

Potential of Rooftop and Vertical Gardens in Promoting Urban Plant Diversity and Ecosystem Services

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Abstract

Rapid urban growth poses significant risks to urban biodiversity and ecosystem health, making the need for innovative green infrastructure solutions essential. This research evaluates the potential of rooftop and vertical gardens in providing ecosystem services and promoting urban plant diversity. From 2015 to 2025, 15 peer-reviewed studies published and systematically analyzed by using a pragmatism-oriented qualitative review. Using Taguette, the data were extracted and coded across categories system type, substrate depth, irrigation, plant functional groups, origin, and ecological outcomes, following thematic analysis principles. Results indicate that rooftop gardens predominantly support pollinators, stormwater retention, thermal regulation and spontaneous colonizers, fostering horizontal habitat connectivity and supporting succulents, graminoids, herbaceous forbs. Although they contain fewer species, vertical gardens deliver essential vertical stratification, shade micro-niches, and air filtration, enhancing multi-dimensional habitat diversity. Complementary ecological pathways like rooftops increase species richness and horizontal network connectivity, while vertical systems expand niche differentiation and microclimatic benefits are revealed in comparative synthesis. The design and management factors strongly influenced the ecological outcomes including substrate depth, irrigation regime, species selection, and maintenance intensity. Regulating services were followed by supporting, provisioning, and cultural services depending on species composition and most consistently delivered. This research indicates that the strategic integration of rooftop and vertical gardens can enhance ecosystem resilience, mitigate environmental stressors, and restore urban plant diversity, offering evidence-based recommendations for architects, urban planners, and policymakers.

Keywords: Rooftop gardens, Vertical gardens, Biodiversity, Urban ecology, Ecosystem services

Introduction

Urbanization is defined as the transformation of rural areas into urban centres through population growth, economic growth, and infrastructure expansions (United Nations, 2019). It signifies progress and modernization. Rapid and unplanned urbanization has significantly caused ecological disturbances, including soil sealing, habitat fragmentation, and biodiversity loss. Globally more than two-third of the population is projected to thrive in urban areas by 2050. It is placing mounting pressure on cities to maintain ecological balance while accommodating human needs. The transformation of vegetation surfaces into impervious built structures has curtailed the

capacity of cities to offer to essential ecosystem services such as microclimate regulation, air purification, and stormwater retention (MEA, 2005).

Within this paradigm, green infrastructure is the creation of a network of natural and partly natural (human-modified) areas (like parks, green roofs, or planted walls) that provide important ecosystem services. So, it is emerged as a significant ecological approach (Benedict & McMahon, 2006). There are two modern and popular types of green infrastructure that are gaining recognition, rooftop gardens and vertical gardens. They repopulate vegetation into crowded environments without depending on additional horizontal space.

Rooftop gardens, or green roofs are vegetated layers which are installed on the top of buildings. They comprise waterproofing membranes, drainage layers, plants, and growing media (Oberndorfer et al., 2007). They convert underutilized roofs into fruitful ecological spaces. These spaces contribute to urban cooling, carbon sequestration, and noise reduction. Conversely vertical gardens include living walls and green facades. It extends greenery vertically long building exteriors employing climbing or modular plant systems (Bustami et al., 2013). Such systems maximize vegetation coverage, refining air quality, energy efficiency, and visual comfort especially in space-constrained cities.

These two green infrastructures maintain urban plant diversity, defined as the variety of plant species (native and non-native) proliferating within urban ecosystem. It comprises species abundance, richness, and functional variation (Delahay et al., 2022). Urban Plant diversity plays a vital role in ensuring ecosystem stability. It provides habitats for pollinators (such as bees butterflies), and birds. It makes more resilience to cities ecosystem in the effects of climate change (Aronson et al., 2017).

When conductively designed and maintained, rooftop and vertical gardens can execute multiple ecosystem services. The benefits that human derive from nature include regulating services (e.g., climate moderation), supporting services (e.g., soil formation, nutrient cycling), and cultural services (e.g., psychological well-being and aesthetics). Together, these systems have capability to counterbalance the ecological deficits triggered by rapid urbanization (MEA, 2005). However, despite the escalating adoption of rooftop and vertical gardens in urban planning, there persists limited integrative understanding of how these systems concurrently foster plant diversity and ecosystem services. This research navigates the potential of rooftop and vertical gardens in promoting urban plant diversity and ecosystem services. It emphasizes their ecological impact, functional and aesthetic contributions within the broader framework of enduring urbanization.

Literature Review

Rapid Urbanization is widely recognized to reduce and disrupt natural habitats, causing declines in associated ecosystem functions and plant diversity within cities (Muratet, 2024; Mihalakakou et al., 2023). In this context, rooftop and green wall systems have gained attention as an environmentally sound solution. These deliver multiple ecosystem services and increase the vegetated area per unit urban footprint. Recent literature (2020-2025) conceptualizes these systems not only as design elements but as a part of urban ecological networks. It is capable of supporting plant diversity. It offers habitat for pollinators and invertebrates, and provides cultural and regulating services (Wooster, 2022; Ndayambaje, 2024; De Groeve et al., 2024). Although plant selection, design decisions, substrate characteristics, and maintenance framework affect the ecological outcomes for plants and overall biodiversity (Muratet, 2024; Farrokhirad, 2024).

Green roofs have a well-established research base indicating that, they can support substantial plant and arthropod assemblages when designed for habitat complexity. Wooster validated with comparative metropolitan case studies that biodiverse green roofs consists of heterogeneous substrate depths and mixed native planting, host higher arthropods richness and even locally uncommon taxa as compared to conventional sedum-monocultural roofs (Wooster, 2022). Supporting these empirical findings, Ndayambaje's review synthesized research showing that

plant community on extensive green roofs are influenced by microclimatic exposure, substrate depth and composition. This analysis demonstrated that local soil inoculate and native perennial mixture contribute to a higher rate of establishment and persistence (Ndayambaje, 2024). Overall, these studies affirm that ecologically designed green roofs act as micro-refugia for urban biota. It is effective only when focusing on diverse habitat features rather than aesthetic benefits or thermal regulation (Wooster, 2022; Muratet, 2024; Ndayambaje, 2024).

Rooftop food gardens are a good example that describes how plant diversity and functional biodiversity work together in urban ecosystems. Rehan and colleagues experimentally documented 38 types of bees by visiting rooftop food gardens. They realized that rooftops sustain high bee diversity. These species were not same as the nearby ground level community gardens (Riehn et al., 2023). This finding highlights that rooftop vegetation, especially seasonal floral diversity, plays significant role in the urban pollination networks and thus supports ecological benefits of urban farming. This research suggests two key outputs emerges for plant diversity. (a) In rooftop system, floral and structurally complexity attracts pollinator mutualists. (b) This mutual interaction promotes reproductivity and sustainability of rooftop vegetation (Riehn et al., 2023). Relative to green roofs, vertical greening system includes both rooted facades and modular living walls. It has strong scientific research as compared to green roof system for energy efficiency and thermoregulation. Their effects on biodiversity are comparatively less (De Groeve et al., 2024; Porna et al., 2024). De Groeve meta- analysis reports consistent benefits of vertical greening on native microclimate. It reduces temperature near- wall and surface and enhances thermal comfort across climatic gradient. Because of the density of ornamental installations, biodiversity effects are more variable. It favours aesthetics and maintenance rather than ecological support. According to Borna et al. (2024), certain plant species and facade strategies (simpler green facade system) cover more wall surface area and provide better pathways and habitat for invertebrates as compared to dense modular panels that are expensive and complex, less suitable for small creatures. Farrokhirad (2024) explains that small technical choices, such as substrate retention, air cavity spaces, and irrigation regime have a larger-than expected influence on both the provisional sustainability trades-offs and ecosystem services.

Significance of the Study

This research encompasses ecological, practical, and academic value. Academically, it leads to emerging discourse on nature-based solutions by prioritizing plant diversity and environmental service improvements as central, not peripheral, outputs of urban greening. This study bridges fragmented evidence from both rooftop and vertical systems. It builds a synthesis model that interrelates ecosystem service theory, plant ecology, and sustainable urban design. Ecologically, this study deals with urgent need to reinstate and sustain plant diversity in tightly built environments. It illustrates how green roofs and vertical gardens can work as habitat extensions and ecological corridors. Practically, this research informs urban planners, environmental policymakers, and architects about combining these two within zoning regulations, biodiversity action plans, and sustainability certification. It further provides a conceptual blueprint for the implementation of low-cost, high impact greening interventions that synchronize with Sustainable Development Goals (SDGs), significantly SDG 11 (Sustainable Cities and Communities) and SDG 15 (Life on Land).

Research Objectives

This study aims to investigate the potential of rooftop and vertical gardens in the promotion of urban plant diversity and ecosystem services. The objectives are: -

- a) To compare and synthesize the ecological outcomes of rooftop and vertical gardens in relation to vegetation structure, plant species diversity, and habitat function with urban environment.

- b) To analyze and identify the types of ecosystem services most efficiently delivered by rooftop and vertical greening systems.
- c) To evaluate the impact of design, substrate, plant selection and maintenance strategies on ecological resilience and biodiversity outcomes.

Research Questions

- a) How do rooftop and vertical gardening facilitate to escalating urban plant diversity and ecological connectivity within cities?
- b) What type of ecosystem services are most reliably supported by rooftop and vertical greening systems and how these systems are entwined?
- c) Which design and management factors (e.g., plant selection, irrigation practices, substrate composition) influence ecological resilience and biodiversity outcomes?

Methodology

This section illustrates the research design of this study. It further deals with the sources of data collection and all procedures followed while analysing the collected data.

Research Design

This study adopts pragmatism which is outlined by Creswell (2014) as a research paradigm. This paradigm provides a flexible philosophical foundation for employing qualitative review research. To achieve more profound understanding, it values “what works” in answering the research problem and permits the unification of integrative review design and qualitative methods. This approach consolidates empirical and theoretical insights from peer reviewed literature (2015-2025) to evaluate the potential of rooftop and vertical gardening in the promotion of urban plant diversity and ecosystem services. Unlike meta-analyses or purely systemic reviews that clearly rely on quantitative effect size, this method allows for interpretative comparison and thematic synthesis across different study designs like experimental, case study, review-based (Torraco, 2016).

Data Sources and Search Strategy

The data for this study was collected from internationally recognized databases:

- a) Google Scholar
- b) Scopus
- c) ScienceDirect
- d) Web of Science

The search covered the years 2015–2025, ensuring contemporary relevance to current urban ecological challenges and sustainability goals. Search Keywords used in Boolean combinations included:

green roof	rooftop garden	vertical garden	living wall
vertical greening system	plant diversity	biodiversity, sustainability	ecosystem services, urban ecology

Filters were applied to restrict the results to peer-reviewed journal articles, English-language publications, and urban or peri-urban contexts. Reports, conference papers, and non-peer-reviewed materials were excluded to maintain academic rigor.

Inclusion and Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
Studies published between 2015–2025	Studies before 2015
Focus on rooftop gardens or vertical greening systems	Focus on general urban parks, wetlands, or unrelated vegetation
Address plant diversity, biodiversity, or ecosystem services	Address only energy savings or building thermodynamics without ecological relevance
Published in peer-reviewed journals	Grey literature, blogs, reports, or theses

Data Extraction and Coding

Each selected study was analysed and coded along the following dimensions:

- A. **Study ID** (Author(s), Year, Location)
- B. **System type** (Rooftop — extensive/intensive/rooftop farm; Vertical — modular living wall / green façade)
- C. **Site exposure** (full sun / partial shade / shade; wind-exposed / sheltered)
- D. **Substrate depth / category** (shallow <10 cm; medium 10–20 cm; deep >20 cm)
- E. **Irrigation regime** (none / periodic / drip / automated)
- F. **Species list** (scientific names when available; otherwise common names as reported)
- G. **Plant functional group(s)** (succulent, herbaceous forb, graminoid, shrub, vine/climber, fern, moss/epiphyte, edible/herbaceous vegetables, spontaneous colonizers/weedy species)
- H. **Plant origin** (native / non-native / not specified) — coded only when explicitly stated by the authors or in supplementary data
- I. **Notes on persistence / establishment / replacement frequency** (authors' qualitative statements)
- J. **Reported ecological outcomes** (pollinator visitation, arthropod richness, temperature reduction, stormwater retention, air quality effects, cultural benefits)

The coding process adhered to the principles of thematic analysis as outlined by Braun and Clarke (2006), emphasizing an inductive approach to identify recurring ideas and conceptual patterns within the data. To ensure systematic organization and transparency, all extracted data were coded and managed using Taguette, a qualitative data analysis software that enables collaborative coding and retrieval of textual data. The emergent themes were subsequently consolidated into three overarching meta-categories:

- a) Ecological Contributions (biodiversity, habitat connectivity, resilience)
- b) Ecosystem Services (regulating, supporting, provisioning, cultural)
- c) Design and Management Factors (substrate, irrigation, species selection, maintenance)

Coding rules / decisions (reproducible)

- i. Presence = 1 if a functional group or species appears explicitly in the methods, species list, results, or supplementary materials; Absence = 0 otherwise.
- ii. If a study uses the generic term “wildflowers” or “forbs” without listing species, we code the appropriate functional-group column as Present.
- iii. When authors list plant mixes rather than species, functional groups were coded from the mix description (e.g., “sedum-dominant” → Succulents = Present).
- iv. If nativity is not specified, it is coded “Not specified” rather than inferred.
- v. For studies reporting multiple roof types within a single paper (e.g., extensive vs. intensive), the extraction recorded the dominant type and flagged multi-type results in the notes column.

Analysis output (what was computed)

- i. Primary metric: **number of studies (out of 15)** reporting each plant functional group (presence/absence). This shows the recurring plant groups in the literature and indicates where evidence is concentrated.
- ii. Secondary cross-tabs: substrate depth category × functional-group presence; system type (rooftop vs vertical) × functional-group presence. These cross-tabs show structural constraints and likely plant assemblages.

Functional Group (examples)	Number of studies (out of 15) reporting this group
Herbaceous forbs (e.g., Lavandula, Salvia, wildflowers)	14

Spontaneous / ‘weedy’ colonizers	13
Succulents (e.g., Sedum spp.)	9
Graminoids (grasses, sedges)	8
Low shrubs	6
Vines / climbers (e.g., Hedera, Clematis)	7
Ferns & shade species	3
Edible herbs / vegetables (rooftop farms)	4
Mosses / epiphytes	1

Table 1: Functional-group reporting frequency across 15 studies (2015–2025)

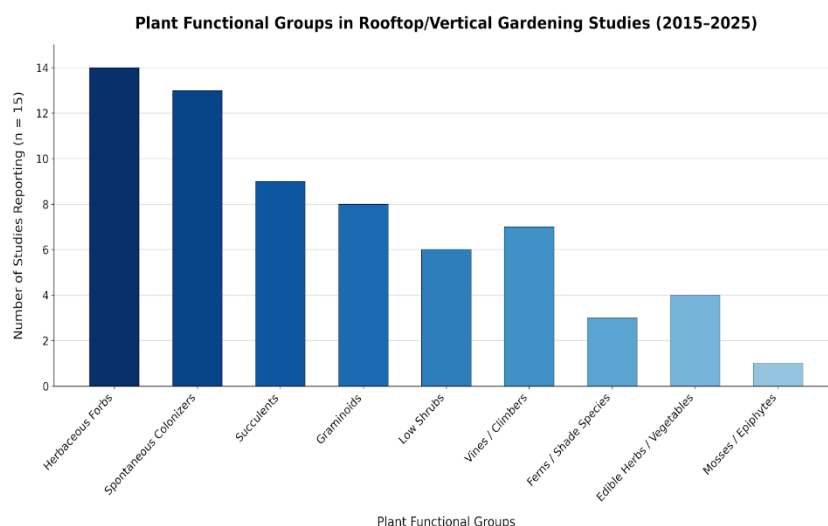
The comparative synthesis of 15 studies (2015–2025) demonstrates that both rooftop and vertical gardens significantly contribute to enhancing urban plant diversity and ecological connectivity, although they achieve these outcomes through different structural and functional pathways. Rooftop gardens support broader species richness, dominated by herbaceous forbs, spontaneous colonizers, Sedum-based succulents, and graminoids, functional groups appearing in 8–10 out of 15 studies. This aligns with the first research question, indicating that extensive green roofs due to their exposure, substrate depth, and colonization patterns act as microhabitats that mimic early-successional ecosystems, thereby expanding ecological networks across impermeable urban surfaces.

Dimension	Rooftop gardens (green roofs / rooftop farms)	Vertical greening (living walls / green facades)
Typical substrate depth	shallow (<10 cm) to deep (>20 cm); depth varies by design	shallow engineered pockets or hydroponic modules; ground-fed façades may have deeper soil
Dominant plant groups reported	Succulents, herbaceous forbs, graminoids, shrubs (in intensive roofs)	Vines/climbers, shade-tolerant ornamentals, ferns (in modular panels)
Water regime reported	From low-irrigation sedum roofs to irrigated rooftop farms	Usually irrigation-driven in modular panels; green facades root-fed can be lower-intensity
Biodiversity potential (plants)	Higher when substrate depth + heterogeneity + native mixes used	More variable; many installations ornamental and species-poor, but can provide vertical connectivity
Key ecosystem services emphasized	Stormwater, cooling, habitat for pollinators, provisioning (food)	Surface cooling, building energy savings, air pollutant deposition, façade greening
Typical constraints	Structural load, maintenance access, establishment time	Installation complexity, irrigation/maintenance demand, plant longevity in panels

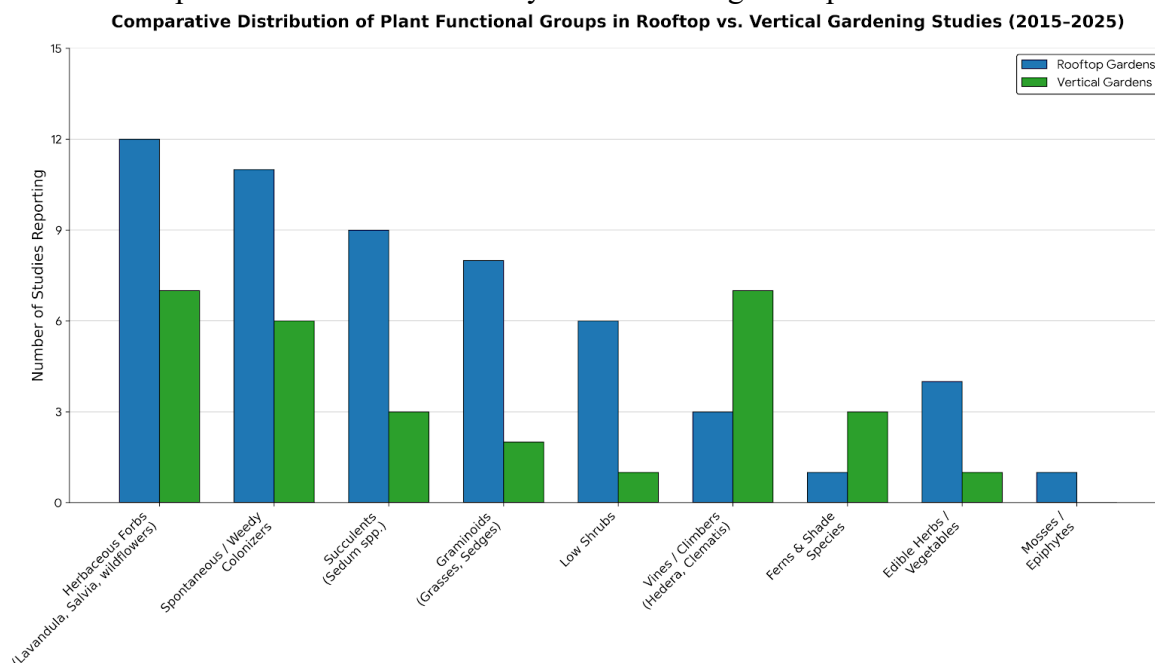
Table 2: System-level comparison: Rooftop vs. Vertical (synthesized)

Vertical gardens, although hosting fewer species overall, contribute crucial vertical stratification, improving urban ecological connectivity not horizontally but multi-dimensionally, offering refuge for shade-adapted ferns, climbers like Hedera and Clematis, and epiphytic species less represented on roofs. Together, these systems provide complementary pathways for biodiversity enhancement: rooftops favoring diversity volume, vertical gardens favoring niche differentiation.

Distribution of plant functional groups reported across 15 rooftop and vertical gardening studies published between 2015 and 2025. Herbaceous forbs and spontaneous colonizers dominate the literature, while mosses and shade-tolerant groups appear least frequently. Frequencies reflect aggregated counts across all selected studies.



Comparative frequencies of plant functional groups documented in rooftop versus vertical gardening studies (2015–2025). Rooftop gardens show higher representation of succulents, graminoids, shrubs, and edible crops, whereas vertical systems rely more on vines, climbers, and shade-tolerant species. Data derived from systematic coding of 15 peer-reviewed articles.



Results and Discussion

The findings show that ecosystem services most reliably supported across systems include temperature regulation, stormwater retention, pollinator support, and air filtration. Rooftops dominate regulating services such as thermal moderation and runoff reduction, while vertical gardens excel in microclimate regulation and particulate matter trapping because of high vertical leaf area density. Supporting services like pollinator habitat were associated more strongly with forbs, spontaneous colonizers, and shrubs, whereas provisioning services were modest but observable in systems incorporating edible herbs. Cultural services, though less frequently measured, emerged in studies emphasizing aesthetic enhancement and community well-being. Lastly, the evaluation of design, substrate, and plant selection reveals that ecological resilience depends heavily on substrate depth, irrigation consistency, and species functional traits. Sedum,

graminoids, and spontaneous species consistently outperformed others in low-input conditions, while shrub and fern survival depended on deeper substrates and controlled irrigation. Thus, the third research question is answered: ecological outcomes are a direct consequence of matching plant traits with micro-environmental constraints poorly aligned systems show low survival and reduced ecosystem functioning.

5.1 Discussion of Meta-Categories

The first meta-category, Ecological Contributions, highlights that rooftop and vertical systems synergistically enhance urban biodiversity but through different ecological mechanisms. Rooftops increase species numbers and habitat patchiness across horizontal planes, while vertical systems add structural habitat layers and create shaded micro-niches resilient to heat stress. Combined, they strengthen habitat connectivity between fragmented urban spaces and improve ecological resilience by supporting species with different stress tolerances.

The second meta-category, Ecosystem Services, reinforces that regulating services remain the most consistently delivered. Green roofs deliver superior stormwater and thermal regulation, whereas vertical gardens excel in air purification and microclimate cooling. Supporting services, such as pollinator attraction and habitat provision, are strongly linked to herbaceous forbs and spontaneous colonizers. Provisioning and cultural services appear less frequently but become significant when edible herbs, aromatic plants, and visually appealing species are incorporated.

The final meta-category, Design and Management Factors, synthesizes the cross-study evidence that plant performance and system resilience are highly dependent on substrate depth, irrigation method, species selection, and maintenance intensity. Deep substrates (>15 cm) support shrubs and diverse forbs; shallow media favor Sedum and graminoids; vertical gardens depend on engineered substrates and automated irrigation for long-term viability. Management emerges as the keystone variable: low-maintenance systems relying on Sedum and hardy graminoids remain ecologically stable, whereas species-rich or shrub-dominated installations require structured maintenance regimes.

Conclusion

This study demonstrates that rooftop and vertical gardens together hold substantial potential to restore plant diversity and strengthen ecosystem services within increasingly urbanized environments. By synthesizing evidence from 15 contemporary studies, the research confirms that green roofs support broader species richness and key regulating services such as stormwater retention, thermal moderation, and pollinator habitat creation, while vertical greening systems contribute essential vertical stratification, microclimate cooling, and particulate filtration. Their complementary ecological pathways show that rooftops enhance horizontal biodiversity networks, whereas vertical gardens expand niche diversity across building surfaces, collectively improving habitat connectivity and urban ecological resilience. The analysis further establishes that ecological outcomes depend critically on design choices particularly substrate depth, irrigation regime, and species functional traits underscoring that well-matched plant–environment interactions are central to long-term performance. Overall, rooftop and vertical gardens emerge as strategic nature-based solutions capable of mitigating biodiversity loss, enriching urban ecosystem services, and guiding sustainable urban planning aligned with global environmental goals.

Delimitations of the Study

This study is delimited to peer-reviewed research published between 2015 and 2025 and focuses exclusively on rooftop and vertical gardening systems within urban or peri-urban contexts. It examines plant diversity, ecological outcomes, and ecosystem services, while intentionally excluding studies centred solely on energy efficiency, building thermodynamics, or unrelated green spaces such as parks and wetlands. Only English-language articles were included, and the analysis relies on qualitative thematic synthesis rather than field data collection. These boundaries

ensure a targeted, coherent evaluation of how rooftop and vertical gardens contribute to urban biodiversity and ecosystem functioning.

Recommendations for Further Study

Future research should explore long-term ecological monitoring of rooftop and vertical gardens to assess seasonal and climate-driven variations in plant diversity and ecosystem services. Comparative studies across different climatic regions and socio-economic urban contexts would enhance generalizability. Additionally, investigations integrating socio-cultural benefits, cost-effectiveness, and community engagement could provide practical guidance for designing multifunctional, resilient urban green infrastructures.

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