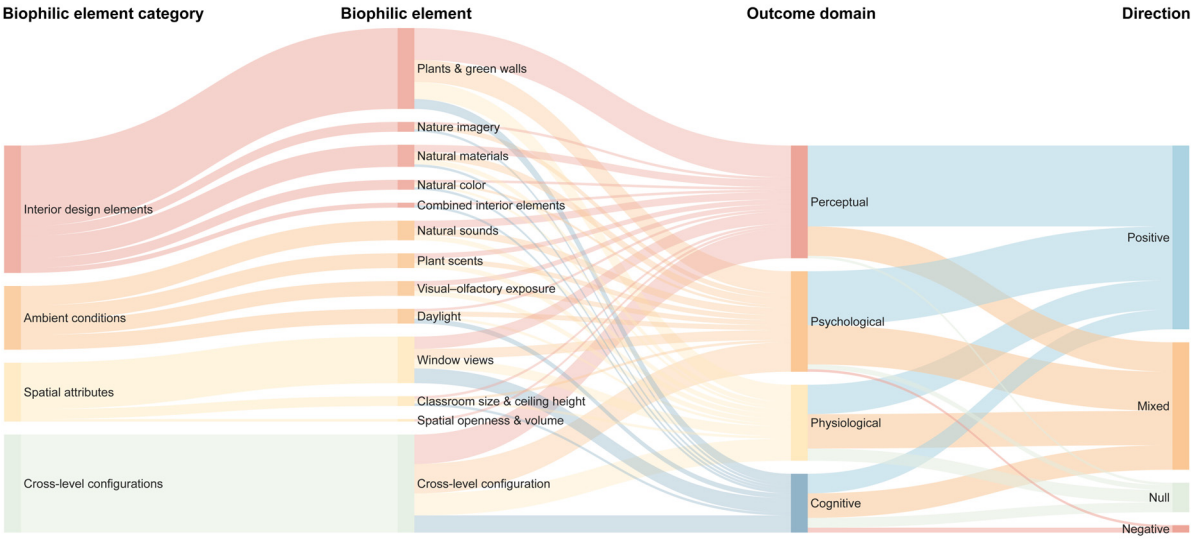


Figure 11. Evidence flows from biophilic elements to outcome domains and directions.

3.4.1. Interior Design Elements

Interior design elements accounted for 23 studies. Fourteen examined indoor plants or green walls as the primary element, three examined two-dimensional nature imagery, three

examined natural materials, and 1 examined natural color. The remaining two combined two or more interior design elements.

Indoor plants and green walls were the most studied input in this class, with 14 studies. The interventions fell into three groups. The first compared greenery with a bare or alternative condition. Examples included Yan et al.'s plant watering task [50], Shibata's plant versus magazine comparison [51], and the study room and student well-being programs by van den Bogerd et al. and Adama et al. [52,53]. The second group varied green quantity or visibility. Ma et al. tested 0%, 5%, and 15% Green View Index (GVI) conditions, with the 5% and 15% green walls centered in the primary visual field of seated participants [54]. The study reported gains in arithmetic speed and working memory. Li et al. increased potted plants from 50 to 101 and found no additional benefit [32]. Han et al. held visible greenery constant and found no effect of plant number or distance on perception [55]. The third group varied configuration and appearance. Lee et al. found scattered planting and real greenery preferred over artificial greenery [56]. Li et al. found large-leaved plants more restorative than small-leaved plants [57]. Three studies compared foliage and flower color and found preferences that differed by cultural background [44,46,48]. Hsu found curvilinear and geometric green walls equally restorative, with no effect of form [58]. Latini et al. found that supplementary grow lights in a VR green wall increased perceived glare without altering physiological response [40]. Across the 14 studies, perceptual evidence was positive in seven of the 13 measuring studies, mixed in five, and null in one. Psychological evidence was positive in two of nine, mixed in five, and null in two. Physiological evidence was positive in four of seven, mixed in two, and null in one. Cognitive evidence was positive in one of four and mixed in three.

Two-dimensional nature imagery, including photographs, posters, and digital images, was examined in three studies. Perceptual evidence was positive in the one study that measured it. Psychological evidence was positive in one of two studies and mixed in one, while cognitive evidence was positive in the one study that measured it. None of the three studies measured physiological outcomes. Ning found that viewing digital nature images increased positive affect, nature relatedness, and environmental preference in university students relative to city and object images [59]. Lebasi et al. compared live plants, 2D plant photographs, and a bare classroom for divergent thinking among architecture students [33]. Both nature conditions outperformed the control. The two nature conditions differed by task component, with live plants supporting fluency and originality and photographs supporting elaboration. Jia et al. tested green walls made from plant posters for 4 weeks in real classrooms with 311 students [34]. A single wall of posters reduced anxiety, depression, perceived stress, and daytime sleepiness, and improved self-reported memory. Coverage of the full wall weakened or reversed these gains, with higher stress and lower positive affect at 2 weeks. The authors attributed this inverse dose effect to a sense of enclosure.

The three wood studies all manipulated wood coverage ratio. They reported positive perceptual or psychological responses, but only one measured cognition. Kimura et al.'s two within-subjects model room studies stepped coverage across four rooms, calculating ratios from interior finish surfaces except the entrance wall, rather than floor area or wall coverage alone [60,61]. In the cedar wood study, Kimura et al. used a two-digit arithmetic task [60]. Perceived comfort peaked at 45.5% coverage, and rated atmosphere rose steadily up to the 97.7% room. Arithmetic speed and error rate did not differ across rooms. In the hiba wood study, Kimura et al. added wood scent and did not measure cognition [61]. Perceived naturalness and relief of POMS fatigue were strongest in the room with the highest coverage. Blood pressure and salivary amylase fell most in the rooms with intermediate coverage. Li et al. extended the dose test to a VR informal learning space [62]. The study varied wood ratio from 0 to 100% in five steps, together with the form of wood

application. Restorative quality was highest at 60 to 80% wood and declined above 80%. Perceived naturalness and preference mediated this effect. Perceptual and psychological responses were positive, but no behavioral measure of cognition was recorded.

Natural color was examined as the primary factor in one study. Liu et al. compared five VR classroom wall colors [38]. Cool colors, including blue and green, maximized pleasure and relaxation. Warm colors, including yellow and red, maximized attention and objective performance on Stroop, calculation, and reading tasks. The white wall commonly used in contemporary classrooms had the lowest scores across the measured dimensions. No single color performed best across outcomes.

Two studies combined multiple interior design elements without extending into ambient conditions or spatial attributes. Purwaningsih et al. added potted plants and a modular green wall to a renovated classroom [31]. Compared with the same classroom without plants, the planted condition shortened simple and choice reaction times by 42.9% and 25.5%, respectively. In the retained indoor comparisons, van den Bogerd et al. found that nature posters and real greenery, including green walls and potted plants, were preferred to standard designs [63]. Nature posters and green walls also outperformed a colorful non-nature poster.

3.4.2. Ambient Conditions

Ambient conditions accounted for 10 studies. These comprised natural sounds in four studies, plant scents in two, visual–olfactory comparisons centered on plant scent in two, and daylight in two.

Natural sounds, mostly birdsong and flowing water recordings, were isolated in four studies. These studies varied sound source, sound level, and exposure duration. Liu et al. found that natural sound, set against traffic noise, co-activated alpha and beta rhythms and shifted neural dynamics toward a stable critical state [64]. Zhang et al. tested several sound pressure levels and found an inverted-U pattern, with responses peaking near 50 dBA [47]. Suko et al. showed that 10 min of daily listening produced restorative gains that accumulated and carried over across seven days [65]. Suko et al. found that daily natural sound outperformed silence and matched music for students who did not habitually use music to self-regulate [66]. Perceptual evidence was positive in two of three measuring studies and mixed in one. Psychological evidence was positive in two of three and mixed in one. Physiological evidence was positive in one of two and mixed in one. None of the four studies measured cognition.

Plant scents were isolated in two studies. Both compared several scents and identified individual preference as a moderator of benefit. Zhang et al. compared spearmint, rose, and lavender against a control and found spearmint most effective at rebalancing EEG dynamics, with gender-specific effects [45]. Sun et al., with 1013 participants, screened 29 essential oils [67]. Nine oils improved mood; sweet orange performed best; and the size of the benefit tracked how much students liked the scent. Both studies reported positive psychological and perceptual findings. Physiological findings were positive in Zhang et al. and mixed in Sun et al. [45,67]. Neither study measured cognition.

Two studies compared olfactory-only exposure with combined visual–olfactory contact with living plants. Cai et al.'s gardenia study and Zhang et al.'s spearmint study both found positive perceptual, psychological, and physiological outcomes, while adding the visual channel produced only modest strengthening [68,69]. Neither study measured cognition.

Daylight was isolated in two studies, and both reported boundary conditions rather than uniformly positive effects. Wang et al. found that daylight produced more efficient neurovisual processing than light-emitting diode (LED) lighting under a low-cognitive-load two-back task [35]. Under a high-cognitive-load Stroop task, performance decreased under

daylight above 900 lx, while LED lighting provided greater stability. Their experiment used north-to-south daylighting and blackout curtains but included neither dynamic shading nor direct solar-radiation monitoring. Gou and Lau found larger declines in positive affect under natural than artificial lighting [49]. Cognitive performance in their study was negatively correlated with light intensity and local thermal asymmetry. Although the window orientation was not stated, the study provided a sun-path analysis, adjusted blinds before each session, and logged illuminance and thermal variables every 10s. No dynamic shading was reported.

3.4.3. Spatial Attributes

Spatial attributes accounted for 11 studies. These comprised window views in nine studies, classroom size and ceiling height in one, and spatial openness and volume in one.

The window view studies compared window presence, view content, view openness, or physical and virtual exposure. Chang directly compared windowed and windowless examination rooms [27]. Benfield et al. compared otherwise similar classrooms with nature and concrete wall views [28], while Wang compared landscape characteristics and alternative classroom view conditions [30]. Binarti et al. found a dense forest view the most neurologically restorative and an urban view cognitively overstimulating, with window orientation also affecting outcomes [36]. Zhang et al. found a natural tree view superior to a building view on brainwaves, mood, and a learning task [29]. Jang et al. found daytime natural views best for valence and perceived spaciousness, while night and city views were least liked [37]. Two studies separated openness from naturalness. Ozdemir and Feng et al. both found openness to be the stronger driver of perceived spaciousness and satisfaction [70,71]. Emamjomeh et al. found that an immersive VR window reproduced the effect of a real window on negative affect, but not its effects on positive affect, memory, or stress [72]. Perceptual evidence was positive in three of five measuring studies and mixed in two. Psychological evidence was positive in one of four and mixed in three. Physiological evidence was positive in one of four, mixed in two, and null in one. Cognitive outcomes were measured in six studies and split into two positive, two mixed, and two null findings. The null group included Chang's study conducted during a real examination, which found no effect on exam score and reported statistical power of 0.19 [27].

Spatial scale was examined in one study. Zhang et al. crossed classroom size and ceiling height in a 2×2 within-subjects VR experiment [39]. Subjective pleasure, relaxation, and focus were highest in the large high-ceiling room. Objective scores on Stroop, calculation, and reading tasks were highest in the small low-ceiling room, 20.1% above the small high-ceiling room. Ceiling height, rather than classroom size alone, drove the cognitive effect. HRV and EEG-β rose in both the large high-ceiling and the small low-ceiling rooms, giving mixed physiological results across spatial conditions.

Spatial openness and volume were examined in one field study. Wu et al. used spatial openness modeling, timed behavior mapping, and student interviews in a multistory teaching atrium [73]. Greater openness was associated with waiting, observation, and see-and-be-seen activities, while spaces with more varied openness supported social gathering and group study. The lowest single-story volume was used more for individual study.

3.4.4. Cross-Level Configurations

Cross-level configurations accounted for 19 studies. Eleven integrated interior design elements, ambient conditions, and spatial attributes. Four combined interior design elements with spatial attributes, three combined interior design elements with ambient conditions, and one combined ambient conditions with spatial attributes.

Among the 11 studies integrating all three architectural levels, perceptual findings were positive in all six studies that measured this domain. Psychological findings were positive in five of six and mixed in one. Terblanche and Khumalo, Al-Dmour et al., Mahrous, Sakip et al., and You et al. reported favorable subjective responses in study areas, offices, design studios, libraries, and classrooms [41,74–77]. Ryu et al. found that visual nature paired with scent best supported subjective stress recovery, whereas visual nature paired with sound did not deepen relaxation because sound sustained cognitive arousal [78]. Hosny mapped preferences for broad biophilic patterns by learning style rather than coding a positive or negative outcome direction [79].

Physiological findings among these 11 studies were positive in three of five and null in two. Hasa et al. and Sakip et al. reported lower blood pressure or heart rate in VR dormitory and library settings [77,80]. Kim et al. reported lower electrodermal arousal and higher prefrontal activation in biophilic corridors, with weaker effects in stairwells [81]. Cognitive or neurocognitive findings were positive in three of five studies, mixed in one, and null in one. Latini et al. reported positive effects on three executive tasks, with the acoustic factor showing larger effects than the visual factor [82]. The largest acoustic contrasts occurred between traffic and natural or office sounds, whereas differences across the visual conditions were smaller. Natural and traffic sounds were both presented at 54 dB (A), and the authors related their contrasting cognitive effects to sound type and semantic meaning rather than sound level. Mahrous reported improved executive task performance in a VR design studio [76]. Colomer-Granero et al. identified a VR classroom configuration that performed best for memory and attention [43]. You et al. found no significant change in attention or creativity [41], while Kim et al. reported mixed fNIRS activation patterns [81].

Four studies combined interior design elements with spatial attributes. Perceptual findings were positive in two of the three studies measuring this domain and mixed in one. Psychological findings were positive in both measuring studies, while physiological findings were mixed in all three measuring studies. Song et al. identified all four restorative themes in library interviews and found a preference for back-to-wall, observation-oriented seating that provided prospect and refuge [83]. Kim and Kim identified optimal conditions for wall color and ceiling height, with blue supporting comfort and relaxation and 4–5 m ceilings balancing neural and self-reported responses [84]. Kim found that gaze was divided between a green wall and wood flooring, so visual attention did not simply accumulate across elements [42]. Kim reported positive perceptual and psychological findings and mixed EEG responses in a VR library, but the plant, green wall, wood, cool color, and irregular ceiling condition reduced divergent thinking fluency and flexibility relative to a minimalist control [85]. This was the negative cognitive finding in this subgroup and one of the two negative cognitive findings across the included studies.

Three studies combined interior design elements with ambient conditions. Perceptual findings were positive in both studies that measured this domain. Psychological findings were positive in two studies and mixed in one, while physiological and cognitive findings were mixed in the single study measuring each domain. Janeczko et al. found that 20 min of 2D forest video paired with natural sound improved psychological restoration and subjective vitality and reduced anxiety, tension, and anger [86]. Reading a forest textbook for the same duration produced no measurable change. Yoshida et al. paired greenery, birdsong, and simulated airflow and found that participants remained comfortable at 28–29 °C, above the thermal comfort standard [87]. Visual naturalness outweighed temperature as the driver of comfort. Kim compared visual, visual–auditory, and visual–olfactory conditions [88]. Visual nature paired with scent best supported subjective stress recovery, whereas visual nature paired with sound produced the most consistent improvements in cognition and frontal EEG responses.

One study combined ambient conditions with spatial attributes. Shin et al. found that adding natural sound and scent to an open window view did not outperform the visual-only window, although both conditions outperformed a windowless room on perceptual and psychological outcomes [89].

3.5. Three Asymmetries in the Evidence Base

3.5.1. Effect Chain Asymmetry

The most pervasive asymmetry concerns the outcome domains through which biophilic effects were reported. Figure 12 shows, for each domain, how many of the included studies measured that domain and how the measured findings were distributed across positive, mixed, null, and negative directions. Perceptual evaluation was measured in 46 of the 63 included studies, psychological state in 41, physiological response in 31, and cognitive performance in 24. Measurement coverage therefore declined from 73% for perceptual evaluation to 38% for cognitive performance.

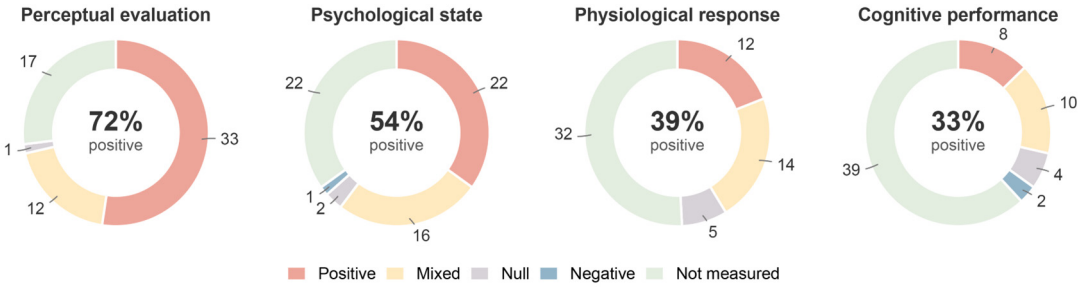


Figure 12. Outcome direction by domain.

The direction of findings followed the same order. Perceptual evaluation had 33 positive, 12 mixed, and one null finding, with no negative findings. Psychological state had 22 positive, 16 mixed, two null, and one negative finding. Physiological response had 12 positive, 14 mixed, and five null findings, with no negative findings. Cognitive performance had eight positive, 10 mixed, four null, and two negative findings. Within the measured subset of each domain across all included studies, the positive rate declined from 72% for perceptual evaluation to 54% for psychological state, 39% for physiological response, and 33% for cognitive performance. Negative findings were rare, but cognitive performance contained the largest number of negative findings.

To examine whether the overall pattern differed by exposure modality, we compared 21 immersive VR studies with 22 real physical environment studies. In VR studies, the positive proportions were 71% for perceptual, 57% for psychological, 27% for physiological, and 36% for cognitive outcomes. In real physical environment studies, the corresponding proportions were 61%, 41%, 46%, and 27%. Perceptual outcomes therefore remained the leading domain in both modalities, but the ordering of the other domains differed.

3.5.2. Setting–Element Pairing Asymmetry

The second asymmetry concerned how spatial settings were paired with the four biophilic element categories. Of the 63 studies, 39 were situated in recognizable campus spaces, and 24 were decontextualized. The decontextualized group contained 22 laboratory simulations and two unspecified campus interior studies. Among the laboratory simulations, 12 examined interior design elements, nine ambient conditions, and one cross-level configuration. The two unspecified campus interior studies were split between interior design elements and cross-level configurations. No spatial attribute study was decontextualized. Nine of the 10 ambient condition studies were laboratory simulations, while 17 of the 19 cross-level configuration studies were situated in recognizable campus spaces.

In the situated group, coverage was concentrated in classrooms and cross-level configurations. Among the 17 classroom studies, seven examined spatial attributes, six interior design elements, three cross-level configurations, and one ambient condition. The 3 library studies were all cross-level configurations. The four office studies split evenly between spatial attributes and cross-level configurations, while the four public learning space studies comprised two cross-level configurations, one interior design element study, and one spatial attribute study. The three indoor lounge studies all examined cross-level configurations. Dormitories were represented by one interior design element study and one cross-level configuration study, while the two design studio studies both examined cross-level configurations. The single self-study room study examined interior design elements, and the corridor and stairwell study examined cross-level configurations. The two mixed-setting studies split between spatial attributes and interior design elements. Cafeterias and social commons were absent, and no dedicated lecture hall was studied as a primary setting.

3.5.3. Paradigm Asymmetry

The third asymmetry concerned the study paradigm used to test biophilic effects. A restorative paradigm treated biophilic exposure as a post-stressor or between-task recovery condition. A protective paradigm kept the biophilic condition present during a resource-consuming cognitive task. Classification therefore relied on cognitive-task performance during exposure, not a post-task cognitive-load rating, although some studies also recorded concurrent neurophysiology. Of the 63 studies, 16 adopted a protective paradigm, accounting for 25% of the included studies. The remaining 47 studies adopted a restorative paradigm, accounting for 75%.

Paradigm use differed sharply by outcome domain. Among the 24 studies that measured cognitive performance, 16 used a protective design, corresponding to 67%. By contrast, protective designs accounted for nine of 46 perceptual studies, 11 of 41 psychological studies, and nine of 31 physiological studies. These proportions correspond to 20%, 27%, and 29%, respectively. Within the 16 protective studies, cognitive findings were heterogeneous. The directions were five positive, five mixed, four null, and two negative. The two negative cognitive findings were reported by Gou and Lau and by Kim [49,85].

Paradigm use also differed by setting. The protective paradigm was concentrated in classrooms, where it appeared in 10 of 17 studies. Among the 22 identifiable non-classroom campus settings, 19 were assessed through restorative designs and three through protective designs. The three protective non-classroom studies covered a VR library and two VR office settings. The decontextualized group contained three protective studies and 21 restorative studies. No protective design was identified for dormitories, public learning spaces, indoor lounges, circulation spaces, design studios, study rooms, or mixed campus settings.

4. Discussion

This review synthesizes a young but rapidly expanding body of evidence relevant to indoor biophilic design for higher education environments. The 39 situated studies provide direct evidence about identifiable campus interiors, whereas the 24 decontextualized studies characterize university student responses under controlled conditions and require spatial validation before informing setting-specific design guidance. Taken together, the studies support limited claims about perceived environmental quality, comfort, and short-term affect, but they do not yet justify broad claims about learning, sustained cognition, or transferable design rules across campus space. The central issue is not whether biophilic design matters, but where the evidence is mature enough to guide design and where it remains concentrated, provisional, or undertested.

4.1. A Rapidly Growing Evidence Base with Provisional Conclusions

Regarding research question 1 (RQ1), the evidence base is growing rapidly, but its conclusions remain provisional. Most studies are recent, geographically concentrated, and dispersed across disciplines.

The first feature is temporal concentration. The evidence base is sizeable enough to show recurrent patterns, but most studies were published within a short period. Most appeared in the last three years, while annual output is still rising. Early concentrations in element choice, setting, method, and outcome may therefore reflect the topics that were easiest to study first rather than stable evidence about what works across campuses.

The second feature is geographic concentration. More than half of the studies came from East Asian higher education contexts, whereas the broader biophilic design literature has been led mainly by Europe and North America [6]. This regional profile is valuable because it broadens a field often framed through Western settings, but it also means that cultural expectations, campus types, study habits, and institutional routines may shape the observed responses. Generalizing these findings to other higher education systems requires replication rather than assumption.

The third feature is disciplinary dispersion. The studies appear across more than forty journals and four broad fields, which shows that the topic now matters to architecture, environmental psychology, education, and health-related research. This disciplinary dispersion also contributes to inconsistent research standards. The MMAT findings reinforce this caution, particularly because randomized trials often described randomization incompletely and mixed-methods studies showed limited integration. Study designs, exposure descriptions, outcome measures, and reporting practices are not yet sufficiently aligned for strong cumulative comparison. The most defensible reading is therefore provisional. Current evidence supports a growing case that indoor biophilic design can improve how students perceive and feel in learning environments, but the field has not yet reached the level of maturity needed for settled design rules that apply across contexts.

4.2. Dense Evidence Around a Narrow Design Space

Regarding RQ2, the included studies occupy a dense but narrow design space. The architecture-oriented framework developed here organizes biophilic elements according to their locus and mode of operation in higher education interiors. It distinguishes interior design elements, ambient conditions, spatial attributes, and cross-level configurations, thereby relating the evidence to decisions about localized interior features, environmental conditions, spatial organization, and integrated design. This structure allows the evidence to be compared without requiring every study to fit a general pattern taxonomy. Interior design elements and cross-level configurations dominate the evidence base, whereas ambient conditions and spatial attributes receive less attention. Experimental exposures occur mainly in physical or virtual environments and are concentrated in classrooms and generic laboratory settings. The literature combines heterogeneous self-report measures with increasingly common neurophysiological recordings. Situated studies outnumbered decontextualized ones.

Interior design elements and cross-level configurations dominate the evidence base, but they answer different design questions. The former mainly concerns plants and green walls, with much smaller bodies of evidence on nature imagery, natural materials, and natural color. The latter offers greater contextual realism but rarely isolates the contribution of individual elements. Ambient conditions and spatial attributes occupy opposite ends of the setting distribution. Ambient studies are mostly decontextualized laboratory experiments, whereas spatial attribute studies are situated but concentrated on window views. The evidence can therefore speak most clearly about plants and green walls, window

views, and responses to integrated designs. It remains much less informative about sound, scent, daylight, materials, color, and spatial attributes beyond window views as separable biophilic elements.

The same narrowing is visible in method and sensory channel. Immersive virtual reality and neurophysiological recording have helped the field accelerate, especially since 2024, by making controlled exposure and objective response measurement easier. However, short simulated exposures can isolate visual cues and capture rapid affective or physiological changes, but they say less about behavior, social use, longitudinal adaptation, and whole-semester academic work. The visual channel dominates for similar reasons. In classrooms and examination settings, that focus may be appropriate because sound, scent, and tactile stimulation can distract from concentration. In residence halls, lounges, circulation spaces, cafeterias, and informal study areas, multisensory contact may be more relevant to restoration, comfort, social use, and sustained self-directed work. The present evidence is still too heavily concentrated on visual exposure to determine how the relevance of different sensory channels varies by setting.

Setting narrows the design space further. Classrooms have become the default higher education test bed, producing useful evidence for teaching rooms but underrepresenting the spaces where students also study, recover, wait, socialize, and move between tasks. Outside classrooms, cross-level configurations dominate libraries, lounges, design studios, and public learning spaces. These studies tie evidence to named campus functions but make it difficult to separate which element produces which response. Residence halls and circulation spaces remain sparsely represented, while cafeterias and social commons are absent. Ambient conditions have rarely been tested in identifiable campus settings. The field therefore clusters around window-related spatial attributes and interior design elements in classrooms, together with integrated designs in recognizable campus spaces. It does not yet offer balanced comparisons of the four biophilic element categories across higher education functions.

4.3. Strong Perceptual Gains but Uncertain Cognitive Transfer

Regarding RQ3, perceptual outcomes showed the most consistent positive associations across all included studies, followed by psychological outcomes. Physiological and cognitive findings were less consistently positive, although their relative ordering varied by quality restriction and exposure modality. Uneven coverage across spatial typologies also prevents firm setting-specific conclusions.

Perceptual outcomes were assessed most often, whereas cognitive outcomes were assessed least often. Negative findings were rare but occurred most often in cognition. This distribution reflects the field's theory base as much as the effects of biophilic design itself. Attention restoration theory and stress reduction theory direct researchers toward self-report measures of perceived restoration and mood. Many studies therefore stopped at these outcomes. For example, Zhang et al. paired a plant scent intervention with the POMS and EEG but included no cognitive task [45], while Hsu assessed green walls through perceived restorativeness alone [58]. A cognitive outcome appears only when a study deliberately adds a separate and more demanding task. The weak cognitive evidence also reflects the indirect link between task scores and academic life. A perceptual or affective response is experienced directly in the space, whereas a Stroop score, divergent thinking score, or working memory score is only a proxy for learning. Cognitive tasks also set a stricter evidential threshold than the self-report measures that dominate the other domains. Weak cognitive transfer therefore should not be read simply as evidence that biophilic design fails to support cognition. It shows that the current evidence is better suited to claims

about perceived quality, comfort, mood, and restoration than to claims about learning or sustained academic performance.

These quality-based restrictions clarified how the MMAT appraisal informed the review conclusions. Both retained perceptual and psychological outcomes as the two most consistently positive domains. The stricter restriction reversed the relative order of physiological and cognitive positive proportions. We therefore interpret the evidence as a broad contrast rather than a fixed decline across all four domains. This analysis also requires caution because the stricter restriction excluded six of 12 randomized controlled trials and two of four mixed-methods studies. The result partly reflects design-specific MMAT reporting requirements, especially incomplete descriptions of randomization and mixed-methods integration.

The modality comparison supports a shared perceptual signal but not a fixed ordering across the remaining domains. Psychological findings ranked second in VR studies, whereas physiological findings ranked second in real physical environment studies. This divergence may reflect differences in study year, design, setting, intervention, or measurement, rather than the exposure medium itself. It also limits direct transfer of short-term VR findings to occupied campus spaces. VR can screen design configurations under controlled conditions, but field studies remain necessary to test whether responses persist during authentic academic use.

The same evidence also challenges the assumption that more biophilic design is better. The few studies that graded dose, by varying wood coverage, greening ratio, or green wall area, converge on an intermediate optimum. Comfort or restoration tends to peak at a moderate level and fall away beyond it, consistent with an inverted-U dose–response associated with arousal. The point extends from amount to quality. Across the included studies, perceived quality often mattered more than physical quantity. The content and openness of a view mattered more than the mere presence of a window, and multisensory design helped only when the combination fitted the goal. Outcomes in cross-level configurations may likewise depend on how their constituent biophilic elements are combined. Kim's library combined plants, a green wall, wood, cool color, and an irregular ceiling [85]. This cross-level configuration reduced divergent thinking fluency and flexibility relative to the minimalist control. By contrast, the most restrained cross-level configuration in Colomer-Granero et al.'s classrooms best supported attention and memory [43]. Taken together, these findings suggest that biophilic design should be calibrated rather than maximized, although current evidence is insufficient to identify transferable optimal doses or configurations.

4.4. Evidence Gaps That Limit Transferable Design Guidance

Regarding RQ4, the validity and transferability of current conclusions are constrained by weak cognitive evidence, narrow setting and element coverage, the dominance of restorative paradigms outside classrooms, and unresolved dose–response relationships.

The first gap lies at the cognitive end of the effect chain. Although cognition is central to higher education, it remains the area of greatest uncertainty. Prior reviews also noted weaker cognitive evidence [16,90], but did not explain why it remained weak. Direct testing during realistic and sustained academic work is therefore needed before perceptual and affective benefits can be treated as evidence for learning.

The second gap concerns setting and element coverage. The evidence base forms two uneven clusters. Classroom research concentrates on window-related spatial attributes and interior design elements, whereas cross-level configurations predominate in libraries, lounges, design studios, and public learning spaces. These integrated studies improve contextual realism but usually cannot identify which element produces which response.

Ambient conditions show the reverse pattern and have largely been tested in decontextualized laboratory experiments. Spatial-attribute evidence is situated but remains dominated by window views. Other attributes, including prospect and refuge, spatial complexity, mystery, and transitional space, appear mainly within cross-level configurations. Evidence for interior design elements other than plants, green walls, and nature imagery is similarly sparse. Even within greenery research, Hsu's isolated comparison of green wall form found no difference between curvilinear and geometric conditions [58]. Circulation spaces rely on a single study [81], while cafeterias and social commons are absent. Dedicated lecture halls have not been examined independently. Peters and D'Penna similarly found incomplete coverage of Browning's patterns in the earlier literature [16]. The larger evidence base broadens coverage but still does not link individual elements reliably to campus functions, learning tasks, and intended outcomes. Design guidance for non-classroom spaces therefore cannot yet rest on directly applicable evidence.

The third gap concerns paradigm. Recovery and protection are not simply imbalanced; they have become tied to setting. Protective designs are concentrated in classrooms, while studies outside classrooms examine almost only recovery. Yet lounges, libraries, and rest areas also function as informal study spaces and may need to support students during work as well as after it. Kim's VR study illustrates the problem [88]. Its biophilic rest space resembled spaces used for informal study, but the study assessed only recovery after a stressor. This framing follows from the field's anchoring in attention restoration theory and stress reduction theory, which orient measurement toward self-report and pre–post comparison. Salutogenic design instead emphasizes sustaining health during demanding work [6,16], a goal that fits student study conditions more directly but remains insufficiently tested. The convention also reflects available instruments. Demonstrating protection requires continuous behavioral or physiological measures during sustained exposure, whereas most included studies used self-report scales before and after exposure. Even newer continuous tools are often still applied in a discrete pre–post design. Affective protection is therefore a missed opportunity because the field's strongest evidence concerns affect, yet it has largely been gathered after tasks. Li et al. demonstrate the feasibility of assigning different paradigms to different school spaces while measuring physiological and cognitive responses [91].

The fourth gap concerns dose. Study-specific optima cannot yet support transferable guidance because each has been identified for a different element and outcome. The clearest optimal levels concern comfort rather than sustained cognition, and no study has tested whether the number or intensity of elements within a cross-level configuration follows the same inverted-U pattern. Until dose–response relationships are tested in relation to sustained cognitive outcomes, the amount of biophilic design required for a given space and task remains unresolved.

4.5. Future Research

Future research should be organized around five linked priorities. The aim is not to expand the topic list indefinitely, but to turn a fast-growing evidence base into transferable design knowledge. These priorities follow from the four gaps identified above and are ranked by their combined theoretical importance, design relevance, and methodological feasibility.

Priority 1 should extend protective paradigm research beyond classrooms and match sensory configurations to the functions and tasks of non-classroom spaces. Library study areas, learning commons, study lounges, dormitory study zones, and other spaces used for independent academic work should be examined under sustained biophilic exposure during realistic tasks. These studies should test whether such conditions protect cognitive per-

formance, stress regulation, and affective stability while work is under way, with academic outcomes added where feasible. Sensory channels should not be prescribed uniformly across settings. Predominantly visual and multisensory configurations should instead be compared across space functions. Visual contact may better support concentration-focused spaces, whereas natural soundscapes, scent, airflow, and tactile materials may be more suitable in recuperative, transitional, and social settings, such as lounges, corridors, atria, cafeterias, and social commons. Hybrid spaces require direct comparison because the same environment may support study at one time and recovery at another. Treating space function and task as moderators would help address the limited evidence on cognitive outcomes. It would also show when multisensory exposure supports protection or recovery and when it becomes distracting.

Priority 2 should map dose–response relationships systematically. Experiments need at least three levels of biophilic intensity and explicit variation in the specific elements and configurations being tested. Tasks should resemble academic work, including sustained reading, examinations, problem solving, and design studio activity. Objective performance measures should be paired with neurophysiological indicators, such as EEG and fNIRS. The goal is to test whether the inverted-U pattern found most clearly for comfort also applies to sustained cognition. Dose–response studies should translate element-specific optima into guidance on how much of each element, and which combinations of elements, are appropriate for particular spaces and tasks.

Priority 3 should expand research on biophilic spatial attributes beyond the current concentration on window views. This priority draws on Kellert and Calabrese's experience of space and place, particularly prospect and refuge, organized complexity, integration of parts to wholes, transitional spaces, and mobility and wayfinding. Future studies should translate these biophilic spatial qualities into testable architectural variables and evaluate them in relation to defined higher education functions, learning tasks, and intended outcomes.

Priority 4 should use field and longitudinal studies for staged validation. Studies conducted in real built spaces are costly and difficult to control, which helps explain the field's reliance on virtual reality and laboratory experiments. They should therefore confirm promising effects rather than search broadly for them. Once an intervention shows convergent effects across VR and laboratory studies, it can be installed selectively in monitored campus spaces and tracked over a semester or academic year. This would test whether controlled effects survive real-world variation and time.

Priority 5 should broaden cross-cultural and cross-institutional replication. Multi-site studies across more regions and institution types are needed to identify which patterns travel beyond the evidence base dominated by East Asian studies. Some space types are culturally specific, including the writing center common in Western universities and the dedicated study room common on East Asian campuses. They should be treated as distinct settings rather than directly interchangeable ones. Study habits and cultural relationships with nature may also moderate response. Without this wider replication, culturally contingent patterns cannot be separated from patterns that genuinely generalize.

4.6. Limitations

First, eight reports identified during full-text screening could not be retrieved through accessible sources and were reported as a separate stream in the PRISMA flow. Their absence is unlikely to alter the broad conclusions, given the evidence base, but it could affect counts in sparsely represented settings, elements, or outcome domains.

Second, although no language restriction was applied, the searches used English-language terms in predominantly English-indexed databases. Empirical work published

only in Chinese, Korean, Japanese, or other languages may therefore be underrepresented, which is a relevant caveat given the East Asian concentration of the evidence base.

Third, the search drew on two databases, Scopus and the Web of Science Core Collection. These large multidisciplinary indexes capture much of the peer-reviewed literature in this field, so the evidence base is likely to be broadly representative, but it is not exhaustive. Subject-specific databases, dissertation repositories, gray literature sources, and conference-only records were not searched, so some technical or practice-based evaluations may have been missed. This coverage limitation may also introduce publication bias. Studies reporting positive results may be more likely to enter the peer-reviewed literature than studies reporting null or negative findings. Because the synthesis compares proportions of positive, mixed, null, and negative findings, these proportions may overstate the consistency of beneficial effects. Formal statistical assessment of publication bias was not feasible because the review did not pool comparable effect sizes and the evidence was heterogeneous across designs, interventions, and outcomes. The direction proportions should therefore be interpreted as descriptive patterns in the available literature, not as unbiased estimates of intervention effectiveness.

Fourth, two reviewers independently screened titles and abstracts. For full-text eligibility, data extraction, and coding, one reviewer completed the work and a second reviewer audited it. These stages were therefore not performed independently in duplicate. This procedure reduces but does not eliminate the risk of eligibility, extraction, or coding errors. To limit this risk, we used a predefined coding framework and retained per-study verification records; the full coding sheet is provided in Supplementary Material S3 for independent scrutiny.

5. Conclusions

This systematic mixed-methods review synthesized 63 primary empirical studies relevant to indoor biophilic design for higher education environments, published between 2004 and 2026. The evidence comprised 39 situated studies of identifiable campus spaces and 24 decontextualized studies of university student responses, with only the former providing direct evidence about higher education spatial typologies. Using PRISMA-compliant procedures, MMAT 2018 quality appraisal, and convergent integrated synthesis, it maps a specific intersection of setting and topic that has not previously been synthesized in this form. It also identifies three asymmetries that show which conclusions are currently supported by the evidence on biophilic design in higher education.

The review identified three asymmetries. First, perceptual evidence was most consistently positive. The ordering of psychological, physiological, and cognitive evidence varied across sensitivity comparisons, leaving sustained academic performance uncertain. Second, classroom studies concentrate on window-related spatial attributes and interior design elements, while non-classroom research relies mainly on integrated designs that rarely isolate individual effects. Ambient conditions remain largely decontextualized, and spatial attributes beyond window views are rarely studied. Third, protective designs are concentrated in classrooms, while other settings and outcomes are assessed mainly through restorative post-exposure designs. Together, these patterns show that strong perceptual and affective evidence cannot yet be treated as evidence of sustained cognitive or academic benefit. Research should therefore examine both recovery after academic work and the maintenance of attention, cognition, and affect while work is under way.

For design practice, the evidence supports three levels of confidence. Plants and green walls can be used with reasonable confidence in classrooms and similar instructional spaces to improve perceived environmental quality, comfort, and short-term affect. Window views can also be considered, but their effects depend on view quality. More cautiously,

biophilic richness should be moderated rather than maximized because dose–response evidence points to an intermediate optimum, and sensory channels should be matched to the space. Visual contact may be more suitable for classrooms, where shared sensory inputs are difficult to avoid, auditory stimuli may interfere with teaching, and responses to olfactory stimuli may differ across users. Multisensory contact may be better suited to informal recuperative and social settings, where students can select spaces according to their sensory preferences. Evidence is least secure for sustained cognitive performance in real academic work, effects in non-classroom settings, the applicability of ambient condition findings to identifiable campus spaces, and biophilic spatial attributes beyond window views. These findings should be applied only after the function of the target space has been specified, including whether it is intended to support recovery between tasks or protect attention during work.

Further research should clarify how biophilic effects vary by setting, paradigm, and dose, providing designers with a stronger basis for tailoring choices to the spaces and tasks in which students live, study, and work.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings16183665/s1, Supplementary Material S1, Complete Database Search Syntax; Supplementary Material S2, Screening and Full-Text Eligibility Boundary Rules, including representative borderline cases [92,93]; Supplementary Material S3, Complete Coding Table for the 63 Included Studies and Coding Rules.

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Abbreviations

The following abbreviations are used in this manuscript:

ART	Attention Restoration Theory
DASS	Depression Anxiety Stress Scales
EEG	Electroencephalography
fNIRS	functional near-infrared spectroscopy
HRV	heart rate variability
HVAC	heating, ventilation, and air conditioning
LED	light-emitting diode
MMAT	Mixed Methods Appraisal Tool
OSPAN	operation span task
PAD	pleasure–arousal–dominance model
PANAS	Positive and Negative Affect Schedule
PICOS	Population, Intervention, Comparison, Outcomes, and Study Design

POMS	Profile of Mood States
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PROSPERO	International Prospective Register of Systematic Reviews
PRS	Perceived Restorativeness Scale
PSS	Perceived Stress Scale
RCT	randomized controlled trial
ROS	Restoration Outcome Scale
RQ	research question
RT	reaction time
SRT	Stress Reduction Theory
STAI	State–Trait Anxiety Inventory
UGR	unified glare rating
VAS	visual analogue scale
VR	virtual reality
WHO	World Health Organization

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