The Role of Private Outdoor Greenery in Enhancing Indoor Air Quality, Thermal Comfort and Energy Efficiency: A Critical Review

Shishebori, Vali, Izadyar, Nima, Jamei, Elmira, Bamdad, Keivan and Sadeghi, Mahsan (2026) The Role of Private Outdoor Greenery in Enhancing Indoor Air Quality, Thermal Comfort and Energy Efficiency: A Critical Review. Indoor Air, 2026 (1). ISSN 0905-6947

Indoor Air

WILEY

REVIEW ARTICLE OPEN ACCESS

The Role of Private Outdoor Greenery in Enhancing Indoor Air Quality, Thermal Comfort and Energy Efficiency: A Critical Review

Vali Shishebori[1,2] | Nima Izadyar[1,2] | Elmira Jamei[1,2] | Keivan Bamdad[3] | Mahsan Sadeghi[4,5,6]

[1]Built Environment and Engineering Program, College of Sport, Health and Engineering (CoSHE), Victoria University, Melbourne, Victoria, Australia | [2]Institute for Sustainable Industries and Liveable Cities, Victoria University, Melbourne, Victoria, Australia | [3]School of Engineering, Design and Built Environment, Western Sydney University, Sydney, New South Wales, Australia | [4]Commonwealth Scientific Industrial Research Organisation (CSIRO), Melbourne, Victoria, Australia | [5]School of Architecture, Design, and Planning, The University of Sydney, Sydney, New South Wales, Australia | [6]NHMRC Centre for Safe Air, The University of Tasmania, Hobart, Tasmania, Australia

Correspondence: Nima Izadyar (nima.izadyar@vu.edu.au)

Received: 17 September 2025 | **Revised:** 3 June 2026 | **Accepted:** 5 June 2026

Academic Editor: Kalyani Sen

Keywords: green plot ratio | greening strategies | private outdoor spaces | residential buildings | thermal comfort

ABSTRACT

Urbanisation and climate change are degrading indoor conditions by intensifying heat stress, air pollution and reliance on mechanical cooling, yet the role of private residential greenery in mitigating these effects remains insufficiently understood. This review is aimed at critically evaluating how private outdoor greenery influences indoor air quality (IAQ), thermal comfort and energy efficiency in residential buildings. A systematic screening of 3750 Scopus records identified 54 relevant studies, which were synthesised to assess design determinants, climatic sensitivity and methodological approaches. Quantitative findings indicate that private greenery can reduce indoor air temperature by 3.4°C, lower mean radiant temperature by up to 22.9°C and achieve up to 25% cooling energy savings, depending on tree placement and density. Reported magnitudes vary widely across climates, vegetation configurations and methodological approaches. However, direct empirical evidence linking private outdoor greenery to measured indoor IAQ improvements remains limited, with many IAQ-related findings inferred from pollutant deposition, ventilation interactions or outdoor air quality changes rather than direct indoor measurements. Integrated assessments of IAQ, thermal comfort and energy performance are rare in residential contexts, and design thresholds remain undefined. This review contributes a consolidated evidence base and identifies critical research directions to support climate-responsive, evidence-based residential greening strategies.

1 | Introduction

This review does not aim to comprehensively review urban greening but critically synthesises evidence relevant to private residential outdoor greenery and indoor outcomes. Rapid urbanisation and industrialisation have profoundly reshaped the built environment [1, 2], intensifying the urban heat island (UHI) effect [3–6], increasing air pollution [7–10] and driving higher energy demand in residential buildings [11–13]. These pressures directly degrade indoor environmental conditions [14–16], particularly indoor air quality (IAQ) [17–19] and thermal comfort [20, 21], which in turn increase reliance on energy-intensive cooling and ventilation systems [11, 22]. Climate change further exacerbates these challenges by increasing the frequency and intensity of heat events [23–25], reinforcing the need for strategies that can simultaneously improve indoor conditions and reduce building energy consumption [16]. Given that buildings account for approximately 40% of global energy demand [26, 27], addressing these interconnected pressures is critical for achieving sustainable urban development.

The degradation of IAQ and thermal comfort is closely linked to urban densification [28, 29], vegetation loss [30–32] and rising pollution levels [28–30, 33–35]. Elevated outdoor temperatures and pollutant concentrations infiltrate indoor spaces through building envelopes and ventilation systems [36–38], increasing indoor contaminant levels [39–43] and cooling and ventilation energy demand [11, 22]. These effects are particularly pronounced in low-greenery urban areas, where heat-retaining surfaces intensify UHI impacts [44–47] and amplify indoor cooling loads [25]. Expanding urban populations and industrial activity further accelerate pollutant emissions [9, 10], with strong correlations reported between outdoor and indoor $PM_{2.5}$ concentrations [42, 43], as observed in dense urban contexts such as Chennai [48].

To mitigate these challenges, urban design research has increasingly focused on two broad approaches: nature-based solutions (NbS) and artificial solutions (AS). NbS, particularly green infrastructure (GI), are widely recognised for their cost-effectiveness [49, 50] (and multiple environmental, social and economic cobenefits [51–54], whereas AS rely on technically intensive interventions such as cool materials and engineered surfaces [55, 56]. Comparative studies consistently demonstrate that passive, vegetation-based strategies including tree shading [57, 58], green roofs [59, 60] and natural ventilation [61, 62] are among the most effective measures for mitigating UHI effects, highlighting the resilience potential of NbS [63–65]. At the building scale, trees, green roofs and green walls are identified as particularly integrable solutions [66, 67], with trees offering strong microclimatic regulation through shading and evapotranspiration [68], reducing heat stress [69–71] and improving well-being [72–74].

Despite extensive evidence supporting urban-scale greening such as parks, street trees and urban forests [75–78], the role of private residential outdoor greenery (front yards, backyards, small gardens and courtyards) remains underexplored [79]. This omission is significant given the prevalence of these spaces in residential urban form and their direct interaction with building envelopes. Existing reviews either address greenery in general without distinguishing private domains [80, 81], focus narrowly on green roofs and façades [82, 83] or examine outdoor environmental quality without tracing indoor impacts. Moreover, while private outdoor greening faces constraints such as limited space [66, 84] and potential ventilation trade-offs [85], its localised capacity to improve air quality, regulate microclimates and reduce dependence on mechanical systems has not been systematically synthesised [86–90].

Addressing this gap, the present review systematically synthesises evidence from a screening of 3750 publications, identifying 54 studies directly relevant to private outdoor greenery and indoor environmental outcomes. The review focuses on three analytical objectives: (1) examining the functional pathways through which private outdoor greenery influences IAQ, thermal comfort and building energy performance; (2) identifying key design determinants and vegetation characteristics that condition these effects at the residential plot and building scale and (3) critically evaluating the methodological approaches used to quantify greenery-related environmental impacts across different climatic contexts. By structuring the analysis around these mechanisms, determinants and methodological approaches, this paper provides a building-scale, private-domain-focused synthesis of residential greenery research, consolidates quantitative evidence across diverse study methods and critically assesses the feasibility and limitations of existing evaluation approaches across climatic contexts.

2 | Methodology

This review is conducted as a structured narrative review with critical synthesis, following systematic literature screening and selection criteria. This review is not intended as a full systematic review or meta-analysis, because its purpose is to provide an interpretive synthesis of mechanisms, design determinants and methodological patterns, rather than an exhaustive quality appraisal or statistical aggregation of all available evidence.

This review is structured around two analytical objectives that guided the systematic selection, screening and synthesis of the literature. Together, these objectives align with the overarching research aim of clarifying how greening private outdoor spaces can enhance IAQ, thermal comfort and energy performance in residential buildings.

The first objective focuses on synthesising mechanistic evidence linking outdoor greenery to indoor environmental outcomes, whereas the second objective examines the design determinants and methodological pathways through which these effects are mediated across climates and spatial scales.

Figure 1 illustrates the overall research framework, connecting urban-scale pressures, research gaps and greenery-based solutions to the analytical structure of the review.

Table 1 summarises how the analytical components of this review—mechanisms, design determinants, quantification frameworks and methodological approaches—are distributed across the Literature Review and Discussion sections to support an integrated synthesis.

2.1 | Literature Screening and Selection Criteria

A structured literature search was carried out in Scopus to identify literature on the impact of greening private outdoor spaces on IAQ, thermal comfort and thermal performance. As illustrated in Figure 2, the search process utilised keyword combinations categorised into three primary themes: Greenery, Indoor Environment and Building. Both basic and extended keyword sets were iteratively applied to ensure comprehensive coverage across disciplinary boundaries.

During the literature search, the highlighted combination initially yielded 3750 articles. This broad search strategy was employed to ensure comprehensive coverage across various aspects of greenery, IAQ, thermal comfort and building-related studies. To refine the selection, Figure 3 illustrates the application of

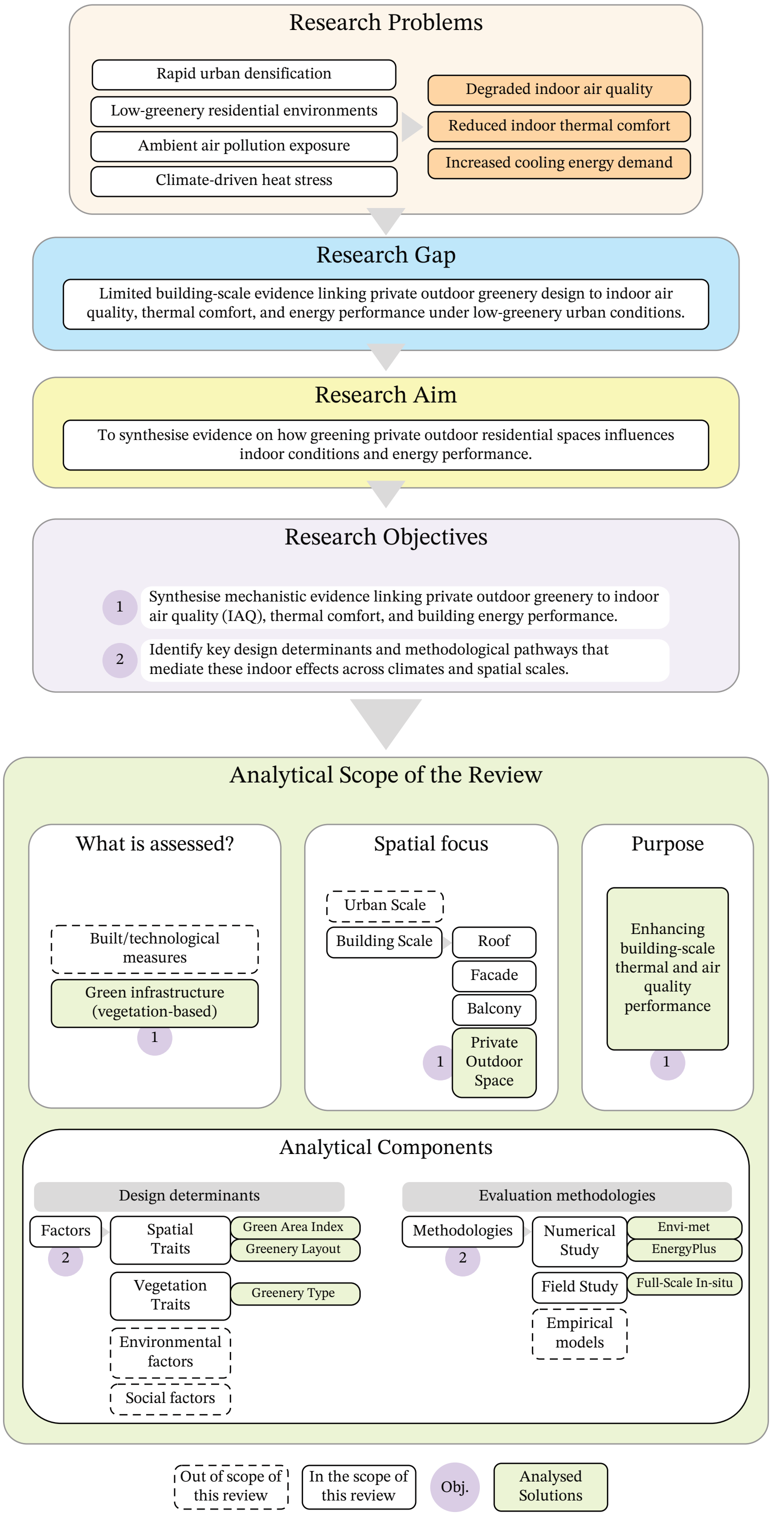

FIGURE 1 | Conceptual framework linking urban research problems, evidence gaps and analytical components for assessing the role of private outdoor greenery in improving indoor condition.

the inclusion and exclusion criteria. During the identification stage, 1761 articles were removed due to irrelevance to the research focus, such as publications outside the Engineering, Environmental Science and Energy fields or pre-2014 articles. In the screening phase, 1513 additional articles were excluded because the articles' titles or abstracts did not align with the research objectives, or the full text was inaccessible.

Of the 476 full-text articles assessed for eligibility, 422 were excluded. These primarily included studies addressing only outdoor environmental quality without indoor implications, investigations focused solely on indoor plants, green roofs or green walls without private outdoor context, or studies limited to psychological or visual comfort outcomes. An additional 44 studies were excluded at the final stage as they addressed only

TABLE 1 | Alignment between analytical components and paper structure.

Analytical component	Section	Section focus
Urban pressures and indoor environmental challenges	3.1	Synthesises evidence on how urbanisation, low greenery and climate-related stressors degrade IAQ, thermal comfort and energy demand in residential buildings.
Greenery as a nature-based solution (NbS)	3.2	Reviews the role of vegetation in modifying microclimates and mitigating indoor environmental stressors, with emphasis on physical mechanisms rather than prescriptive design.
Functional pathways linking outdoor greenery to indoor performance	3.1	Integrates mechanistic evidence (e.g., deposition, shading, evapotranspiration and airflow modulation) connecting private outdoor greenery to indoor outcomes.
Design determinants at the private outdoor scale	3.1, 3.3	Identifies key spatial, vegetative and quantitative factors (e.g., layout, LAI, GPR and canopy geometry) that condition indoor environmental effects.
Quantification and evaluation frameworks	3.3	Reviews indices and metrics used to quantify greenery extent and density, highlighting strengths and limitations for private outdoor applications.
Methodological pathways and validation challenges	3.4	Compares field studies, numerical simulations and empirical models used to assess greenery–IAQ and thermal comfort relationships, including issues of scale transfer and validation.
Interpretive synthesis and research implications	4	Integrates findings across mechanisms, design determinants and methods to identify research gaps, practical implications and future research directions.

outdoor design guidelines or planning frameworks; however, these sources were retained for contextual reference where relevant.

Ultimately, a focused corpus of studies directly addressing IAQ, thermal comfort and/or energy performance in relation to private outdoor greenery formed the evidence base of this review. Figures 4, 5 and 6 are derived from a subset of 10 studies selected from the 54 included studies. These studies were shortlisted based on reported comparable greenery input variables and at least one directly assessed or clearly modelled indoor outcome. For all other tables and figures, data from all 54 studies were used. The limited number of eligible studies highlights a significant research gap at the building and plot scale, reinforcing the need for synthesis-oriented analysis.

2.2 | Analytical Framework

The analytical framework adopted in this review was designed to systematically evaluate how greening private outdoor spaces influences IAQ, thermal comfort and energy performance in residential buildings. Following literature screening, eligible studies were categorised according to research methodology (field measurements, numerical simulations or empirical modelling) and spatial scale (urban/neighbourhood vs. building/private outdoor space).

Key variables extracted from each study included greenery type, spatial layout, density or coverage indicators and the environmental context in which greenery was implemented. These variables were analysed in relation to reported indoor outcomes, including changes in pollutant concentrations, thermal comfort indices and building energy demand.

In addition to performance outcomes, the framework examined methodological limitations and evidence reliability, particularly the balance between simulation-based studies and empirical validation. This approach enabled cross-comparison of findings, identification of dominant research patterns and recognition of structural gaps in current knowledge particularly the underrepresentation of private outdoor spaces and multidomain IAQ and thermal comfort assessment.

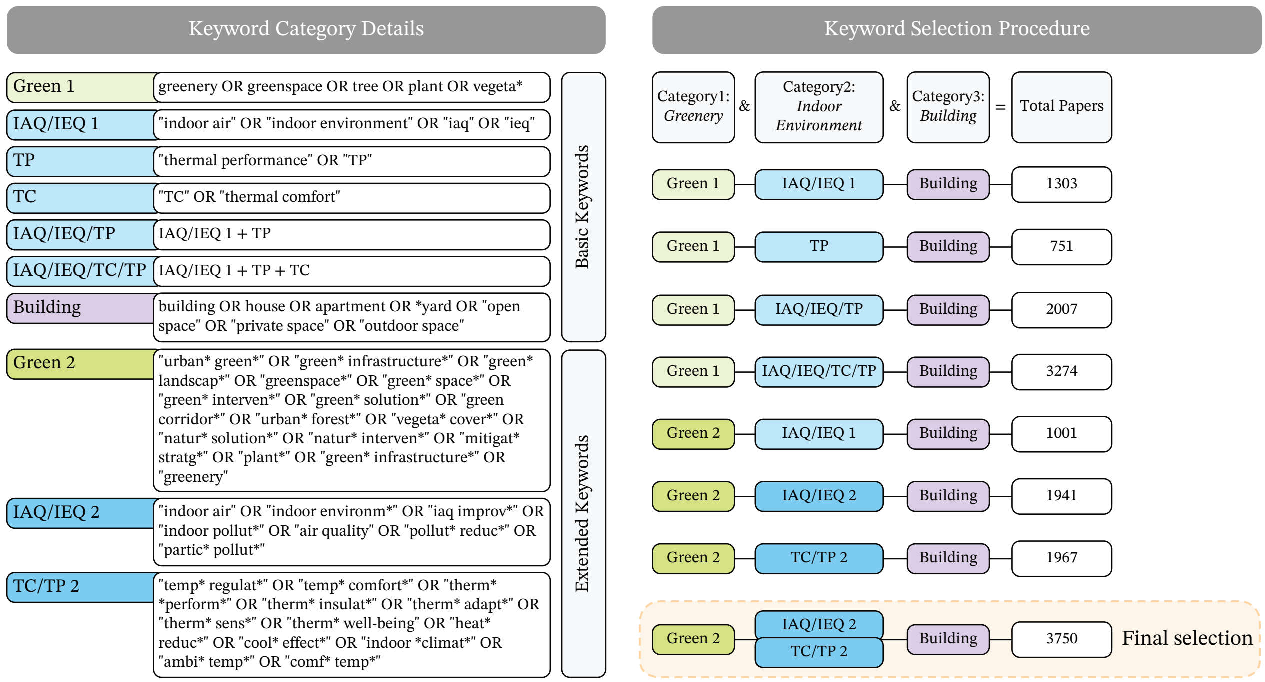

FIGURE 2 | Systematic keyword selection across three thematic domains: Greenery, Indoor Environment and Building.

3 | Literature Review

3.1 | Functional Pathways Linking Private Outdoor Greenery to IAQ, Thermal Comfort and Energy Performance (Objective 1)

Private outdoor greenery influences indoor environmental quality through five interrelated functional mechanisms: (1) pollutant attenuation via deposition and filtration processes, (2) shading and solar radiation control, (3) evapotranspirative cooling (green cooling), (4) wind modulation and ventilation mediation, and (5) vegetation configuration and spatial optimisation effects. Together, these mechanisms link outdoor microclimatic modification to IAQ, thermal comfort and building energy performance. While some pathways operate directly through infiltration and air exchange, others act indirectly by modifying façade heat gains, ambient air temperature or neighbourhood-scale pollutant dispersion patterns. These mechanisms operate through distinct but interacting physical processes, which are synthesised in Table 2 together with their associated design determinants and climatic sensitivities.

Table 2 synthesises evidence-based design determinants influencing the performance of private outdoor greenery at the private plot and building scale. Rather than prescribing implementation strategies, the table summarises key vegetation characteristics and spatial parameters reported in the literature (e.g., LAI, tree height, canopy diameter, GPR, vegetation porosity and façade proximity), together with potential trade-offs and climate sensitivities that may influence indoor outcomes. It highlights how vegetation characteristics and placement influence IAQ, thermal comfort and energy consumption within dwellings. In contrast, Table A1 (in Appendix) consolidates broader urban-scale and district-level evidence that supports the mechanistic plausibility of these pathways. Although much of the empirical literature operates at neighbourhood or street-canyon scale, the underlying physical processes (e.g., deposition, shading, evapotranspiration and airflow modification) remain transferable to the private outdoor context.

Importantly, these mechanisms are nonlinear and involve trade-offs. Pollutant deposition benefits may be offset if dense vegetation suppresses ventilation and reduces air exchange. Similarly, increased GPR enhances thermal comfort up to identified thresholds, beyond which marginal benefits diminish. Shading reduces cooling demand in warm climates but may obstruct beneficial winter solar gains in temperate conditions. Wind modulation can improve cold-climate protection yet increase stagnation risk in polluted corridors. These interactions demonstrate that greening outcomes depend not only on vegetation presence but also on configuration, density and climatic context.

Although much of the quantified evidence originates from urban-scale simulations or monitoring studies, scale transfer to private outdoor spaces is justified by shared boundary-layer processes and building-envelope interactions. Microclimatic modifications occurring within the immediate vicinity of façades, such as reductions in surface temperature, changes in wind velocity and altered pollutant dispersion, directly influence infiltration rates and conductive heat transfer. Therefore, while magnitude may vary with scale, the direction and functional logic of impacts remain consistent between neighbourhood-level greening and private plot interventions. To avoid overloading the main synthesis, Table A2 (Appendix) provides a complementary overview of supporting studies that examine vegetation-related mechanisms at urban or neighbourhood scales.

Figure 7 consolidates quantified ranges of temperature reduction, pollutant attenuation, ventilation modification and

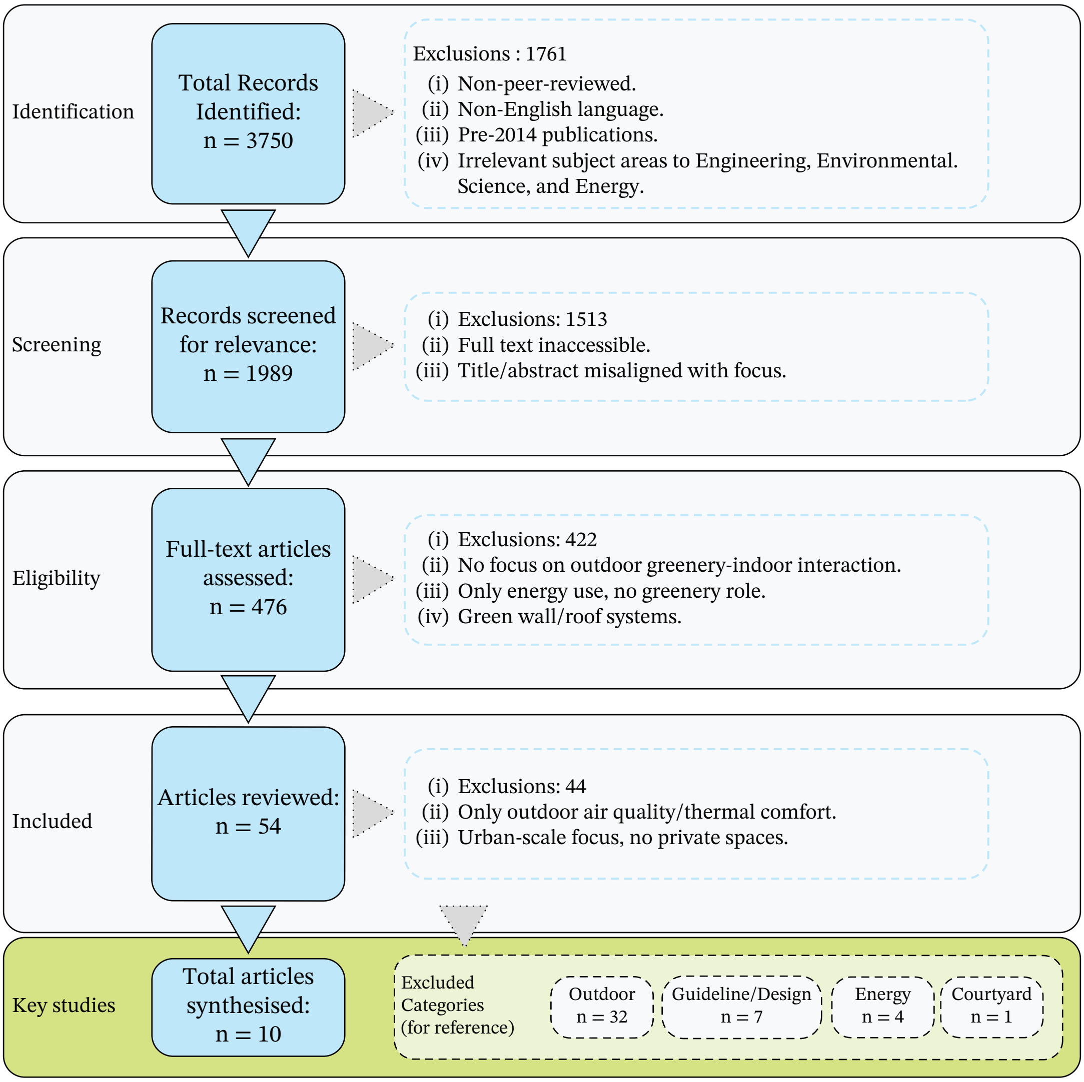

FIGURE 3 | The literature screening workflow based on selection criteria.

energy savings reported across the literature, linking mechanistic pathways (Tables 2 and A1) to measurable environmental outcomes. While outdoor cooling and surface temperature reductions are well documented, direct empirical evidence of IAQ and energy impacts remains limited. The predominance of outdoor-scale quantification suggests strong potential indoor benefits, yet highlights a critical evidence gap in building-scale validation. This reinforces the need for future research to directly measure and model indoor environmental responses to private outdoor greening interventions.

3.2 | Design Determinants and Performance Gaps

To identify the design determinants and methodological pathways mediating indoor environmental performance, this section synthesises quantitative evidence, climate–scale distribution patterns and input–output coupling structures across the reviewed literature. Where indoor IAQ outcomes are inferred from outdoor deposition studies, this is explicitly noted, and such evidence should be interpreted as indicative rather than conclusive.

3.2.1 | Definition of Private Outdoor Greenery

- Private outdoor greenery encompasses residential plot-scale vegetation located within the private residential parcel and directly adjacent to the dwelling, including front and back yards, small gardens, courtyards and terraces. This review focuses on vegetation that is spatially and functionally linked to the dwelling envelope, while excluding public street trees, urban parks and broader neighbourhood greening unless their influence on the specific dwelling is explicitly analysed. Typical vegetation characteristics include the following:
  - o. Tree height: typically, 3–10 m depending on species and site constraints.
  - o. Hedges and shrubs: 0.5–2-m height, often used as privacy screens or windbreaks.
  - o. Lawns and ground cover: contributing to surface cooling and infiltration.
  - o. Vegetation types: deciduous versus evergreen, high-stomatal species for pollutant deposition and species with significant evapotranspiration for cooling.

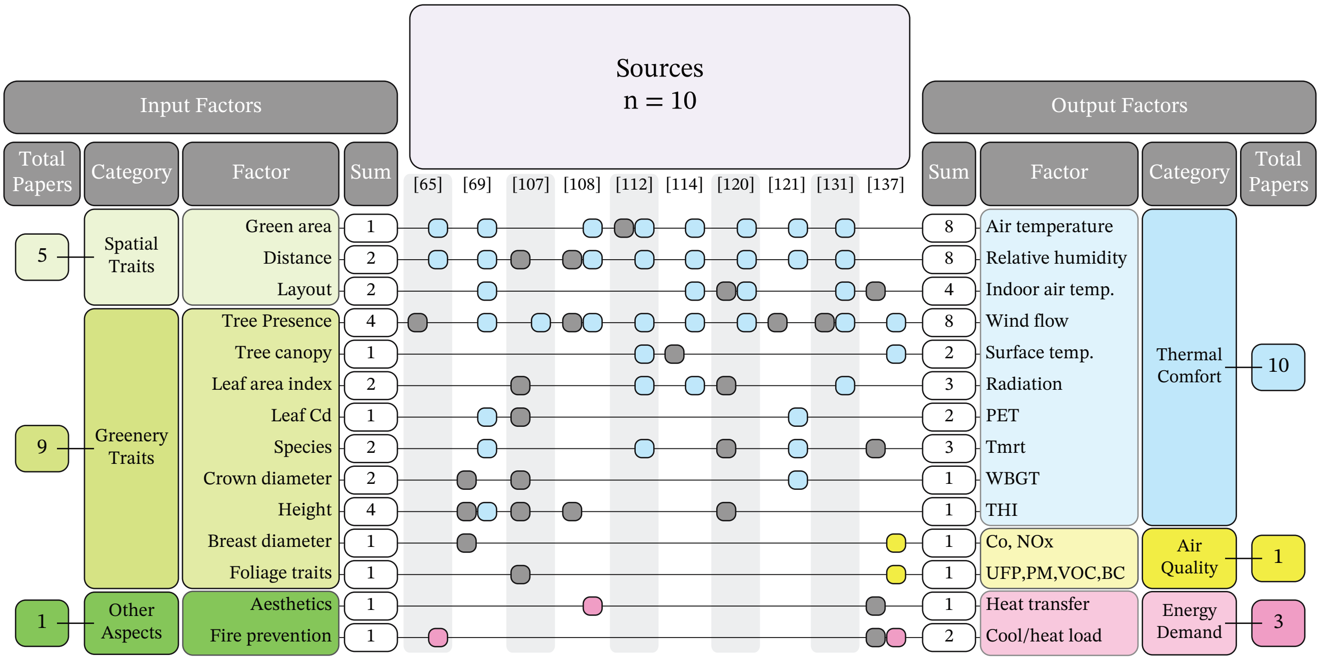

FIGURE 4 | Critical design factors of greenery influencing IAQ, thermal comfort and energy consumption.

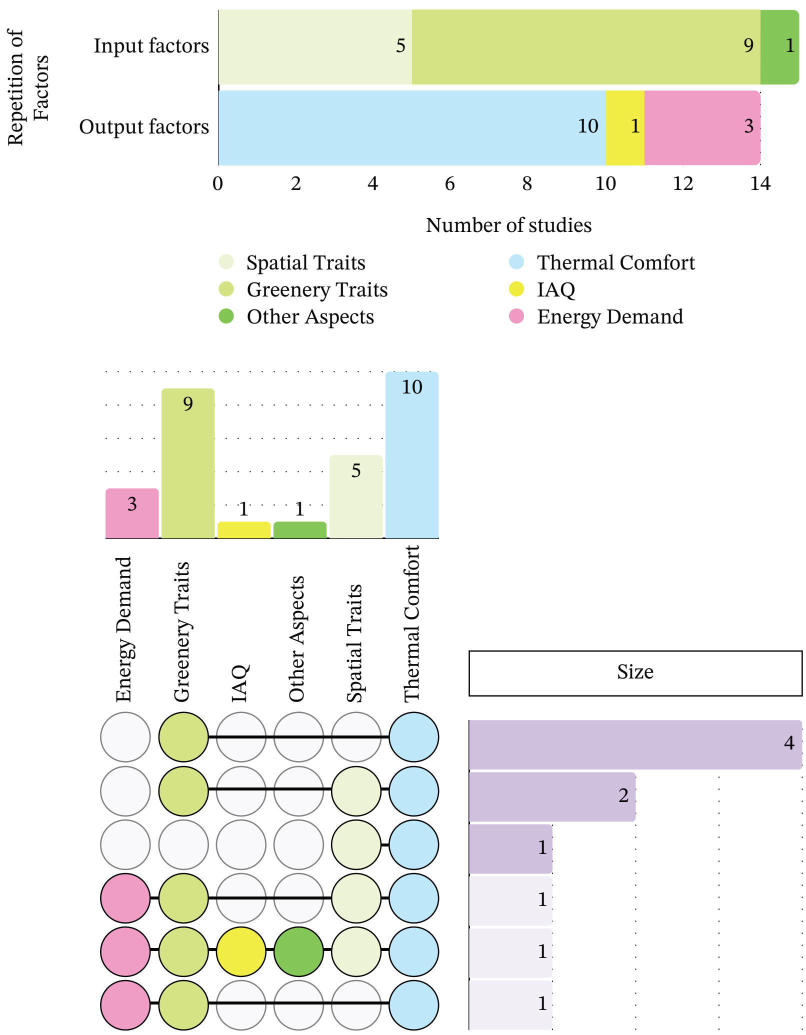

FIGURE 5 | Repetition and co-occurrence of input and output factor categories identified in the reviewed literature.

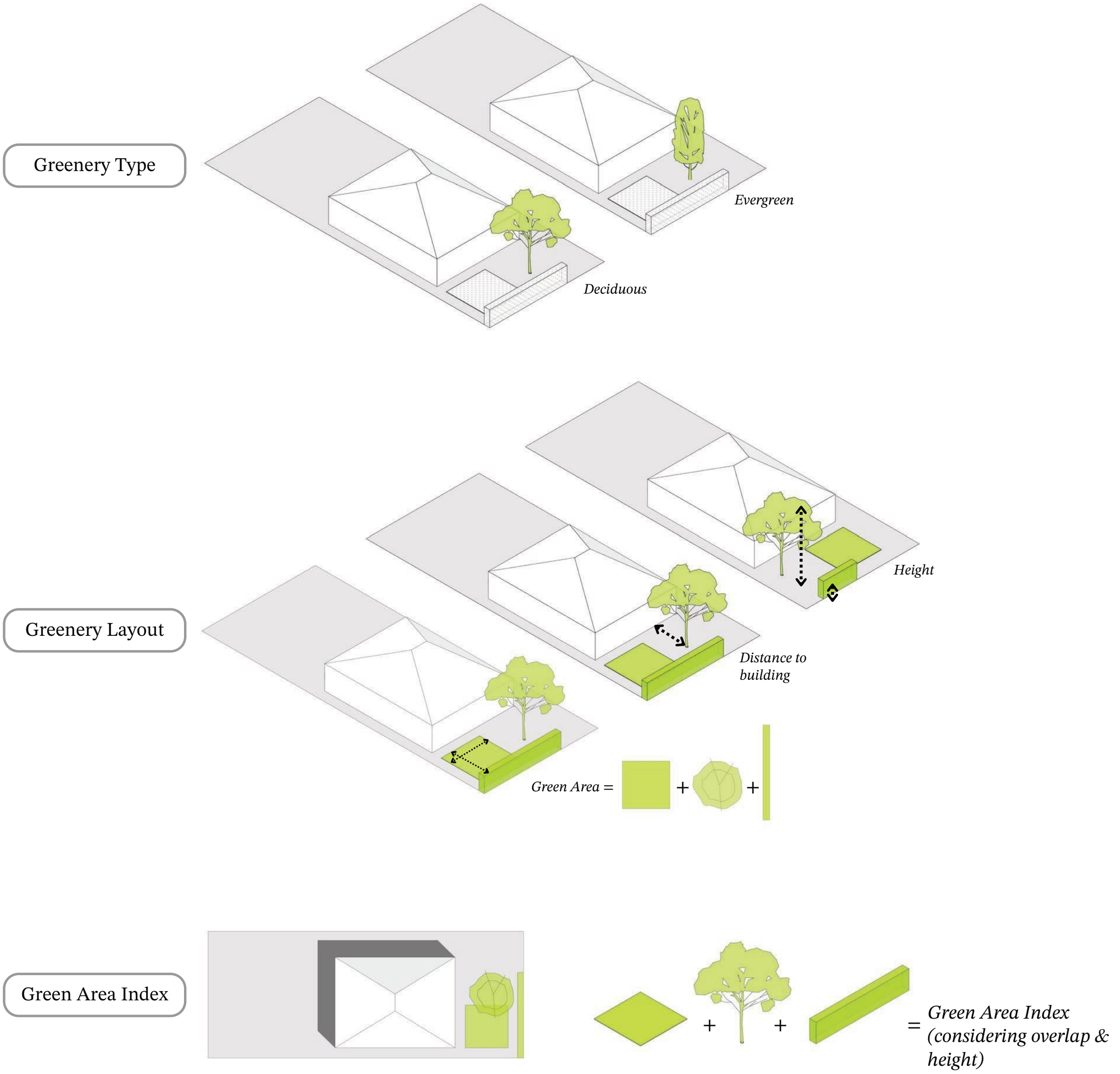

FIGURE 6 | Key design factors influencing the impact of greenery on IAQ, thermal comfort and energy consumption.

These characteristics determine shading capacity, pollutant capture, wind modulation and overall contribution to indoor environmental outcomes.

3.2.2 | Quantitative Evidence Across Climate and Scale

Table 3 summarises reported magnitude ranges of greenery-related environmental impacts across the reviewed studies. To improve transparency, the table distinguishes among three types of evidence: (1) directly measured indoor outcomes at the building scale, (2) outdoor microclimatic outcomes measured at the plot or neighbourhood scale and (3) inferred indoor implications derived from outdoor environmental improvements. This separation clarifies the methodological basis of the reported ranges and avoids conflating indoor measurements with broader urban-scale evidence. Climatic contexts in the reviewed studies are reported according to the Köppen–Geiger classification, a widely used system categorising climates based on temperature and precipitation patterns [146]. Cooling-related outcomes dominate the current evidence base, particularly for outdoor microclimate indicators such as PET, MRT and surface temperature. Direct measurements of indoor air temperature and building energy impacts remain comparatively limited, and IAQ quantification is especially scarce. In many cases, potential IAQ benefits are inferred from outdoor pollutant deposition or dispersion effects rather than directly measured indoor concentration changes. The study-level evidence underpinning these quantitative ranges, including input factors, output variables, Köppen climate classification, spatial scale and methodological approach, is systematically summarised in Table A2 (Appendix).

Climate representation is uneven. Temperate (C-type) regions are disproportionately studied, whereas arid (B-type), tropical (A-type) and cold (D-type) climates remain underrepresented,

TABLE 2 | Evidence-based design determinants and associated trade-offs influencing the performance of private outdoor greenery.

Functional mechanism	Primary indoor objective	Key design determinants	Climate sensitivity	Potential trade-offs/risks
Pollutant attenuation (deposition/filtration)	Reduce outdoor $PM_{2.5}$, PM_{10} and NO_2 infiltration into indoor spaces [48, 91–95]	High LAI; leaf roughness and hairiness; species with high stomatal conductance; proximity to façade openings; vegetation alignment with prevailing wind; buffer width	Stronger effect in polluted urban corridors	Pollutant accumulation on foliage; resuspension; allergen emissions; limited indoor benefit without adequate air exchange control
Shading and solar radiation control	Reduce indoor overheating and cooling loads via façade shading [22, 92, 96–98]	Tree height (~7–8 m effective); canopy diameter; deciduous versus evergreen selection; tree-to-wall distance; façade orientation (west/south priority); canopy density	Most effective in hot climates; deciduous species advantageous in temperate climates	Winter solar obstruction; façade dampness; reduced daylight; increased heating load under evergreen canopy
Evapotranspirative cooling (green cooling)	Lower ambient air temperature influencing indoor thermal comfort [25, 95, 99–102]	Species evapotranspiration capacity; irrigation strategy; soil moisture; canopy coverage ratio; spatial distribution (distributed vs. clustered planting)	More effective during hot, clear days; reduced performance in winter or humid climates	Increased humidity in already humid climates; irrigation demand; diminishing marginal cooling beyond canopy saturation
Wind modulation (green barriers/ ventilation mediator)	Optimise air exchange rates for IAQ and thermal comfort [95, 103]	Vegetation porosity; leaf drag coefficient; tree–building distance (avoid 1H–3.5H stagnation zone); upstream/downstream placement; façade versus roof vegetation strategy	Wind shielding beneficial in cold climates; configuration sensitive in warm climates	Reduced cross-ventilation (up to ~20% reported); potential stagnation near openings; unintended overheating if airflow blocked
Cooling-energy interaction pathway	Reduce cooling energy demand through microclimate modification [22, 96–98, 100, 104–108]	UGF (optimal ~0.5–3.5); vegetation distribution pattern; tree orientation; tree-to-wall distance; canopy diameter; integration with building geometry	Stronger in low-rise, open urban fabrics; diminishing returns beyond threshold GPR	Limited benefit in high-rise blocks; possible nighttime discomfort; winter heating penalties

limiting geographic generalisability. Methodologically, urban-scale simulations and hybrid field–model approaches dominate, whereas empirical building-scale validation of IAQ and energy performance is rare. This imbalance suggests that much of the evidence supporting indoor benefits remains indirectly inferred from outdoor-scale analyses (Figure 8).

3.2.3 | Input–Output Coupling and Research Concentration

Figure 4 maps the recurrence of input and output factors across the reviewed studies, revealing a strong concentration on vegetation traits particularly tree presence, LAI, canopy density, species selection and crown dimensions. Spatial determinants

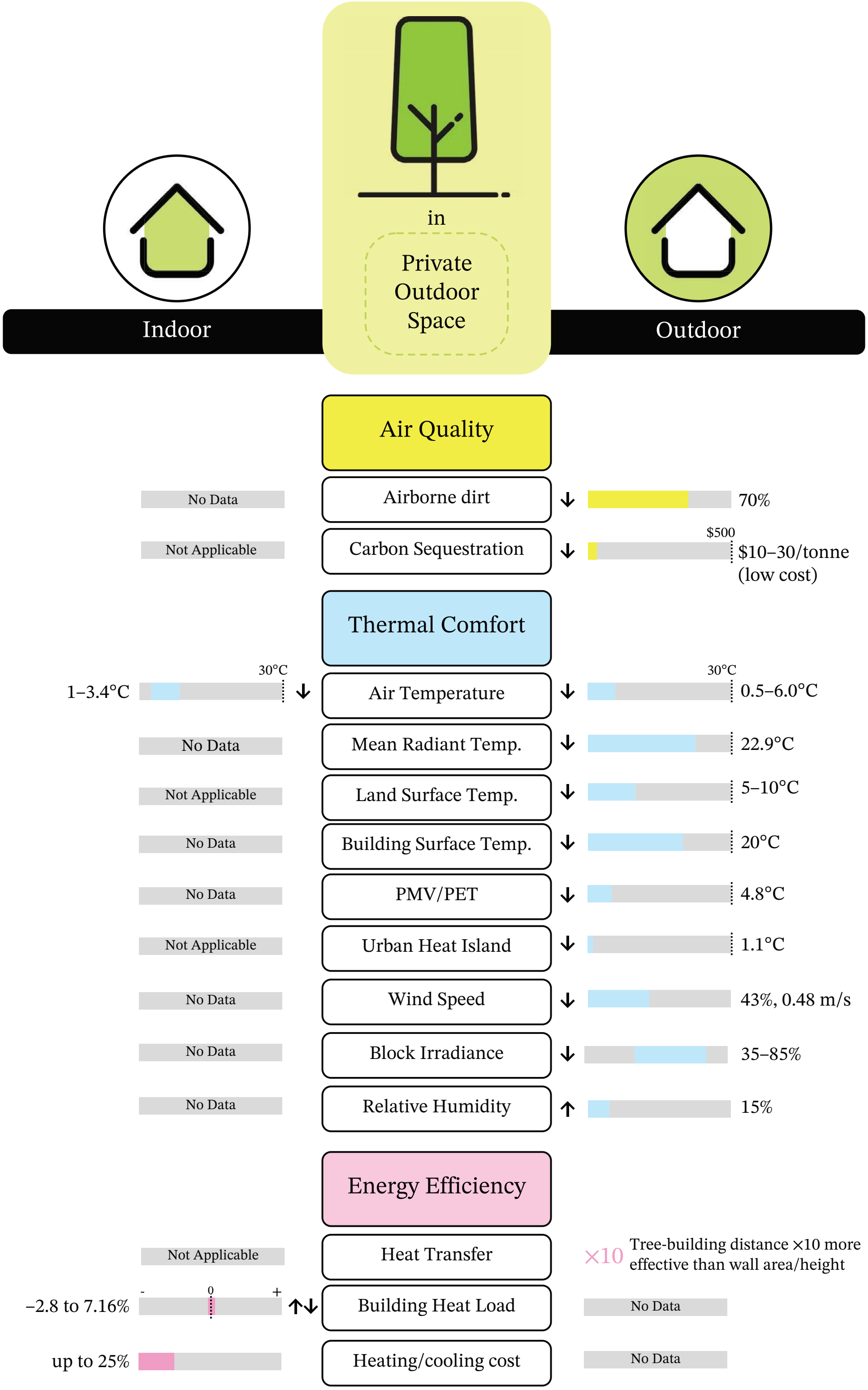

FIGURE 7 | Quantified impact of private outdoor greenery on indoor and outdoor environmental performance.

such as tree-to-wall distance and layout configuration are examined less frequently and are typically analysed in combination with vegetation variables rather than independently.

On the output side, thermal comfort overwhelmingly dominates the literature, appearing in nearly all reviewed studies. Energy performance is examined in a smaller subset, often treated as a secondary outcome of thermal mitigation. IAQ remains marginal, with only limited direct investigation of ventilation-mediated or filtration-based indoor improvements.

Figure 5 synthesises the coupling patterns between input and output categories, demonstrating that vegetation–thermal pathways constitute the primary analytical focus. Multidomain integration,

TABLE 3 | Reported magnitude ranges of greenery-related environmental impacts across reviewed studies, distinguishing directly measured indoor outcomes, outdoor microclimatic effects and inferred indoor implications.

Functional mechanism	Typical quantified outputs	Reported magnitude range	Climate representation	Scale and method concentration	Evidence gap indicators
A. Directly measured indoor outcomes (building-scale evidence)					
Shading and solar radiation control	Indoor air temperature; cooling/heating energy demand	Indoor air temperature reduction 1°C–3.4°C (up to 14°C with dense foliage) [98, 105, 143]; annual cooling/heating reduction 8%–12% [92] and energy consumption 17.3% [145]; summer energy reduction up to 25% [91]	Strong dominance of temperate climates (Cfa and Cfb)	Mixed building-scale simulations and empirical modelling	Limited long-term monitoring validation of indoor temperature impacts
Wind modulation (green barriers/ ventilation mediator)	Air exchange rate (AER); cross-ventilation; wind speed	Trees planted within 1H–3.5H upstream reduce cross-ventilation by 20%–24% [107]; green façade decreases AER by ~19%; green roof increases AER up to 13% [103]	Limited explicit climate differentiation	Building-scale simulations and experimental studies	IAQ consequences of altered ventilation rarely quantified concurrently
B. Outdoor microclimate outcomes (plot or urban-scale evidence)					
Shading and solar radiation control	PET; MRT; outdoor air temperature	PET reduction up to 4.8°C [69]; MRT reduction up to 22.9°C [128]; outdoor air temperature reduction up to 6.0°C [145];	Temperate climates (Cfa and Cfb) dominate	Field measurements and simulation studies at urban and neighbourhood scale	Seasonal heating penalties inconsistently quantified
Evapotranspirative cooling (green cooling)	Land surface temperature (LST); ambient air temperature; canopy air temperature; relative humidity; thermal perception	LST of impervious surfaces 5°C–10°C higher than green surfaces [101]; ambient temperature reduction ~6°C in UGI contexts [119]; 1.1°C campus-scale cooling with 17% tree increase and 20.8% indoor comfort improvement [144]; PET reduction up to 4.8°C [128]; canopy air temperature reductions 0.8°C–3.2°C depending on cloud cover; 'very hot/hot' perception reduced by 16% (sunny) and 11% (cloudy) [99]	Temperate (Cfa and Cfb), continental (Dfa) and semi-arid climates represented	Satellite observations, field monitoring and coupled simulations	Indoor linkage often inferred rather than directly measured; cloud-condition sensitivity rarely modelled

(Continues)

TABLE 3 | (CONTINUED)

Functional mechanism	Typical quantified outputs	Reported magnitude range	Climate representation	Scale and method concentration	Evidence gap indicators
Cooling-energy interaction pathway	MRT; wind speed; thermal stress index; dynamic heat transfer coefficients	Increasing LAI from 0.79 to 4.77 m^2/m^2 reduced MRT by 3.27°C and wind speed by 0.48 m/s [106]; GPR 0.5 → 1.5 reduced thermal stress category; GPR 3.5 achieved 'moderate' UHI intensity [124]; tree-driven variable explains 91.12% weight in wall heat transfer modelling [108]; presence of trees reduces summer energy up to 25% [65]	Predominantly temperate and continental climates (Cfa/Cwa and BSk–Cwa)	Urban block simulations dominate	Empirical validation of simulated energy savings remains limited
C. Inferred indoor implications based on outdoor environmental effects					
Pollutant attenuation (deposition/filtration)	PM capture; dust retention; NO_2 reduction; CO_2 moderation	Up to 70% airborne dirt retained along planted streets; mature trees intercept ~50 lbs particulates/year [92]; measurable PM deposition up to 12 m above ground [109]	Arid (BSh) and temperate (Cfa) contexts represented	Urban-scale field monitoring and review-based assessments dominate	Limited building-scale infiltration modelling; sparse direct indoor PM quantification
Carbon sequestration and atmospheric CO_2 moderation	CO_2 reduction; atmospheric moderation	Urban trees reported as up to 15× more valuable than rural trees for CO_2 limitation; planted streets retain up to 70% airborne dirt [92]	Broad climatic mention; limited stratified comparison	Review-based and policy-scale assessments dominate	Negligible short-term indoor IAQ quantification; scale mismatch at dwelling level

simultaneously assessing IAQ, thermal comfort and energy, is rare. As a result, the literature remains fragmented, with limited understanding of cross-performance trade-offs at dwelling scale.

3.2.4 | Emerging Determinants and Structural Gaps

Figure 6 synthesises the critical design determinants emerging from the reviewed literature and clarifies the analytical boundary of the current study. The framework distinguishes three principal determinant categories influencing indoor environmental outcomes: (i) greenery type, (ii) greenery layout and (iii) greenery area quantification.

Greenery type refers to biological and morphological characteristics, including deciduous versus evergreen selection, canopy density, LAI, species-specific evapotranspiration capacity and seasonal variability. These attributes directly mediate shading efficiency, pollutant deposition potential and microclimatic cooling intensity.

Greenery layout captures spatial configuration parameters such as tree-to-wall distance, planting height relative to façade openings, upstream–downstream positioning with respect to prevailing wind and the degree of canopy overlap. Unlike vegetation traits alone, layout determines how greenery interacts dynamically with airflow, solar exposure and building-envelope heat transfer processes.

Green area quantification represents a third, cross-cutting determinant. Because greenery may include horizontal, vertical and overlapping vegetated elements, its effective extent cannot be described solely by planar coverage. This study therefore adopts the term Green Area Index as a conceptual umbrella for quantifying greenery magnitude and density, acknowledging that multiple operational indices exist. The formal evaluation tools used to calculate greenery coverage and weighting such as GPR, UGF and GFS are discussed in Section 3.3.

The graphic summary further clarifies the scope boundary of the present research. The current study focuses on private outdoor

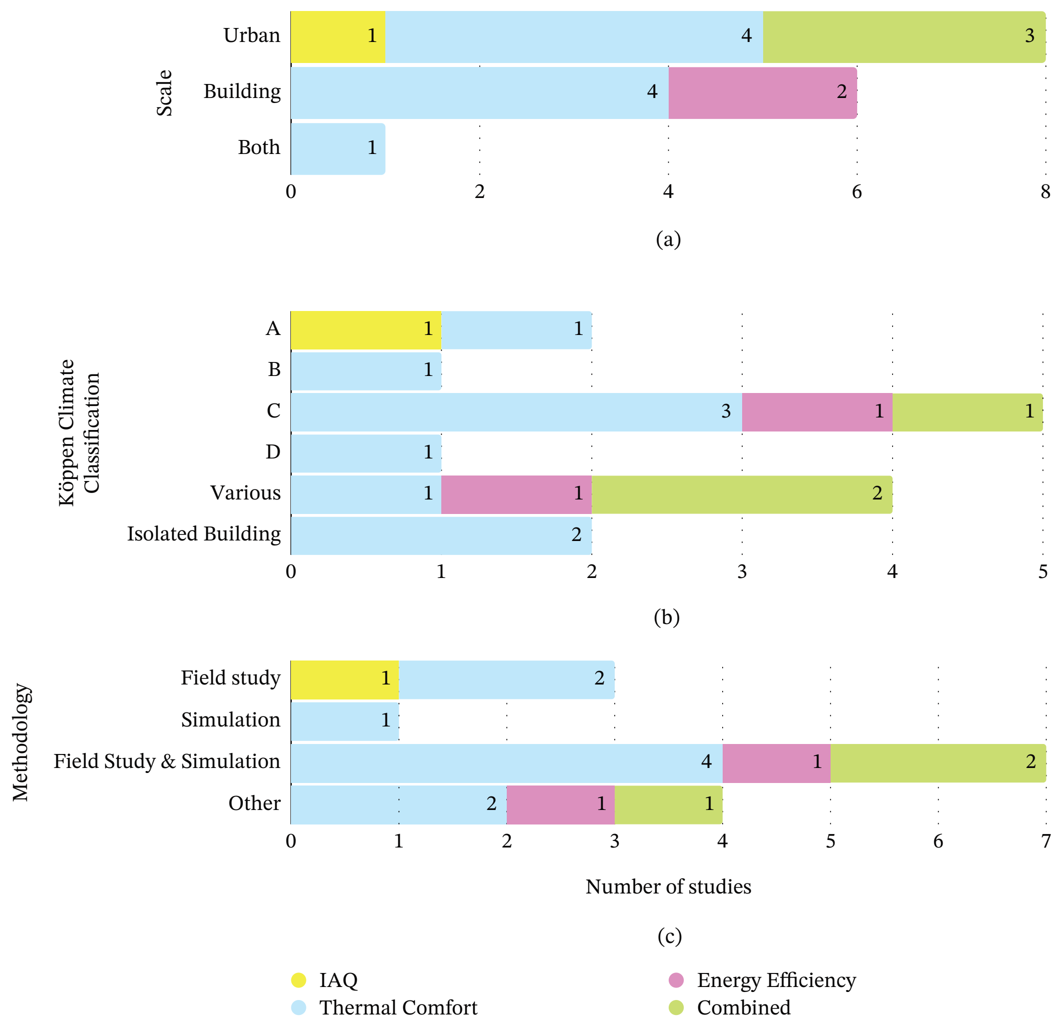

FIGURE 8 | Integrated analysis of scale, climate, focus area and methodology.

greenery at the dwelling scale, examining its influence on IAQ, thermal comfort and energy efficiency. Future research directions include expanding analysis toward (i) building-envelope integration strategies, (ii) interactions with adjacent buildings and (iii) linear nature strips within the broader urban fabric. This staged approach prevents scale conflation while maintaining conceptual continuity with neighbourhood-level processes identified in Section 3.1.

Collectively, this determinant hierarchy emphasises that indoor performance outcomes are not governed by greenery presence alone, but by the interaction between vegetation traits, spatial configuration and quantifiable greenery magnitude. Also, this determinant hierarchy provides the structural foundation for selecting quantification frameworks (Section 3.3) and methodological evaluation pathways (Section 3.4).

3.3 | Quantification Frameworks for Greenery Magnitude and Density

Accurate quantification of greenery magnitude constitutes a critical methodological challenge in assessing its impact on indoor environmental quality. Unlike discrete design variables such as tree height or façade distance, greenery area may involve horizontal surfaces, vertical elements, overlapping canopies and density variations. Consequently, planar coverage alone cannot adequately represent vegetation intensity or performance potential.

To address this complexity, several formal indices have been developed to quantify greenery extent and density. These tools operationalise what was conceptually defined in Section 3.2.3 as the ‘Green Area Index’, enabling standardised comparison across sites and studies. Table 4 summarises three widely applied indices: Green Plot Ratio (GPR), Urban Greening Factor (UGF) and Green Factor Score (GFS).

- GPR is derived from LAI and expresses greenery density as a ratio between leaf surface area and ground area. It provides a vegetation-intensity metric that captures three-dimensional canopy characteristics more effectively than simple coverage ratios. Studies [129, 147] demonstrate its application in linking 3D greenery density to UHI mitigation and thermal stress reduction.
- UGF, introduced by the Mayor of London [150], expands quantification to include both horizontal and vertical greenery through weighted surface-cover scoring. While it improves representation of layered vegetation, its

TABLE 4 | Indices for evaluating greenery coverage and density.

Source	Index	Description	How does it work?
[129, 147]	GPR	Based on leaf area index (LAI), refers to the single-sided leaf area per unit ground area.	The GPR represents the average LAI of site greenery, expressed as a ratio.
[128, 148]	UGF	Based on surface cover types and factor scores.	The UGF is the total area of greenery (including vertical surfaces and overlapping surfaces) with its factor score divided by the total area of the plot.
[149]	GFS	Based on a 'weighted-index' of green infrastructure on a site, to its area.	The GFS is an index-like measure of the volume and efficacy of a site's green infrastructure elements. The 'greening efficacy' of each element is determined by its unique green element weight. This weight is scored on the basis of the element's capacity to service a set of Ecosystem Services, including urban temperature regulation and social cohesion.

formulation does not explicitly account for spatial configuration, which can result in misleading equivalence between differently distributed greenery systems. Empirical application in school environments [139] showed correlations between UGF scores and classroom temperatures but also highlighted configuration-related heat disparities.

- GFS, adopted by the City of Melbourne Council [149], extends beyond physical coverage to incorporate ecosystem service weighting. Each green element receives a performance weight based on functions such as urban cooling, runoff mitigation, habitat provision and social cohesion. Although comprehensive from a planning perspective, GFS introduces subjective weighting that may complicate direct linkage to measurable indoor IAQ and thermal comfort outcomes.

While these indices provide structured quantification methods, none fully integrate vegetation spatial arrangement, airflow interaction or façade proximity—factors shown in Section 3.2 to mediate indoor outcomes. Moreover, indices designed for urban planning objectives may not directly correspond to building-scale IAQ or energy performance metrics. Therefore, although GPR, UGF and GFS offer valuable standardisation tools, adaptation or hybridisation may be required to support dwelling-scale, performance-oriented greenery evaluation frameworks.

3.4 | Methodological Pathways and Validation Challenges

Assessing the indoor impacts of private outdoor greenery requires methodological approaches capable of capturing dynamic interactions among vegetation, microclimate and building performance. Across the reviewed literature, three principal methodological pathways are identified: field studies, numerical simulations and empirical models (Figure 9). To improve transparency regarding how IAQ, thermal comfort and energy performance are assessed across the reviewed studies, Table A3 (Appendix) summarises the tools, sensors, sampling methods and simulation platforms employed in field-based and modelling studies.

3.4.1 | Field-Based Measurement Approaches

Field studies rely on in situ monitoring of thermal, air quality and energy parameters under real environmental conditions. Most reviewed studies adopt full-scale measurements, reflecting strong preference for real-world validation [144]. Experimental setups such as climate-controlled test houses and wind tunnel modelling [103] remain less common but offer controlled investigation of building-scale microclimate interactions. Field studies provide high empirical reliability and contextual accuracy. However, they are resource-intensive, time-consuming and often limited in scenario flexibility.

3.4.2 | Numerical Simulation and Coupled Modelling

Numerical simulations constitute the dominant predictive approach. At the urban microclimate scale, ENVI-met is the most frequently applied tool, appearing in the majority of reviewed simulation-based studies. Its strength lies in modelling vegetation–atmosphere interactions and outdoor thermal fields. At the building scale, EnergyPlus is widely used to simulate indoor thermal behaviour and energy consumption. Several studies demonstrate coupled workflows, where ENVI-met-generated outdoor boundary conditions are integrated into EnergyPlus to assess indoor responses [156, 157]. This approach enables scenario testing and optimisation of

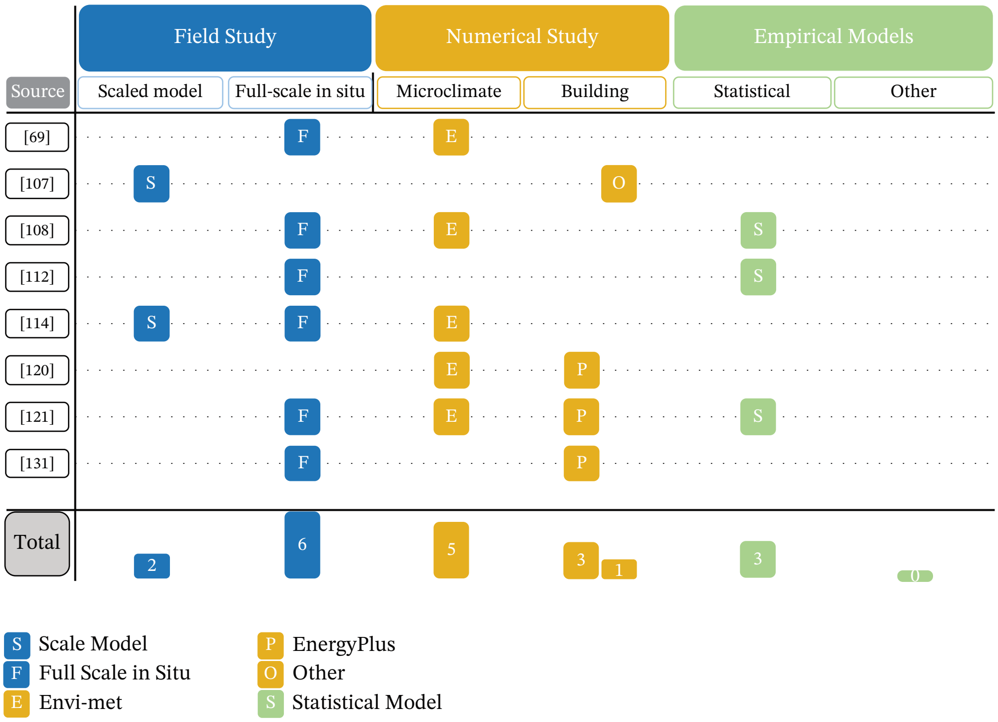

FIGURE 9 | Methodologies employed in relevant studies.

greenery configurations. Despite their scalability and scenario flexibility, simulation models depend heavily on parameter assumptions and require robust validation against field measurements.

3.4.3 | Empirical and Data-Driven Models

Only a limited number of reviewed studies employed empirical statistical models. Machine learning and advanced data-driven approaches were not widely represented, although they offer significant potential for identifying nonlinear relationships and multivariable interactions across climatic contexts. The relative scarcity of empirical modelling suggests an opportunity for integrating data-driven techniques with physics-based simulation to enhance predictive robustness.

3.4.4 | Comparative Resource and Validation Assessment

Figure 10 presents a comparative synthesis of methodological characteristics based on reported cost, time investment and feasibility. Field studies demonstrate high empirical credibility but require substantial resources. Numerical simulations provide moderate resource demand and high scalability, making them suitable for optimisation studies. Empirical models offer cost efficiency but may lack contextual precision for complex building–vegetation interactions. Overall, while numerical simulations particularly ENVI-met coupled with EnergyPlus play a central role in modelling greenery impacts, systematic field validation remains essential to strengthen reliability and improve cross-climate transferability. The predominance of outdoor-scale modelling, combined with limited indoor validation, underscores a critical methodological gap in current research.

4 | Discussion and Synthesis of Findings

This review synthesised mechanistic, design and methodological evidence to clarify how private outdoor greenery mediates indoor environmental quality under conditions of urbanisation, pollution and increasing thermal stress. Rather than treating IAQ, thermal comfort and energy performance as isolated domains, the findings reveal their interdependence through shared microclimatic pathways.

4.1 | From Urban Pressures to Dwelling-Scale Mediation

Urbanisation and industrial activity intensify pollutant exposure and exacerbate UHI effects, increasing cooling demand and degrading indoor environmental conditions. While extensive research has addressed these issues at neighbourhood and city scales, this review demonstrates that similar boundary-layer processes operate at the private dwelling scale. Deposition, shading, evapotranspiration and airflow modulation function as transferable mechanisms capable of influencing façade heat exchange and pollutant infiltration. However, private outdoor greenery remains comparatively underexamined, despite its potential to provide site-specific, building-integrated mitigation strategies. This gap suggests that dwelling-scale greening represents an underutilised lever for enhancing IAQ and thermal comfort within existing urban fabrics.

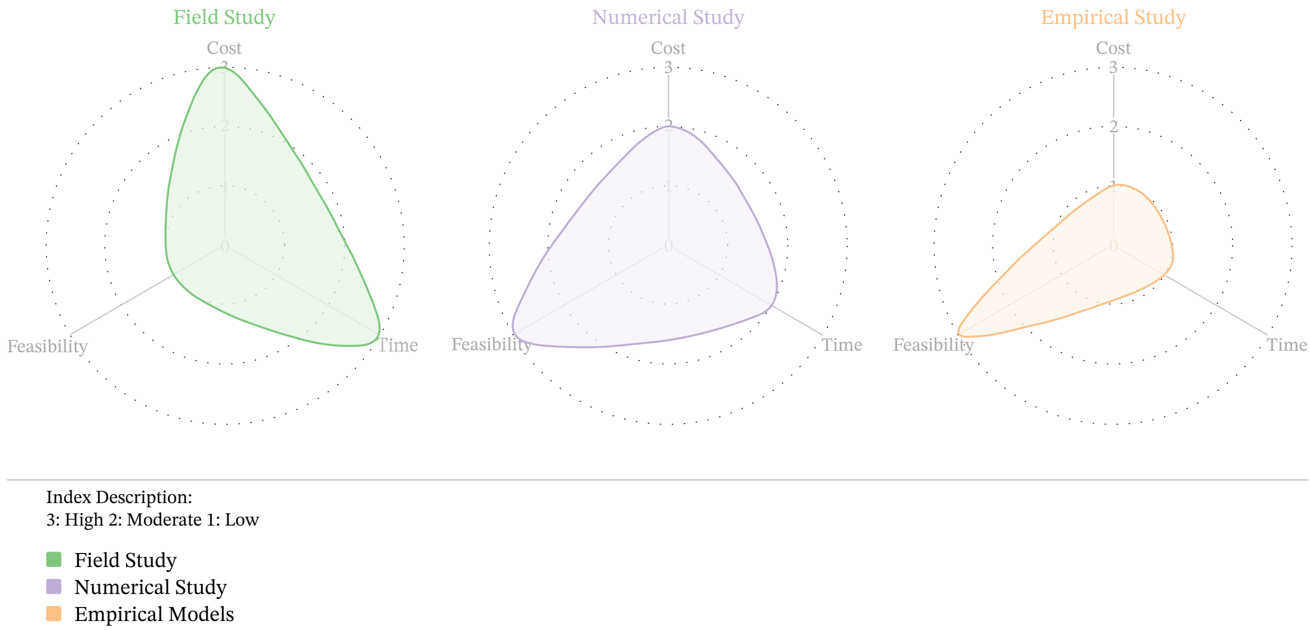

FIGURE 10 | Methodology comparison based on cost, time and feasibility.

4.2 | Potential Risks and Trade-Offs

While private outdoor greenery provides multiple environmental benefits, potential risks and trade-offs should be considered:

- Moisture-related risks: Dense shading may reduce solar penetration, leading to dampness and increased winter heating demand.
- Structural concerns: Large trees with extensive root systems may damage foundations or underground services.
- Maintenance challenges: Irrigation, pruning and pest management require ongoing resources.
- Airflow trade-offs: Poorly configured vegetation may reduce natural ventilation and cause stagnation zones indoors.

These risks reinforce the importance of layout, density thresholds and façade proximity. A balanced design approach, considering both benefits and risks, is critical for effective implementation.

4.3 | Mechanisms, Determinants and Performance Coupling

The synthesis reveals that indoor performance outcomes are governed not merely by greenery presence, but by the interaction between vegetation traits, spatial configuration and quantifiable greenery magnitude. Shading and evapotranspirative cooling consistently reduce thermal stress and cooling loads, yet benefits exhibit threshold behaviour and diminishing returns. Similarly, pollutant deposition and wind modulation may improve IAQ under certain configurations but can also suppress ventilation or create stagnation zones if improperly positioned.

Vegetation–thermal pathways dominate the literature, whereas IAQ and energy efficiency are often treated as secondary outcomes. Multidomain assessments simultaneously evaluating IAQ, thermal comfort and energy remain rare. This imbalance limits understanding of cross-performance trade-offs and reinforces the need for integrated, building-scale evaluation frameworks.

4.4 | Methodological Constraints and Evidence Reliability

The review highlights a methodological landscape dominated by numerical simulations, particularly ENVI-met for outdoor microclimate modelling and EnergyPlus for indoor energy analysis. While coupled modelling approaches enable scenario testing and optimisation, empirical validation at the dwelling scale remains limited.

Field studies provide critical real-world evidence but are resource intensive and often geographically constrained. Empirical and data-driven approaches are underutilised, despite their potential to capture nonlinear interactions and cross-climate variability.

Furthermore, climatic representation is uneven, with temperate regions disproportionately studied. This geographic skew limits transferability of findings to arid, tropical and cold climates, where vegetation performance and cooling dynamics differ substantially.

4.5 | Implications for Design Practice and Research Agenda

The determinant hierarchy identified in this review (e.g., greenery type, layout configuration and quantifiable magnitude) provides a structured foundation for performance-oriented

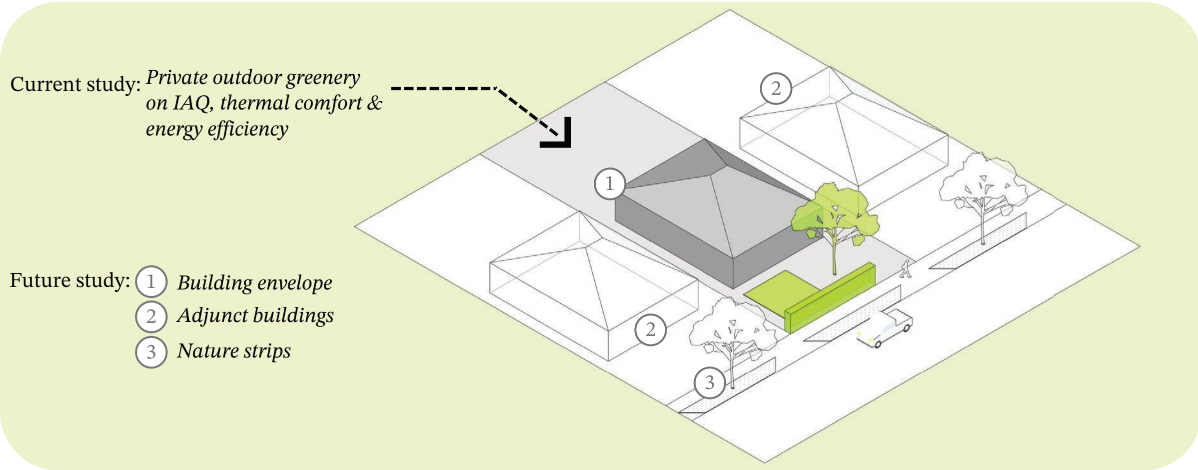

FIGURE 11 | Conceptual shift in research scope from isolated dwelling-scale vegetation to multiscale greening interactions involving building envelopes, neighbouring buildings and street-level vegetation systems.

greening strategies. Effective design requires alignment between vegetation traits, spatial placement relative to façade openings and appropriate density thresholds to balance shading, ventilation and energy effects. Rather than prescriptive guidelines, this review provides evidence-bounded design determinants and performance ranges that can inform future guideline development.

Building upon the design determinants and performance ranges identified in this review, future research should extend beyond isolated dwelling plots toward envelope-integrated greening systems, adjacent-building interactions and linear nature-strip configurations within the broader urban matrix (Figure 11). This staged expansion maintains conceptual continuity while preventing scale conflation.

4.6 | Research Gaps and Strategic Directions

Several structural gaps persist:

- Limited direct measurement of indoor IAQ improvements attributable to private greenery.
- Scarce multidomain studies integrating IAQ, thermal comfort and energy performance.
- Insufficient cross-climate comparative analysis.
- Overreliance on outdoor-scale modelling without building-scale validation.
- Minimal application of data-driven modelling approaches.

Addressing these gaps requires integrated simulation–field validation workflows, standardised greenery quantification metrics tailored to building-scale IAQ and thermal comfort and cross-climate experimental designs. Such advances will enable development of climate-responsive, evidence-based guidelines for private outdoor greening as a nature-based solution for improving indoor environments.

5 | Conclusion

This review evaluated the role of private outdoor greenery in enhancing IAQ, thermal comfort and energy efficiency in residential buildings, addressing a scale and domain that remain underrepresented in urban greening research. Through a systematic synthesis of field measurements, numerical simulations and empirical models, the review indicates that greenery at the building and plot scale has the potential to moderate indoor environmental conditions, particularly by reducing thermal loads and influencing ventilation and pollutant pathways, which may contribute to improvements in IAQ and reduced reliance on mechanical cooling. However, the evidence base remains fragmented across performance domains and climates, with limited studies integrating IAQ, thermal comfort and energy efficiency within a unified assessment framework. Moreover, the absence of standardised design thresholds and climate-responsive guidance constrains the translation of research findings into practice. Addressing these gaps is essential for advancing private outdoor greenery from a qualitative sustainability concept to a quantifiable, evidence-based design strategy for healthier and more energy-efficient housing.

Key conclusions include the following:

Performance potential: Private outdoor greenery can meaningfully improve IAQ, enhance thermal comfort and reduce energy demand at the residential scale, particularly in dense and low-greenery urban contexts.

Design dependency: Outcomes are strongly conditioned by green area index, vegetation type and spatial layout, underscoring the need for climate- and typology-specific design guidance.

Research gap: Integrated assessments and validated design thresholds remain scarce, highlighting priorities for future empirical and multi-scale research.

Nomenclature

GFS	green factor score
GPR	green plot ratio
IAQ	indoor air quality
LAI	leaf area index
LSTs	land surface temperatures
MRT	mean radiant temperature
NO_2	nitrogen dioxide
PET	physiological equivalent temperature
$PM_{2.5}$	particulate matter with aerodynamic diameter $\leq 2.5\mu m$
PM_{10}	particulate matter with aerodynamic diameter $\leq 10\mu m$
RH	relative humidity
UGF	urban greening factor
UGI	urban green infrastructure
UHI	urban heat island

Author Contributions

Vali Shishebori: conceptualisation, methodology, investigation, formal analysis, writing – original draft, writing – review and editing, visualisation. **Nima Izadyar:** conceptualisation, supervision, methodology, writing – review and editing, project administration. **Elmira Jamei:** conceptualisation, supervision, writing – review and editing. **Keivan Bamdad:** supervision, writing – review and editing, validation. **Mahsan Sadeghi:** supervision, writing – review and editing, validation/resources.

Acknowledgments

During the preparation of this work, the authors used an OpenAI tool to enhance language and readability. After using the tool, the authors reviewed and edited the content as needed. They take full responsibility for the final content of the publication. The authors highlight that AI's role was to assist in refining the text and language, and not to replace any critical tasks of the authors.

Funding

This research is supported by an Australian Government Research Training Program (RTP) Scholarship. Also, this work was supported by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), PhD top-up fund (Position Number: 50100673). Open access publishing facilitated by Victoria University, as part of the Wiley - Victoria University agreement via the Council of Australasian University Librarians.

Disclosure

All authors have read and approved the final version of the manuscript. Nima Izadyar had full access to all of the data in this study and takes complete responsibility for the integrity of the data and the accuracy of the data analysis.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

References

1. V. Saxena, "Water Quality, Air Pollution, and Climate Change: Investigating the Environmental Impacts of Industrialization and Urbanization," *Water, Air, & Soil Pollution* 236, no. 2 (2025): 1–40, https://doi.org/10.1007/s11270-024-07702-4.

2. X. Zhang, L. Han, H. Wei, et al., "Linking Urbanization and Air Quality Together: A Review and a Perspective on the Future Sustainable Urban Development," *Journal of Cleaner Production* 346 (2022): 130988, https://doi.org/10.1016/j.jclepro.2022.130988.

3. J. Qian, L. Zhang, U. Schlink, X. Hu, Q. Meng, and J. Gao, "Impact of Urban Land Use and Anthropogenic Heat on Winter and Summer Outdoor Thermal Comfort in Beijing," *Urban Climate* 59 (2025): 102306, https://doi.org/10.1016/j.uclim.2025.102306.

4. S. Cheval, V. A. Amihăesei, Z. Chitu, et al., "A Systematic Review of Urban Heat Island and Heat Waves Research (1991–2022)," *Climate Risk Management* 44 (2024): 100603, https://doi.org/10.1016/j.crm.2024.100603.

5. T. Evgenia, A. Mela, and A. Tseliou, "Thermal Stress in Outdoor Spaces During Mediterranean Heatwaves: A PET and UTCI Analysis of Different Demographics," *Urban Science* 8, no. 4 (2024): 193, https://doi.org/10.3390/urbansci8040193.

6. M. Han, T. Zhang, and Z. Si, "Optimizing Urban Blue-Green Space in Climate Adaptive Planning: A Systematic Review of Threshold Value of Efficiency Thresholds," *Landscape Ecology* 40, no. 1 (2025): 1–20, https://doi.org/10.1007/s10980-024-02036-2.

7. M. Yao, M. Smith, and C. Peng, "Modelling the Effects of Vegetation and Urban Form on Air Quality in Real Urban Environments: A Systematic Review of Measurements, Methods, and Predictions," *Urban Forestry & Urban Greening* 105 (2025): 128693, https://doi.org/10.1016/j.ufug.2025.128693.

8. J. Zhao, E. Uhde, T. Salthammer, et al., "Long-Term Prediction of the Effects of Climate Change on Indoor Climate and Air Quality," *Environmental research* 243 (2024): 117804, https://doi.org/10.1016/j.envres.2023.117804.

9. R. Borck, and P. Schrauth, "Urban Pollution: A Global Perspective," *Journal of Environmental Economics and Management* 126 (2024): 103013, https://doi.org/10.1016/j.jeem.2024.103013.

10. B. Augusto, D. Lopes, S. Rafael, M. C. Coelho, and J. Ferreira, "Assessing the Impact of Different Urban Morphology Scenarios on Air Pollutant Emissions Distribution," *Science of The Total Environment* 950 (2024): 175341, https://doi.org/10.1016/j.scitotenv.2024.175341.

11. L. Obeidat, J. R. Jones, D. M. Mahaftha, A. I. Amhamed, and O. F. Alrebei, "Optimizing Indoor Air Quality and Energy Efficiency in Multifamily Residences: Advanced Passive Pipe System Parametrics Study," *International Journal of Environmental Science and Technology* 21, no. 16 (2024): 10003–10026, https://doi.org/10.1007/s13762-024-05624-6.

12. A. G. Mombeni, and F. Tariku, "Urban Heat Island Effect on Building Energy Consumption: ANN Method Application," in *International Association of Building Physics* (Springer, 2025), 358–363, https://doi.org/10.1007/978-981-97-8309-0_48.

13. M. Wang, and Z. Gou, "The Impact of Cooling Strategies on Urban Microclimates and Building Energy Consumption: A Study of a Street Canyon in Melbourne," *Energy and Built Environment* 7, no. 3 (2026): 571–587, https://doi.org/10.1016/j.enbenv.2025.01.005.

14. S. Xu, Y. Chen, J. Liu, et al., "Comprehensive Improvement of Energy Efficiency and Indoor Environmental Quality for University Library Atrium—A Multi-Objective Fast Optimization Framework," *Frontiers of Architectural Research* 14, no. 2 (2025): 449–470, https://doi.org/10.1016/j.foar.2024.08.010.

15. S. Kumar, K. Sakagami, and H. P. Lee, "Beyond Sustainability: The Role of Regenerative Design in Optimizing Indoor Environmental Quality," *Sustainability* 17, no. 6 (2025): 2342, https://doi.org/10.3390/su17062342.

16. I. L. Niza, A. M. Bueno, M. G. da Silva, and E. E. Broday, "Air Quality and Ventilation: Exploring Solutions for Healthy and Sustainable Urban Environments in Times of Climate Change,"

Results in Engineering 27 (2024): 103157, https://doi.org/10.1016/j.rineng.2024.103157.

17. G. Ulpiani, E. Pisoni, J. Bastos, F. Monforti-Ferrario, and N. Vetters, "Are Cities Ready to Synergise Climate Neutrality and Air Quality Efforts?," *Sustainable Cities and Society* 118 (2025): 106059, https://doi.org/10.1016/j.scs.2024.106059.

18. A. Mansouri, W. Wei, J. M. Alessandrini, C. Mandin, and P. Blondeau, "Impact of Climate Change on Indoor Air Quality: A Review," *International Journal of Environmental Research and Public Health* 19, no. 23 (2022): 15616, https://doi.org/10.3390/ijerph192315616.

19. I. L. Niza, A. M. Bueno, and E. E. Broday, "Indoor Environmental Quality (IEQ) and Sustainable Development Goals (SDGs): Technological Advances, Impacts and Challenges in the Management of Healthy and Sustainable Environments," *Urban Science* 7, no. 3 (2023): 96, https://doi.org/10.3390/urbansci7030096.

20. Z. Qi, and C. Ren, "Optimising Heat Transfer and Ventilation in Interior Architecture for Enhanced Human Thermal Comfort," *International Journal of Heat & Technology* 41, no. 4 (2023): 910–918, https://doi.org/10.18280/ijht.410413.

21. L. Ramakreshnan, and N. Aghamohammadi, "The Application of Nature-Based Solutions for Urban Heat Island Mitigation in Asia: Progress, Challenges, and Recommendations," *Current Environmental Health Reports* 11, no. 1 (2024): 4–17, https://doi.org/10.1007/s40572-023-00427-2.

22. Y. Lin, T. Huang, W. Yang, X. Hu, and C. Li, "A Review on the Impact of Outdoor Environment on Indoor Thermal Environment," *Buildings* 13, no. 10 (2023): 2600, https://doi.org/10.3390/buildings13102600.

23. A. Wang, Y. Dai, M. Zhang, and E. Chen, "Exploring the Cooling Intensity of Green Cover on Urban Heat Island: A Case Study of Nine Main Urban Districts in Chongqing," *Sustainable Cities and Society* 124 (2025): 106299, https://doi.org/10.1016/j.scs.2025.106299.

24. C. Xi, L. Han, J. Wang, Z. Feng, P. Kumar, and S. J. Cao, "How Can Greenery Space Mitigate Urban Heat Island? An Analysis of Cooling Effect, Carbon Sequestration, and Nurturing Cost at the Street Scale," *Journal of Cleaner Production* 419 (2023): 138230, https://doi.org/10.1016/j.jclepro.2023.138230.

25. G. Battista, E. de Lieto Vollaro, P. Ocłoń, and R. de Lieto Vollaro, "Effects of Urban Heat Island Mitigation Strategies in an Urban Square: A Numerical Modelling and Experimental Investigation," *Energy and Buildings* 282 (2023): 112809, https://doi.org/10.1016/j.enbuild.2023.112809.

26. B. Raji, M. J. Tenpierik, and A. Van Den Dobbelsteen, "The Impact of Greening Systems on Building Energy Performance: A Literature Review," *Renewable and Sustainable Energy Reviews* 45 (2015): 610–623, https://doi.org/10.1016/j.rser.2015.02.011.

27. T. Ahmed, P. Kumar, and L. Mottet, "Natural Ventilation in Warm Climates: The Challenges of Thermal Comfort, Heatwave Resilience and Indoor Air Quality," *Renewable And Sustainable Energy Reviews* 138 (2021): 110669, https://doi.org/10.1016/j.rser.2020.110669.

28. A. Hashemi, and M. Dungrani, "Indoor Environmental Quality and Health Implications of Building Retrofit and Occupant Behaviour in Social Housing," *Sustainability* 17, no. 1 (2025): 264, https://doi.org/10.3390/su17010264.

29. D. H. Duarte, P. Shinzato, C. . S. Gusson, and C. A. Alves, "The Impact of Vegetation on Urban Microclimate to Counterbalance Built Density in a Subtropical Changing Climate," *Urban Climate* 14 (2015): 224–239, https://doi.org/10.1016/j.uclim.2015.09.006.

30. A. Kumar, P. Ekka, M. Upreti, Shilky, and P. Saikia, "Urban Green Spaces for Environmental Sustainability and Climate Resilience," in *The Palgrave Handbook of Socio-ecological Resilience in the Face of Climate Change: Contexts from a Developing Country* (Springer, 2023), 389–409, https://doi.org/10.1007/978-981-99-2206-2_23.

31. G. Zheng, H. Xu, F. Liu, and J. Dong, "Impact of Plant Layout on Microclimate of Summer Courtyard Space Based on Orthogonal Experimental Design," *Sustainability* 16, no. 11 (2024): 4425, https://doi.org/10.3390/su16114425.

32. J. Bi, L. A. Wallace, J. A. Sarnat, and Y. Liu, "Characterizing Outdoor Infiltration and Indoor Contribution of PM2. 5 With Citizen-Based Low-Cost Monitoring Data," *Environmental Pollution* 276 (2021): 116763, https://doi.org/10.1016/j.envpol.2021.116763.

33. W. Klemm, B. G. Heusinkveld, S. Lenzholzer, M. H. Jacobs, and B. van Hove, "Psychological and Physical Impact of Urban Green Spaces on Outdoor Thermal Comfort During Summertime in The Netherlands," *Building and environment* 83 (2015): 120–128, https://doi.org/10.1016/j.buildenv.2014.05.013.

34. P. K. Saha, A. Habib, D. R. Prapti, et al., "Characterizing Indoor-Outdoor PM2. 5 Concentrations Using Low-Cost Sensor Measurements in Residential Homes in Dhaka, Bangladesh," *Atmospheric Environment* 342 (2025): 120945, https://doi.org/10.1016/j.atmosenv.2024.120945.

35. A. Jarrahi, A. Aflaki, M. Khakpour, and M. Esfandiari, "Enhancing Indoor Air Quality: Harnessing Architectural Elements, Natural Ventilation and Passive Design Strategies for Effective Pollution Reduction—A Comprehensive Review," *Science of The Total Environment* 954 (2024): 176631, https://doi.org/10.1016/j.scitotenv.2024.176631.

36. R. San Jose, and J. L. Perez-Camanyo, "Modelling Infiltration Rate Impacts on Indoor Air Quality," *International Journal of Thermofluids* 17 (2023): 100284, https://doi.org/10.1016/j.ijft.2023.100284.

37. N. Fu, M. K. Kim, L. Huang, J. Liu, B. Chen, and S. Sharples, "Experimental and Numerical Analysis of Indoor Air Quality Affected by Outdoor Air Particulate Levels (PM1. 0, PM2. 5 and PM10), Room Infiltration Rate, and Occupants' Behaviour," *Science of The Total Environment* 851 (2022): 158026, https://doi.org/10.1016/j.scitotenv.2022.158026.

38. S. Falasca, M. Zinzi, A. M. Siani, G. Curci, L. Ding, and M. Santamouris, "Investigating the Effects of the Greenery Increase on Air Temperature, Ventilation and Cooling Energy Demand in Melbourne With the Weather Research and Forecasting model and Local Climate Zones," *Science of the Total Environment* 953 (2024): 176016, https://doi.org/10.1016/j.scitotenv.2024.176016.

39. B. Biagi, E. Brattich, C. Cintolesi, F. Barbano, and S. di Sabatino, "Dynamical and Chemical Impacts of Urban Green Areas on Air Pollution in a City Environment," *Urban Climate* 60 (2025): 102343, https://doi.org/10.1016/j.uclim.2025.102343.

40. X. Duan, H. Gu, S. S. Lam, et al., "Recent Progress on Phytoremediation of Urban Air Pollution," *Chemosphere* 349 (2024): 140821, https://doi.org/10.1016/j.chemosphere.2023.140821.

41. M. S. Gustafsson, J. Lindén, E. M. M. Johansson, Å. K. Watne, and H. Pleijel, "Air Pollution Removal With Urban Greenery–Introducing the Vegetation Impact Dynamic Assessment model (VIDA)," *Atmospheric Environment* 323 (2024): 120397, https://doi.org/10.1016/j.atmosenv.2024.120397.

42. A. Yasmin, I. Ahmed, M. Haider, M. K. Hossain, M. A. Motalib, and M. S. Hossain, "Characterizing Indoor Air Quality and Identifying Factors Influencing Air Quality at Home Microenvironment in Dhaka City," *Indoor Environments* 1, no. 4 (2024): 100056, https://doi.org/10.1016/j.indenv.2024.100056.

43. Q.-O. Lu, W. H. Chang, H. J. Chu, and C. C. Lee, "Enhancing Indoor PM2. 5 Predictions Based on Land Use and Indoor Environmental Factors by Applying Machine Learning and Spatial Modeling Approaches," *Environmental Pollution* 363 (2024): 125093, https://doi.org/10.1016/j.envpol.2024.125093.

44. P. Sanju, "The Role of Urban Green Spaces in Mitigating Urban Heat Island Effect Amidst Climate Change," *Research Journal of*

Chemistry and Environment 29, no. 1 (2025): 75–84, https://doi.org/10.25303/291rjce075084.

45. B. Gherri, "Urban Green Spaces and Their Role in Responding to the Heat Island Effect in Historical Urban Context," in *Sustainability in Energy and Buildings* (Springer, 2024), 457–470, https://doi.org/10.1007/978-981-99-8501-2_40.

46. M. Aboulnaga, A. Trombadore, M. Mostafa, et al., "Understanding Urban Heat Island Effect: Causes, Impacts, Factors, and Strategies for Better Livability and Climate Change Mitigation and Adaptation," in *Livable Cities: Urban Heat Islands Mitigation for Climate Change Adaptation Through Urban Greening* (Springer, 2024), 283–366, https://doi.org/10.1007/978-3-031-51220-9_2.

47. A. Mohajerani, J. Bakaric, and T. Jeffrey-Bailey, "The Urban Heat Island Effect, Its Causes, and Mitigation, With Reference to the Thermal Properties of Asphalt Concrete," *Journal Of Environmental Management* 197 (2017): 522–538, https://doi.org/10.1016/j.jenvman.2017.03.095.

48. M. B. Karuppasamy, U. Natesan, S. Karuppannan, et al., "Multivariate Urban Air Quality Assessment of Indoor and Outdoor Environments at Chennai Metropolis in South India," *Atmosphere* 13, no. 10 (2022): 1627, https://doi.org/10.3390/atmos13101627.

49. C. M. Raymond, N. Frantzeskaki, N. Kabisch, et al., "A Framework for Assessing and Implementing the Co-Benefits of Nature-Based Solutions in Urban Areas," *Environmental Science & Policy* 77 (2017): 15–24, https://doi.org/10.1016/j.envsci.2017.07.008.

50. T. E. Panduro, D. Nainggolan, and M. Zandersen, "Cost-Effectiveness Analysis of Urban Nature-Based Solutions: A Stepwise Ranking approach," *Solutions* 6 (2024): 100186, https://doi.org/10.1016/j.nbsj.2024.100186.

51. M. Li, R. P. Remme, P. M. van Bodegom, and A. P. E. van Oudenhoven, "Solution to What? Global Assessment of Nature-Based Solutions, Urban Challenges, and Outcomes," *Landscape and Urban Planning* 256 (2025): 105294, https://doi.org/10.1016/j.landurbplan.2025.105294.

52. J. Sahani, P. Kumar, and S. E. Debele, "Efficacy Assessment of Green-Blue Nature-Based Solutions Against Environmental Heat Mitigation," *Environment International* 179 (2023): 108187, https://doi.org/10.1016/j.envint.2023.108187.

53. V. Enzi, B. Cameron, P. Dezsényi, D. Gedge, G. Mann, and U. Pitha, "Nature-Based Solutions and Buildings–The Power of Surfaces to Help Cities Adapt to Climate Change and to Deliver Biodiversity," in *Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice* (Springer International Publishing, 2017), 159–183, https://doi.org/10.1007/978-3-319-56091-5_10.

54. UNEP, "Nature-Based Solutions: Opportunities and Challenges for Scaling Up," (2022), https://wedocs.unep.org/handle/20.500.11822/40783.

55. R. Bologna, and G. Hasanaj, "A Systematic Catalogue of Design Solutions for the Regeneration of Urban Environment Contrasting the Climate Change Impact," in *Technological Imagination in the Green and Digital Transition* (Springer, 2023), 601–616, https://doi.org/10.1007/978-3-031-29515-7_54.

56. C. Wang, Z. H. Wang, K. E. Kaloush, and J. Shacat, "Cool Pavements for Urban Heat Island Mitigation: A Synthetic Review," *Renewable and Sustainable Energy Reviews* 146 (2021): 111171, https://doi.org/10.1016/j.rser.2021.111171.

57. L. Gillerot, D. Landuyt, P. de Frenne, B. Muys, and K. Verheyen, "Urban Tree Canopies Drive Human Heat Stress Mitigation," *Urban Forestry & Urban Greening* 92 (2024): 128192, https://doi.org/10.1016/j.ufug.2023.128192.

58. A. Shaamala, T. Yigitcanlar, A. Nili, and D. Nyandega, "Strategic Tree Placement for Urban Cooling: A Novel Optimisation Approach for Desired Microclimate Outcomes," *Urban Climate* 56 (2024): 102084, https://doi.org/10.1016/j.uclim.2024.102084.

59. A. Saqib, M. S. U. Khan, and I. A. Rana, "Bridging Nature And Urbanity Through Green Roof Resilience Framework (GRF): A Thematic Review," *Nature-Based Solutions* 6 (2024): 100182, https://doi.org/10.1016/j.nbsj.2024.100182.

60. Y. Fang, X. Du, H. Zhao, M. Hu, and X. Xu, "Assessment of Green Roofs' Potential to Improve the Urban Thermal Environment: The Case of Beijing," *Environmental Research* 237 (2023): 116857, https://doi.org/10.1016/j.envres.2023.116857.

61. A. Xu, J. Shi, L. Zhao, T. Ji, and X. Meng, "Urban Ventilation Network Identification to Mitigate Heat Island Effect," *Sustainable Cities and Society* 125 (2025): 106364, https://doi.org/10.1016/j.scs.2025.106364.

62. A. Aflaki, M. Mirnezhad, A. Ghaffarianhoseini, et al., "Urban Heat Island Mitigation Strategies: A State-of-the-Art Review on Kuala Lumpur, Singapore and Hong Kong," *Singapore and Hong Kong. Cities* 62 (2017): 131–145, https://doi.org/10.1016/j.cities.2016.09.003.

63. Y. Zhao, J. Yang, Z. Fang, X. Zhang, T. Guo, and Y. Li, "Passive Design Strategies to Improve Student Thermal Comfort: A Field Study in Semi-Outdoor Spaces of Academic Buildings in Hot-Humid Areas," *Urban Climate* 53 (2024): 101807, https://doi.org/10.1016/j.uclim.2024.101807.

64. C. Díaz-López, A. Serrano-Jiménez, J. Lizana, E. López-García, M. Molina-Huelva, and Á. Barrios-Padura, "Passive Action Strategies in Schools: A Scientific Mapping Towards Eco-Efficiency in Educational Buildings," *Journal of Building Engineering* 45 (2022): 103598, https://doi.org/10.1016/j.jobe.2021.103598.

65. Y. L. Song, K. S. Darani, A. I. Khdair, G. Abu-Rumman, and R. Kalbasi, "A Review on Conventional Passive Cooling Methods Applicable to Arid and Warm Climates Considering Economic Cost and Efficiency Analysis in Resource-Based Cities," *Energy Reports* 7 (2021): 2784–2820, https://doi.org/10.1016/j.egyr.2021.04.056.

66. X. Guo, C. Liu, S. Bi, and Y. Tang, "Identification of Inequities in Green Visibility and Ways to Increase Greenery in Neighborhoods: A Case Study of Wuhan, China," *Applied Sciences* 15, no. 2 (2025): 742, https://doi.org/10.3390/app15020742.

67. G. Mihalakakou, M. Souliotis, M. Papadaki, et al., "Green Roofs as a Nature-Based Solution for Improving Urban Sustainability: Progress and Perspectives," *Renewable and Sustainable Energy Reviews* 180 (2023): 113306, https://doi.org/10.1016/j.rser.2023.113306.

68. D. Lai, Y. Liu, M. Liao, and B. Yu, "Effects of Different Tree Layouts on Outdoor Thermal Comfort of Green Space in Summer Shanghai," *Urban Climate* 47 (2023): 101398, https://doi.org/10.1016/j.uclim.2022.101398.

69. C. Lin, Z. Wu, H. Li, J. Huang, and Q. Huang, "Comprehensive Analysis on the Thermal Comfort of Various Greening Forms: A Study in Hot-Humid Areas," *Environmental Research Communications* 6, no. 2 (2024): 025010, https://doi.org/10.1088/2515-7620/ad277e.

70. J. Li, Z. Zhai, Y. Ding, et al., "Effect of Optimal Allocation of Urban Trees on the Outdoor Thermal Environment in Hot and Humid Areas: A Case Study of a University Campus in Guangzhou, China," *China. Energy and Buildings* 300 (2023): 113640, https://doi.org/10.1016/j.enbuild.2023.113640.

71. N. Meili, G. Manoli, P. Burlando, et al., "Tree Effects on Urban Microclimate: Diurnal, Seasonal, and Climatic Temperature Differences Explained by Separating Radiation, Evapotranspiration, and Roughness Effects," *Urban Forestry & Urban Greening* 58 (2021): 126970, https://doi.org/10.1016/j.ufug.2020.126970.

72. A. Ehab, G. Burnett, and T. Heath, "Elevating the Public Realm: A Framework for Designing Resilient Urban Green Spaces in Hyperdense Cities," *Discover Sustainability* 6, no. 1 (2025): 10, https://doi.org/10.1007/s43621-024-00755-9.

73. S.-H. Hung, "Does Perceived Biophilic Design Contribute to Human Well-Being in Urban Green Spaces? A Study of Perceived Naturalness, Biodiversity, Perceived Restorativeness, and Subjective Vitality," *Urban Forestry & Urban Greening* 107 (2025): 128752, https://doi.org/10.1016/j.ufug.2025.128752.

74. J. Krischke, A. Beckmann-Wübbelt, R. Glaser, S. Dey, and S. Saha, "Relationship Between Urban Tree Diversity and Human Well-being: Implications for Urban Planning," *Sustainable Cities and Society* 124 (2025): 106294, https://doi.org/10.1016/j.scs.2025.106294.

75. F. Zhang, and H. Qian, "A Comprehensive Review of the Environmental Benefits of Urban Green Spaces," *Environmental Research* 252 (2024): 118837, https://doi.org/10.1016/j.envres.2024.118837.

76. S. Khalili, P. Kumar, and L. Jones, "Evaluating the Benefits of Urban Green Infrastructure: Methods, Indicators, and Gaps," *Heliyon* 10, no. 19 (2024): , https://doi.org/10.1016/j.heliyon.2024.e38446e38446.

77. J. Liao, and H. Y. Kim, "The Relationship Between Green Infrastructure and Air Pollution, History, Development, and Evolution: A Bibliometric Review," *Sustainability* 16, no. 16 (2024): 6765, https://doi.org/10.3390/su16166765.

78. N. Abdollahzadeh, and N. Biloria, "Outdoor Thermal Comfort: Analyzing the Impact of Urban Configurations on the Thermal Performance of Street Canyons in the Humid Subtropical Climate of Sydney," *Frontiers of Architectural Research* 10, no. 2 (2021): 394–409, https://doi.org/10.1016/j.foar.2020.11.006.

79. C. Silveira, A. T. C. Dias, F. G. Amaral, G. de Gois, and N. Pistón, "The Importance of Private Gardens and Their Spatial Composition and Configuration to Urban Heat Island Mitigation," *Sustainable Cities and Society* 112 (2024): 105589, https://doi.org/10.1016/j.scs.2024.105589.

80. S. Zheng, C. He, J. M. Guldmann, H. Xu, and X. Liu, "Heat Mitigation Benefits of Urban Trees: A Review of Mechanisms, Modeling, Validation and Simulation," *Forests* 14, no. 12 (2023): 2280, https://doi.org/10.3390/f14122280.

81. Y. Luo, Z. Yin, Q. Liang, et al., "Effects of Tree Characteristics and Arcade Design on the Traffic Pollutant Dispersion Inside the Asymmetric Street Canyon," *Sustainable Cities and Society* 122 (2025): 106244, https://doi.org/10.1016/j.scs.2025.106244.

82. A. Harbiankova, and M. Manso, "Integrating Green Roofs and Green Walls to Enhance Buildings Thermal Performance: A Literature Review," *Building and Environment* 270 (2025): 112524, https://doi.org/10.1016/j.buildenv.2025.112524.

83. Y. A. Basyouni, and H. Mahmoud, "Affordable Green Materials for Developed Cool Roof Applications: A Review," *Renewable and Sustainable Energy Reviews* 202 (2024): 114722, https://doi.org/10.1016/j.rser.2024.114722.

84. S. Batasuma, W. Cao, N. A. Atigah, E. A. Garnet, J. K. Bonzo, and J. Gyimah, "Drivers in the Conservation of Urban Green Space Depletion: A Case Study of Wa Municipality, Ghana," *City and Environment Interactions* 25 (2025): 100186, https://doi.org/10.1016/j.cacint.2024.100186.

85. X. Guo, Z. Gao, R. Buccolieri, M. Zhang, and J. Shen, "Effect of Greening on Pollutant Dispersion and Ventilation at Urban Street Intersections," *Building and Environment* 203 (2021): 108075, https://doi.org/10.1016/j.buildenv.2021.108075.

86. D. Murugadoss, H. Singh, and P. Thakur, "Urban Forests and Microclimate Regulation," in *Urban Forests, Climate Change and Environmental Pollution* (Springer, 2024), 531–550, https://doi.org/10.1007/978-3-031-67837-0_25.

87. C. Pereira, I. Flores-Colen, and M. P. Mendes, "Guidelines to Reduce the Effects of Urban Heat in a Changing Climate: Green Infrastructures and Design Measures," *Sustainable Development* 32, no. 1 (2024): 57–83, https://doi.org/10.1002/sd.2646.

88. B. M. Ali, and M. Akkaş, "The Green Cooling Factor: Eco-Innovative Heating, Ventilation, and Air Conditioning Solutions in Building Design," *Applied Sciences* 14, no. 1 (2024): 195, https://doi.org/10.3390/app14010195.

89. R. C. Nnaemeka-Okeke, and C. A. Umerie, "Integrating Nature-Based Solutions and Green Building Standards in Healthcare Facilities in Winnipeg, Canada," in *Housing and Sustainability-Achieving a Sustainable Future* (IntechOpen, 2024), https://doi.org/10.5772/intechopen.1007403.

90. N. Rawat, and P. Kumar, "Interventions for Improving Indoor and Outdoor Air Quality in and Around Schools," *Science of The Total Environment* 858 (2023): 159813, https://doi.org/10.1016/j.scitotenv.2022.159813.

91. J. Lindén, M. Gustafsson, J. Uddling, Å. Watne, and H. Pleijel, "Air Pollution Removal Through Deposition on Urban Vegetation: The Importance of Vegetation Characteristics," *Urban Forestry & Urban Greening* 81 (2023): 127843, https://doi.org/10.1016/j.ufug.2023.127843.

92. K. Xhexhi, "Climate Parameters, Heat Islands, and the Role of Vegetation in the City," in *Ecovillages and Ecocities: Bioclimatic Applications From Tirana, Albania* (Springer International Publishing, 2023), 149–170, https://doi.org/10.1007/978-3-031-20959-8_6.

93. B. Hong, H. Qin, R. Jiang, M. Xu, and J. Niu, "How Outdoor Trees Affect Indoor Particulate Matter Dispersion: CFD Simulations in a Naturally Ventilated Auditorium," *International Journal of Environmental Research and Public Health* 15, no. 12 (2018): 2862, https://doi.org/10.3390/ijerph15122862.

94. M. Taleghani, A. Clark, W. Swan, and A. Mohegh, "Air Pollution in a Microclimate; The Impact of Different Green Barriers on the Dispersion," *Science of the Total Environment* 711 (2020): 134649, https://doi.org/10.1016/j.scitotenv.2019.134649.

95. L. Rui, R. Buccolieri, Z. Gao, W. Ding, and J. Shen, "The Impact of Green Space Layouts on Microclimate and Air Quality in Residential Districts of Nanjing, China," *Forests* 9, no. 4 (2018): 224, https://doi.org/10.3390/f9040224.

96. J. Ge, Y. Wang, H. Akbari, D. Zhou, Z. Gu, and X. Meng, "Cooling Energy Saving by Vegetation Planting in High-Density Districts: Evaluation Using the Coupled Simulation," *Building and Environment* 232 (2023): 110054, https://doi.org/10.1016/j.buildenv.2023.110054.

97. Q. Dong, X. Xu, and M. Zhen, "Assessing the Cooling and Buildings' Energy-Saving Potential of Urban Trees in Severe Cold Region of China During Summer," *Building and Environment* 244 (2023): 110818, https://doi.org/10.1016/j.buildenv.2023.110818.

98. Y. Park, Q. Zhao, J. M. Guldmann, and E. A. Wentz, "Quantifying the Cumulative Cooling Effects of 3D Building and Tree Shade With High Resolution Thermal Imagery in a Hot Arid Urban Climate," *Landscape and Urban Planning* 240 (2023): 104874, https://doi.org/10.1016/j.landurbplan.2023.104874.

99. Y. Wang, F. Bakker, R. de Groot, H. Wortche, and R. Leemans, "Effects of Urban Trees on Local Outdoor Microclimate: Synthesizing Field Measurements by Numerical Modelling," *Urban Ecosystems* 18, no. 4 (2015): 1305–1331, https://doi.org/10.1007/s11252-015-0447-7.

100. Y. Wang, U. Berardi, and H. Akbari, "Comparing the Effects of Urban Heat Island Mitigation Strategies for Toronto," *Canada. Energy and Buildings* 114 (2016): 2–19, https://doi.org/10.1016/j.enbuild.2015.06.046.

101. O. Soydan, "Effects of Landscape Composition and Patterns on Land Surface Temperature: Urban Heat Island Case Study for Nigde, Turkey," *Urban Climate* 34 (2020): 100688, https://doi.org/10.1016/j.uclim.2020.100688.

102. C.-M. Hsieh, J. J. Li, L. Zhang, and B. Schwegler, "Effects of Tree Shading and Transpiration on Building Cooling Energy Use," *Energy and Buildings* 159 (2018): 382–397, https://doi.org/10.1016/j.enbuild.2017.10.045.

103. V. Pappa, D. Bouris, W. Theurer, and C. Gromke, "A Wind Tunnel Study of Aerodynamic Effects of Façade and Roof Greening on Air Exchange From a Cubic Building," *Building and Environment* 231 (2023): 110023, https://doi.org/10.1016/j.buildenv.2023.110023.

104. A. R. Trihamdani, H. Lee, T. Kubota, and T. Phuong, "Configuration of Green Spaces for Urban Heat Island Mitigation and Future Building Energy Conservation in Hanoi Master Plan 2030," *Buildings* 5, no. 3 (2015): 933–947, https://doi.org/10.3390/buildings5030933.

105. X. Xiao, J. Yuan, Z. Jiao, et al., "Shading Effects on Building Energy Performance: A Multi-City Analysis," *Results in Engineering* 27 (2025): 106870, https://doi.org/10.1016/j.rineng.2025.106870.

106. J. Ge, Y. Wang, D. Zhou, Z. Gu, and X. Meng, "Effects of Urban Vegetation on Microclimate and Building Energy Demand in Winter: An Evaluation Using Coupled Simulations," *Sustainable Cities and Society* 102 (2024): 105199, https://doi.org/10.1016/j.scs.2024.105199.

107. X. Zhang, J. W. G. Buddhika, J. Wang, A. U. Weerasuriya, and K. T. Tse, "Numerical Investigation of Effects of Trees on Cross-Ventilation of an Isolated Building," *Journal of Building Engineering* 73 (2023): 106808, https://doi.org/10.1016/j.jobe.2023.106808.

108. L. Deng, J. Wu, Y. Guo, W. Wang, F. Jiang, and X. Li, "Virtual Wall: Numerical Model on Interaction Between Trees and Building Façade to Quantify Heat Exchange and Microclimate in Urban Context," *Urban Climate* 56 (2024): 102001, https://doi.org/10.1016/j.uclim.2024.102001.

109. S. Adhikari, M. Struwig, and S. J. Siebert, "Identifying Common Trees and Herbaceous Plants to Mitigate Particulate Matter Pollution in a Semi-Arid Mining Region of South Africa," *Climate* 11, no. 1 (2023): 9, https://doi.org/10.3390/cli11010009.

110. N. J. Paull, P. J. Irga, and F. R. Torpy, "Active Botanical Biofiltration of Air Pollutants Using Australian Native Plants," *Air Quality, Atmosphere & Health* 12 (2019): 1427–1439, https://doi.org/10.1007/s11869-019-00758-w.

111. T. Grylls, and M. van Reeuwijk, "How Trees Affect Urban Air Quality: It Depends on the Source," *Atmospheric Environment* 290 (2022): 119275, https://doi.org/10.1016/j.atmosenv.2022.119275.

112. C. Miao, S. Yu, Y. Hu, et al., "Seasonal Effects of Street Trees on Particulate Matter Concentration in an Urban Street Canyon," *Sustainable Cities and Society* 73 (2021): 103095, https://doi.org/10.1016/j.scs.2021.103095.

113. Y. Yang, Y. Xu, Y. Duan, et al., "How Can Trees Protect Us From Air Pollution and Urban Heat? Associations and Pathways at the Neighborhood Scale," *Landscape and Urban Planning* 236 (2023): 104779, https://doi.org/10.1016/j.landurbplan.2023.104779.

114. J. Yan, W. Y. Chen, Z. Zhang, W. Zhao, M. Liu, and S. Yin, "Mitigating PM2.5 Exposure With Vegetation Barrier and Building Designs in Urban Open-Road Environments Based on Numerical Simulations," *Landscape and Urban Planning* 241 (2024): 104918, https://doi.org/10.1016/j.landurbplan.2023.104918.

115. A. Islam, N. Pattnaik, M. M. Moula, T. Rötzer, S. Pauleit, and M. A. Rahman, "Impact of Urban Green Spaces on Air Quality: A Study of PM10 Reduction Across Diverse Climates," *Science of the Total Environment* 955 (2024): 176770, https://doi.org/10.1016/j.scitotenv.2024.176770.

116. H. Ai, X. Zhang, and Z. Zhou, "The Impact of Greenspace on Air Pollution: Empirical Evidence From China," *Ecological indicators* 146 (2023): 109881, https://doi.org/10.1016/j.ecolind.2023.109881.

117. A. Diener, and P. Mudu, "How Can Vegetation Protect Us From Air Pollution? A Critical Review on Green Spaces' Mitigation Abilities for Air-Borne Particles From a Public Health Perspective-With Implications for Urban Planning," *Science of the Total Environment* 796 (2021): 148605, https://doi.org/10.1016/j.scitotenv.2021.148605.

118. D.-Y. Lin, S. T. Waller, and M.-Y. Lin, "A Review of Urban Planning Approaches to Reduce Air Pollution Exposures," *Current Environmental Health Reports* 11, no. 4 (2024): 557–566, https://doi.org/10.1007/s40572-024-00459-2.

119. L. Ji, C. Shu, A. Gaur, L. Wang, and M. Lacasse, "A State-of-the-Art Review of Studies on Urban Green Infrastructure for Thermal Resilient Communities," *Building and Environment* 257 (2024): 111524, https://doi.org/10.1016/j.buildenv.2024.111524.

120. E. Simá, M. A. Chagolla-Aranda, G. Huelsz, R. Tovar, and G. Alvarez, "Tree And Neighboring Buildings Shading Effects On The Thermal Performance Of A House In A Warm Sub-Humid Climate," *Building Simulation* 8 (2015): 711–723, https://doi.org/10.1007/s12273-015-0247-2.

121. Y. He, H. Yu, A. Ozaki, N. Dong, and S. Zheng, "A Detailed Investigation of Thermal Behavior of Green Envelope Under Urban Canopy Scale in Summer: A Case Study in Shanghai Area," *Energy and Buildings* 148 (2017): 142–154, https://doi.org/10.1016/j.enbuild.2017.03.014.

122. O. Rotem-Mindali, Y. Michael, D. Helman, and I. M. Lensky, "The Role of Local Land-Use on the Urban Heat Island Effect of Tel Aviv as Assessed From Satellite Remote Sensing," *Applied Geography* 56 (2015): 145–153, https://doi.org/10.1016/j.apgeog.2014.11.023.

123. M. Vatani, K. Kiani, M. Mahdavinejad, and M. Georgescu, "Evaluating the Effects of Different Tree Species on Enhancing Outdoor Thermal Comfort in a Post-Industrial Landscape," *Environmental Research Letters* 19, no. 6 (2024): 064051, https://doi.org/10.1088/1748-9326/ad49b7.

124. Y. Xiao, Y. Huang, and X. Pan, "Optimizing Thermal Comfort in Urban Squares of Hot-Humid Regions: A Case Study Considering Tree Growth, Species, and Planting Intervals," *Atmosphere* 16, no. 1 (2025): 63, https://doi.org/10.3390/atmos16010063.

125. S. Zheng, J. M. Guldmann, Z. Liu, and L. Zhao, "Influence of Trees on the Outdoor Thermal Environment in Subtropical Areas: An Experimental Study in Guangzhou, China," *Sustainable Cities and Society* 42 (2018): 482–497, https://doi.org/10.1016/j.scs.2018.07.025.

126. H.-W. Wu, P. Kumar, and S.-J. Cao, "Implementation of Green Infrastructure for Improving the Building Environment of Elderly Care Centres," *Journal of Building Engineering* 54 (2022): 104682, https://doi.org/10.1016/j.jobe.2022.104682.

127. A. Habiby, and L. Yaseen, A. Arora, F. Belaïd, and S. Lechtenberg-Kasten, "Riyadh's Urban Greenwave: Fostering City Resilience Through Large-Scale Greening," in *Climate-Resilient Cities* (Springer, 2025), 341–353, https://doi.org/10.1007/978-3-031-73090-0_16.

128. Y. Namazi, S. Charlesworth, A. Montazami, and M. Taleghani, "The Impact of Local Microclimates and Urban Greening Factor on Schools' Thermal Conditions During Summer: A Study in Coventry, UK," *Building and Environment* 262 (2024): 111793, https://doi.org/10.1016/j.buildenv.2024.111793.

129. J. Zheng, Z. Li, and B. Zheng, "A Study on the Effect of Green Plot Ratio (GPR) on Urban Heat Island Intensity and Outdoor Thermal Comfort in Residential Areas," *Forests* 15, no. 3 (2024): 518, https://doi.org/10.3390/f15030518.

130. J. Hurley, "Urban Policy and Planning - A Countermeasure to Urban Heat?," in *UHI 2023* (RMIT University, 2023)https://2uhi2023.com/.

131. Y. Yin, S. Li, X. Xing, et al., "Cooling Benefits of Urban Tree Canopy: A Systematic Review," *Sustainability* 16, no. 12 (2024): 4955, https://doi.org/10.3390/su16124955.

132. J. Wang, W. Zhou, Z. Zheng, M. Jiao, and Y. Qian, "Interactions Among Spatial Configuration Aspects of Urban Tree Canopy Significantly Affect Its Cooling Effects," *Science of The Total Environment* 864 (2023): 160929, https://doi.org/10.1016/j.scitotenv.2022.160929.

133. C. He, L. Zhou, Y. Yao, W. Ma, and P. L. Kinney, "Cooling Effect of Urban Trees and Its Spatiotemporal Characteristics: A Comparative Study," *Building and Environment* 204 (2021): 108103, https://doi.org/10.1016/j.buildenv.2021.108103.

134. F. Tariku, and A. Gharib Mombeni, "ANN-Based Method for Urban Canopy Temperature Prediction and Building Energy Simulation With Urban Heat Island Effect in Consideration," *Energies* 16, no. 14 (2023): 5335, https://doi.org/10.3390/en16145335.

135. M. A. Rahman, L. M. F. Stratopoulos, A. Moser-Reischl, et al., "Traits of Trees for Cooling Urban Heat Islands: A Meta-Analysis," *Building and Environment* 170 (2020): 106606, https://doi.org/10.1016/j.buildenv.2019.106606.

136. F. Marando, M. P. Heris, G. Zulian, et al., "Urban Heat Island Mitigation by Green Infrastructure in European Functional Urban Areas," *Sustainable Cities and Society* 77 (2022): 103564, https://doi.org/10.1016/j.scs.2021.103564.

137. X. D. Xiao, L. Dong, H. Yan, N. Yang, and Y. Xiong, "The Influence of the Spatial Characteristics of Urban Green Space on the Urban Heat Island Effect in Suzhou Industrial Park," *Sustainable Cities and Society* 40 (2018): 428–439, https://doi.org/10.1016/j.scs.2018.04.002.

138. T. Bao, X. Li, J. Zhang, Y. Zhang, and S. Tian, "Assessing the Distribution of Urban Green Spaces and Its Anisotropic Cooling Distance on Urban Heat Island Pattern in Baotou, China," *ISPRS International Journal of Geo-Information* 5, no. 2 (2016): 12, https://doi.org/10.3390/ijgi5020012.

139. J. Park, J. H. Kim, W. Sohn, and D. K. Lee, "Urban Cooling Factors: Do Small Greenspaces Outperform Building Shade in Mitigating Urban Heat Island Intensity?," *Urban Forestry & Urban Greening* 64 (2021): 127256, https://doi.org/10.1016/j.ufug.2021.127256.

140. J. Gao, C. Duan, J. Song, L. Ma, and W. Cai, "PM2.5 Can Help Adjust Building's Energy Consumption," *Journal of Environmental Management* 331 (2023): 117235, https://doi.org/10.1016/j.jenvman.2023.117235.

141. Z. Peng, Y. Cheng, M. Jiang, S. Shu, and X. Geng, "Potential Combination Strategies to Establish a Low-Energy Ventilation System for School Buildings in the Cold Climate Zone of China—A Demand-Oriented Review," *Journal of Building Engineering* 76 (2023): 107065, https://doi.org/10.1016/j.jobe.2023.107065.

142. P. Fitch, M. Battaglia, A. Lenton, et al., "Australia's Carbon Sequestration Potential: A Stocktake and Analysis of Sequestration Technologies," (2022)https://www.csiro.au/-/media/Missions/TNZ/CCA-report/CCA-Report-Australias-Potential-Sequestration-Final-28-November-2022.pdf.

143. G. Visvanathan, K. Patil, Y. Suryawanshi, V. Meshram, and S. Jadhav, "Mitigating Urban Heat Island and Enhancing Indoor Thermal Comfort Using Terrace Garden," *Scientific Reports* 14, no. 1 (2024): 9697, https://doi.org/10.1038/s41598-024-60546-0.

144. M. Taleghani, A. Marshall, R. Fitton, and W. Swan, "Renaturing a Microclimate: The Impact of Greening a Neighbourhood on Indoor Thermal Comfort During a Heatwave in Manchester, UK," *Solar Energy* 182 (2019): 245–255, https://doi.org/10.1016/j.solener.2019.02.062.

145. C. Xi, D. Wang, and S.-J. Cao, "Impacts of Trees-Grass Area Ratio on Thermal Environment, Energy Saving, and Carbon Benefits," *Urban Climate* 47 (2023): 101393, https://doi.org/10.1016/j.uclim.2022.101393.

146. M. C. Peel, B. L. Finlayson, and T. A. McMahon, "Updated World Map of the Köppen-Geiger Climate Classification," *Hydrology And Earth System Sciences* 11, no. 5 (2007): 1633–1644, https://doi.org/10.5194/hess-11-1633-2007.

147. B. L. Ong, "Green Plot Ratio: An Ecological Measure for Architecture and Urban Planning," *Landscape And Urban Planning* 63, no. 4 (2003): 197–211, https://doi.org/10.1016/S0169-2046(02)00191-3.

148. London Assembly, "London Plan Guidance: Urban Greening Factor," (2023)https://www.london.gov.uk/sites/default/files/2023-02/London%2520Plan%2520Guidance%2520-%2520Urban%2520Greening%2520Factor.pdf.

149. Council COM, "Green Factor Score," (2024)https://www.greenfactor.com.au/.

150. M. Mannan, and S. G. Al-Ghamdi, "Indoor Air Quality in Buildings: A Comprehensive Review on the Factors Influencing Air Pollution in Residential and Commercial Structure," *International Journal of Environmental Research and Public Health* 18, no. 6 (2021): 3276, https://doi.org/10.3390/ijerph18063276.

151. T. Mamani, R. F. Herrera, F. Muñoz-la Rivera, and E. Atencio, "Variables That Affect Thermal Comfort and Its Measuring Instruments: A Systematic Review," *Sustainability* 14, no. 3 (2022): 1773, https://doi.org/10.3390/su14031773.

152. A. M. Hassan, "UMC-Based Models: An Integrating UMC Performance Analysis and Numerical Methods," *Renewable and Sustainable Energy Reviews* 181 (2023): 113307, https://doi.org/10.1016/j.rser.2023.113307.

153. National Institute of Standard and Technology, "CONTAM," (2024)https://www.nist.gov/services-resources/software/contam.

154. A. D. Nimbarte, N. Smith, and B. Gopalakrishnan, "Human Factors Evaluation of Energy Visualization Dashboards," *Ergonomics in Design* 32, no. 1 (2024): 39–47, https://doi.org/10.1177/10648046211028693.

155. V. F. Mendes, A. S. Cruz, A. P. Gomes, and J. C. Mendes, "A Systematic Review of Methods for Evaluating the Thermal Performance of Buildings Through Energy Simulations," *Renewable and Sustainable Energy Reviews* 189 (2024): 113875, https://doi.org/10.1016/j.rser.2023.113875.

156. L. Pastore, R. Corrao, and P. K. Heiselberg, "The Effects of Vegetation on Indoor Thermal Comfort: The Application of a Multi-Scale Simulation Methodology on a Residential Neighborhood Renovation Case Study," *Energy and Buildings* 146 (2017): 1–11, https://doi.org/10.1016/j.enbuild.2017.04.022.

157. T. E. Morakinyo, K. W. D. K. C. Dahanayake, O. B. Adegun, and A. A. Balogun, "Modelling the Effect of Tree-Shading on Summer Indoor and Outdoor Thermal Condition of Two Similar Buildings in a Nigerian University," *Energy and Buildings* 130 (2016): 721–732, https://doi.org/10.1016/j.enbuild.2016.08.087.

Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Supporting Information.**

Appendix

TABLE A1 | Broader urban-scale and indirect evidence supporting functional pathways linking private outdoor greenery to indoor IAQ and thermal comfort.

Functional mechanism	Scale of evidence	Key findings	Supporting studies	Indoor relevance pathway
Pollutant attenuation (deposition and filtration)	Urban vegetation modelling; urban monitoring; regional source attribution;	Leaf roughness, branch complexity, stomatal conductance critical for PM and NO_2 deposition; up to 70% airborne dirt retained by planted streets; mature trees intercept up to 50 lbs particulates/year	[48, 91–95, 109–118]	Outdoor pollutant reduction influences indoor exposure via infiltration and air exchange
Shading and solar radiation control	Urban microclimate; neighbourhood simulations; building studies	7.5-m tree → 8%–12% annual cooling/heating savings; AC savings 25%–80%; deciduous trees block 35% winter and 85% summer irradiance	[22, 92, 96–99, 106, 119–127]	Reduced façade solar gains and cooling loads
Evapotranspirative cooling and UHI mitigation	Urban square; neighbourhood; satellite LST; district modelling	Grass pavers −1.35°C; vegetation −0.60°C; LST 5°C–10°C lower over green surfaces; distributed green spaces more effective than centralised	[25, 95, 99–102, 113, 128–136]	Reduced ambient air and surface temperatures affecting building envelope heat exchange
Vegetation configuration and spatial optimisation	District-scale coupled simulations	GPR 0.5–3.5 improved comfort; diminishing benefit when GPR > 3.5; low-rise districts show greater cooling-energy benefit	[96, 104, 137–139]	Quantifies threshold effects relevant for private plot greening
Wind modulation and air exchange	Wind tunnel building-scale experiment	Façade greening ↓ air exchange up to 19%; roof greening ↑ air exchange up to 13%	[95, 103]	Directly modifies ventilation-driven IAQ pathway
Energy–pollution interaction pathway	Building monitoring and regression analysis; building systems	1% increase indoor $PM_{2.5}$ → 1.478% increase lighting energy intensity; using low-energy ventilation systems	[22, 96–98, 100, 104, 105, 140, 141]	Demonstrates interaction between pollution and building energy use
Carbon sequestration and long-term atmospheric regulation	Regional climate strategy; urban vegetation literature	Forests absorbed ~19% state emissions; urban trees up to 15× more valuable than rural trees in CO_2 limitation	[92, 142]	Long-term atmospheric moderation (indirect indoor relevance)

TABLE A2 | Effects of greenery on indoor/outdoor environment.

Source	Input factor(s)	Output factor(s)	Results	Köppen classification	Scale	Methodology
[109]	●Leaf surface of six trees and six forbs	○Particulate matter pollution	●Tree and forb cultivation: captures large amounts of dust particles reaching up to 12 m above ground.	BSh	Urban	Field study
[119]	●UGI	○Thermal comfort	●UGI reduces ambient temperatures (~6°C) and building surface temperatures (up to 20°C), increases relative humidity (15%) and decreases wind speed near facades (43%).	Various	Urban/building	Review
[69]	●Input: greenery forms (tree height, crown diameter, diameter at breast height, green facades and green roofs)	○PET and THI	●Planting trees can reduce PET up to 4.8°C (0.2°C) in PET (temperature–humidity index or THI)	Cfa	Urban	Field study + simulation
[143]	●Grow bags in terrace garden	○Temperature and humidity (indoor and outdoor)	●Temperature reduction: lowers internal room temperature by 4°C–11°C; up to 14°C with a 2–3-ft soil bed and dense foliage.	As	Building	Field study + simulation
[128]	●UGF ●Tree shade ●Materials	○Air temperature, relative humidity, wind speed, globe temperature and surface temperature	●Tree shade: lowering air temperature and mean radiant temperature by up to 6.4°C and 22.9°C. ●Ts of natural grass was constantly less than 35°C.	Cfb	Building	Field study

(Continues)

Source	Input factor(s)	Output factor(s)	Results	Köppen classification	Scale	Methodology
[107]	●Trees' locations ●Geometry (height, width and thickness) ●Foliage (shape and thickness) ●Leaf area density ●Leaf drag coefficient	○Wind flow	●Trees shorter than 0.25H and thinner than 0.168H, with sparse conical foliage, are suitable upstream of buildings but should not be planted within 1H–3.5H, as they reduce cross-ventilation by 20%–24%. ●Maintain airflow, trees should be arranged either beyond 10H or closer than 1H upstream of ventilation openings.	Isolated simulated building	Building	Simulation
[103]	●Vegetation position	○Air exchange	●Green façade: decreases local air exchange rates by nearly 19%. ●Green roof: increases local air exchange rates by up to 13%.	Isolated simulated building	Building	Field study
[101]	●Landscape composition and patterns	○Land surface temperatures (LSTs)	●LSTs of the impervious surfaces are 5°C–10°C higher than that of the green surfaces.	BSk	Urban	Satellite imagery
[144]	●Land cover	○UHI ○Indoor thermal comfort	●By adding 17% more trees cooled the campus by 1.1°C and improved indoor thermal comfort by 20.8% on the hottest day.	Cfb	Urban	Field study + simulation

(Continues)

Source	Input factor(s)	Output factor(s)	Results	Köppen classification	Scale	Methodology
[99]	●Trees	○Local urban microclimate ○Human thermal comfort	●Trees reduced 'very hot' and 'hot' perception by 16% on sunny and 11% on cloudy days during the hottest hours. ●No substantial changes in CR and Ta/RH range among sites on cloudy/cool days ($p > 0.05$); significant differences on clear/hot days ($p < 0.0005$). ●On maximum and average Ta within the tree canopy were 1.8°C (SD = 0.7°C) and 0.8°C (SD = 0.2°C) lower on cloudy days; differences increased to 3.2°C (SD = 0.5°C) and 1.5°C (SD = 0.2°C) on clear days.	Dfa	Urban	Field study + simulation
[108]	●Tree height ●Distance between trees and buildings ●Distance between trees ●Wall area ●Building height	○Dynamic and static equivalent heat transfer coefficients and thermal resistances for the virtual wall	●X1, driven by tree height, tree–building distance (d1) and tree spacing (d2)—accounts for 91.12% of the weight, whereas X2—dominated by wall area and building height—accounts for only 8.86%.	Cfa/Cwa	Building	Field study + simulation

(Continues)

Source	Input factor(s)	Output factor(s)	Results	Köppen classification	Scale	Methodology
[65]	●Presence of trees	○Energy reduction	●Presence of trees can reduce energy consumption up to 25% in summer.	Various	Building	Review
[106]	●Original epw weather data: air temperature, relative humidity, wind direction and speed, solar and sky radiation ●Block configuration: building geometries, vegetation configurations and pavement materials	○Heating load analysis ○Microclimate analysis: variation of air temperature, relative humidity, radiation and wind speed	●Increasing the leaf area index of green land from 0.79 to 4.77 m^2/m^2 reduced mean radiant temperature by 3.27°C, lowered wind speed by 0.48 m/s and raised air temperature by 0.47°C at the block scale. ●In three blocks, the BHL of thermal zones within tree canopy height increased by 7.16%, 1.52% and 3.57% on sunny days, but decreased by 2.80%, 0.55% and 0.06% on cloudy days (evergreen trees in winter)	BSk-Cwa	Urban	Field study + simulation
[96]	●Original epw weather data: air temperature, relative humidity, wind direction and speed, solar and sky radiation ●Simulation cases: building geometries and materials, vegetation configurations	○Cooling load analysis ○Microclimate analysis: air temperature variation, relative humidity variation and radiation ○Variation, wind speed variation	●GPR 0.5 to 1.5: reduces thermal stress from 'very strong' to 'strong' in building overhead and north-south street spaces. ●GPR 3.5: results in 'moderate' UHI intensity for all four space types.	BSk-Cwa	Urban	Field study + simulation

(Continues)

TABLE A2 | (CONTINUED)

Source	Input factor(s)	Output factor(s)	Results	Köppen classification	Scale	Methodology
[92]	●Presence of the vegetation	○UHI ○Cooling microclimate ○Sound barrier ○CO_2 reduction ○Dust absorption	●Single tree (7.5 m tall): reduces annual cooling/heating costs by 8%–12%; air-conditioning savings 25%–80%. ●Creepers: lower indoor temperature from 17°C–33°C to 18°C–28°C; constant 2.5°C cooling effect. ●Deciduous trees: block ~25% sunlight in winter; reduce irradiance by 35% in winter, 85% in summer. ●CO_2 reduction: urban trees 15× more valuable than rural; well-planted streets retain up to 70% airborne dirt; mature trees intercept up to 50 lbs of particulates/year.	Cfa	Urban	Review

TABLE A3 | Tools and equipment used to assess IAQ, thermal comfort and energy consumption.

Category	Measured variable	Field study: Tool/sampling method	Ref.	Simulation: Software/tool	Ref.
Thermal comfort	CO_2 concentration	CO_2 sensor	[151]		[152]
	Air temperature	Air temperature sensor		Envi-met, ANSYS-Fluent, OpenFoam, UMEP and Ladybug	
		Thermo-hygrometric sensor			
	Globe temperature	Globe thermometer			
		Heat stress meter			
	Relative humidity	Humidity sensor		Envi-met, ANSYS-Fluent, OpenFoam, UMEP and Ladybug	
		Thermo-hygrometric sensor			
	Air velocity	Air velocity sensor		Envi-met, ANSYS-Fluent, OpenFoam, UMEP and Ladybug	
		Anemometer			
	Solar radiation	Pyranometer		Envi-met, ANSYS-Fluent, UMEP and Ladybug	
	Surface temperature	Thermal camera		Envi-met, UMEP and Ladybug	
IAQ	CO_2, RH and temperature	Q-Trak monitor (TSI Inc.): nondispersive infrared analyser	[150]	CONTAM Envi-met	[152, 153]
		Integrated data loggers (Hobo HO-8) IAQ meter (IAQ-CALC model 7545)			
	CO	Electrochemical sensor (Draeger Pac III) FIM CO- Tester Tx for exhaled air			
	NO_2	Passive samplers (Palmes tubes) containing triethanolamine absorbent and analysed by a spectrophotometer			
	PM_{10}	Dust-Trak air monitor (Model 8520, TSI Inc.), light scattering pumped gravimetric method Model 2100 Mini- Partisol air sampler (Ruprecht & Patashnick Co.) coupled to a ChemPass model 3400 GRIMM environmental dust monitor, light scattering technology Minivol portable air sampler (Airmetrics, PAS 201) with pall flex membrane filter (47 mm)			
	$PM_{2.5}$	PTFE filters (37-mm diameter, 2-μm porosity)			
		Low volume sampling pump (model 224-PCXR8) with PEM impactor			
	VOC	Diffusive samplers			
		Proton transfer reaction mass spectrometer (PTR-MS) Air collected on adsorbent tubes and analysed by gas chromatography-mass spectrometry			

(Continues)

TABLE A3 | (CONTINUED)

		Field study		Simulation	
Category	**Measured variable**	**Tool/sampling method**	**Ref.**	**Software/tool**	**Ref.**
Energy efficiency	Electricity	Current (current transducer)	[154]	EnergyPlus, Design Builder, TRNSYS and IES-VE	[155]
	Natural gas	Natural gas meter			
	Water consumption	Water flow (water meter)			