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Biodiversity of urban green spaces and human health: a systematic review of recent research

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Although recent studies have explored links between landscape biodiversity and human health, the exact effects of specific types of biodiversity—such as the variety of species or genera—on health outcomes are still uncertain. In this review, we evaluate our current knowledge of how landscape biodiversity influences human health in different cultural contexts. We systematically assessed peer-reviewed literature to: 1) summarize the links between biodiversity variability and human health outcomes; 2) describe the pathways used to examine these links; 3) compare subjective perceptions of biodiversity with objective measures; and 4) describe any known connections between perceived biodiversity and health outcomes. We analyzed 41 studies published between 2018 and 2023, covering research from 15 countries on five continents. A key finding was the lack of significant links between biodiversity variability, like species richness, and health outcomes; only one-third of studies reported positive health effects. We identified two main pathways: restoring health capacities (mental health) and building health capacities (physical health). The public could identify different biodiversity levels, with perceived biodiversity correlating with health. Future research should explore varied mechanisms, physical health outcomes, causal relationships, and effects across diverse populations and regions.

KEYWORDS

urban biodiversity, health and well-being, perceptions of urban green space, urban nature exposure, species richness

1 Introduction

In urban settings, green spaces are essential for fostering stable habitats and resources for wildlife, thereby enhancing the quality of urban ecosystems (Ives et al., 2016; Oke et al., 2021; Parris and Hazell, 2005). Recent studies have explored the connection between biodiversity and health outcomes for urban residents (Aerts et al., 2018; Houlden et al., 2021; Marselle et al., 2021b). The specific relationships between narrowly defined biodiversity— taxonomic or species richness, which refers to the number of different genera or species within a given area —and health outcomes, however, remain unclear. This measure of biodiversity is particularly relevant as it captures the variety of life forms present, whether counted at the species or genus level. Understanding these interactions is crucial, as they are influenced by individual perceptions of the biodiverse environments and by cultural contexts. This systematic review summarizes recent findings regarding the relationships between biodiversity and human health and reports findings regarding the objectively measured levels of biodiversity and people's perceptions of biodiversity.

The association between the biodiversity of urban green spaces and health outcomes could unfold in three broad ways. First, biodiverse landscapes may harm human health and well-being. Some studies have found that densely and diversely vegetated urban green spaces evoke negative perceptions and feelings due to concerns over contact with wildlife, safety issues, or crimes within or around these areas (Cariñanos et al., 2017; Sreetheran and van den Bosch, 2014; Qiu et al., 2013). Biodiverse green spaces are associated with a series of negative health outcomes, such as declined mental health, well-being, and a higher prevalence of asthma and allergic reactions (Astell-Burt and Feng, 2019; Jiang et al., 2020; Reid et al., 2017; Zhang et al., 2021).

Second, it is possible that there is no relationship between levels of biodiversity and human health and well-being. Indeed, several recent studies did not find a connection between landscape biodiversity and health or well-being (Dallimer et al., 2012; Marselle et al., 2020; Methorst et al., 2021a). Third, it is possible that exposure to higher levels of biodiversity leads to a range of positive health outcomes. Biodiverse urban nature offers ecosystem services that benefit health or well-being across multiple dimensions, including physiological health, psychological health, life expectancy, resilience, and overall well-being (Sandifer et al., 2015). Due to these mixed results, we examine the extent to which urban green spaces with varying levels of biodiversity are associated with human health or well-being.

Scholars sometimes wonder whether the ability to recognize species or discern the degree of biodiversity is necessary to experience health benefits from a biodiverse green space (Wu, 2024). Previous studies have found both positive and negative correlations between objectively measured biodiversity and subjectively perceived biodiversity, influenced by individuals' varying levels of knowledge (Dallimer et al., 2012; Fuller et al., 2007). Moreover, individuals who perceived greater biodiversity tended to report greater levels of well-being, regardless of how accurate their perceptions were (Dallimer et al., 2012; Kothencz et al., 2017; Marselle et al., 2016). This discrepancy in people's ability to perceive biodiversity introduces another level of complexity in the relationship between natural landscapes and health. Thus, in this review, we explore the degree to which subjectively measured biodiversity aligns with objectively measured biodiversity, bridging human perspectives and ecological functionality in research and landscape design.

Several recent review studies have synthesized the growing body of literature examining the links between biodiversity and health and well-being. A systematic review of research from 2006 to 2018 revealed pathways and outcomes that connected biodiversity to human health (Aerts et al., 2018). A narrative review using a broad definition of biodiversity, including factors related to abundance and variability of biodiversity, described the extent to which different biodiversity metrics correlate with mental and physical health outcomes (Marselle et al., 2021b). A recent summary of both empirical research and review studies focused on the relationship between biodiversity and mental health outcomes, concluded there was a need for more empirical studies to obtain results generalizable to a wider range of environments (Houlden et al., 2021).

Although these reviews provide valuable insights, they do not fully address how species richness in biodiversity affects human health. While previous reviews have examined the links between biodiversity and human health, it is crucial to focus on the health impacts of species richness. Species richness has unique ecological functions that differ from abundance factors when considering biodiversity, potentially leading to distinct health outcomes. Additionally, given the surge in publications, we must update and clarify how biodiversity connects to human health and well-being.

To bridge these gaps, we reviewed research published from 2018 to 2023, summarizing the connections between biodiversity and human health in urban settings. Our review differentiated between factors related to biodiversity abundance, like animal counts and plant coverage areas, and those that emphasize biodiversity variability, such as habitat heterogeneity and species richness, focusing on the latter. Our review was guided by four research questions:

1. What are the pathways through which studies examined relationships between biodiversity and human health?
2. To what extent does biodiversity correlate with human health?
3. To what extent does the perceived biodiversity correlate with the objectively measured biodiversity?
4. To what extent does the perceived biodiversity correlate with health outcomes?

2 Methods

2.1 Research scope, keywords, and inclusion criteria

To identify relevant literature for this review, we conducted a search using three groups of keywords related to biodiversity, health, and the environmental scope of the research, summarized in Table 1. Biodiversity, or biological diversity, is defined by the *Convention on Biological Diversity* (Convention on Biological Diversity, 1994) as "the variability among living organisms from all sources." Our inclusion criteria spanned multiple levels: within-species, between-species, and between ecosystem diversity. The data sources for biodiversity included primary investigations or secondary databases.

We drew from the World Health Organization (2020) definition of human health as "a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity." Consequently, we included health measures of mental health, physical health, general health, and well-being. The scope of physical environments was limited to built environments and developed settlements in urban or suburban areas. This approach narrowed our review to focus on the impacts of natural landscapes people encounter on a daily basis.

Studies were included in our review if they met the following criteria:

1. The research measured biodiversity, reflecting the richness of organisms (number of different species or genera) within species, between species, or at the ecosystem scale. The data could be continuous, such as investigation outcomes, or categorical, where researchers designated diversity levels.
2. The research measured health outcomes related to mental health, physical health, or well-being. We also include behavioral outcomes closely related to health, such as frequency and intensity of physical activities.
3. The research sites were within suburban or urban areas developed for human settlements.
4. They were quantitative, qualitative, or mixed methods studies, including randomized controlled trials, quasi-experimental studies, natural experiments, and observational studies.

Studies were excluded for any of the following reasons:

1. They measured only indirect biodiversity or used only proxies for biodiversity, such as plant cover (area), abundance, or landscape structure.
2. They exclusively measured indirect outcomes unrelated to human health outcomes or that did not directly reflect the health status of the human body, such as studies reporting the number of human disease vectors present.
3. They focused solely on assessing environmental quality regarding restorativeness, such as perceived restorativeness of the environment or preference.
4. The research site was only in natural areas without human development.
5. They included only one group in the biodiversity variable, such as a case study.
6. They were not written in English.
7. They were not published in peer-reviewed journals.
8. They were not empirical research.

2.2 Search strategies

We conducted multiple searches of the literature between 12 – 13 July 2023. We searched in three electronic databases: ISI Web of Science, Scopus, and PubMed. In the search fields, we used "OR" to connect keywords within each category to cover the most possibilities and used "AND" to connect the three keyword categories to refine the research only exploring relationships between biodiversity and human health in built environments. We searched these keywords in the title, abstract, and author keywords fields, and we identified the publication dates between January 01, 2018, and July 12, 2023.

2.3 Data extraction and analysis

To address the four research questions, we extracted relevant information from each included paper, containing research questions, research environment, spatial scale, study types, independent and dependent variables, covariates, pathways, and findings (see Table 2). Specifically, for the extent to which biodiversity correlates with human health, we categorized the results based on whether they showed positive, negative, or no-relationship effects. We then calculated the total number and percentage of results within each health outcome category. This approach provides an overview of current research trends and findings on the relationship between biodiversity and health outcomes.

In identifying pathways connecting biodiversity and health, we considered their research questions, the theories or mechanisms cited, and the health measures used. To better organize the information, we referenced the framework proposed by Marselle et al. (2021a), categorizing pathways into four groups: restoring capacities, building capacities, reducing harm, and causing harm. In Marselle et al. (2021a), relevant theories and mechanisms were specified in each category. Additionally, we remained open to other pathways that emerged during the extraction process.

TABLE 1 Keywords for literature search about biodiversity-health relations.

Biodiversity	Health	Environmental Scope
"Biological divers*" Biodivers* "Species richness" "Number of species"	"Human health" "Public health" "Psychological health" "Physiological health" "Mental health" "Physical health" "General health" "Well-being" Wellbeing Mortalit* Morbidit* Disease* "Physical activit*" "Activity frequency" "Activity intensity"	Urban Suburban City "Built environment"

TABLE 2 Summary of the studies exploring the correlations between biodiversity and human health.

Authors	Research Env.	Study Types	Sample Size	Independent Variables	Dependent Variables	Plant Control[1]	Age	Pathways	Findings
Cameron et al., 2020	Urban Parks	Cor	114	Bird species richness; Bird abundance; Habitat types	Emotions (Happy); Recovering quality of life	U	Avg. 29	Not specified	Bird richness, abundance, and habitat diversity were positively related to emotions.
Cavaleiro Rufo et al., 2020	Campus env.; habitats in 0.1 km radius from campus	Cor	845	Vertebrate species richness index	Diagnosed asthma; Lung functioning; Air way inflammation; Allergic sensitization; Atopic dermatitis; General health	–	Avg. 9	Biodiversity Hypothesis	Vertebrate richness was associated with a greater prevalence of atopic dermatitis, but no relation with allergic disease and asthma prevalence.
Cavaleiro Rufo et al., 2021	Living env. in 0.1, 0.2, 0.3 km radii	Cor	1,050	Vertebrate species richness index; Avg. NDVI	Self-reported: diagnosed allergy, dry cough, asthma, rhinitis, eczema; wheezing symptoms	–	4 and 7	Biodiversity Hypothesis	Vertebrate richness was correlated with increased asthma. NDVI was correlated with decreased asthma but not correlated with other indices.
Chen et al., 2023	US counties	Cor	2,751	Rarefied bird data	Life expectancy; Changes of life expectancy; Mortality risk	–	0 – 85	One health	Rarefied bird species richness was associated with increased life expectancy and overall health, and decreased mortality.
Corney and Neave, 2019	Urban riparian	Qua	23	Macro-invertebrate index; GreenPrint score	Feelings about the nature they perceived	U	18 – 74	ART; SRT	Participants experienced biophysical characteristics of the high biodiversity environments mentioned more positive perceptions, e.g., calm, relaxing, clear mind.
Donovan et al., 2021a	Living Env.	Cor	899,126	Plant species richness, NDVI	Acute lymphoblastic leukemia (ALL)	U	5	Biodiversity Hypothesis	Higher plant genera richness protected against ALL. No correlation was found between NDVI and ALL.
Donovan et al., 2021b	500 largest cities in the US	Cor	16,367	Plant diversity; NDVI	Asthma rates; Health-risk factors; Health-promotion activities	U	Adults	Hygiene hypothesis	Plant taxonomic diversity and NDVI were associated with increased adult asthma rate.
Douglas and Evans, 2022	Parks	Exp	87	Bird species richness	Digit span test (DS), PRS; Enjoyment and Restoration	–	>18	ART	Bird richness was correlated with higher levels of restorative perceptions. No relationship was shown between richness and DS.
Fernández et al., 2021	Overall env. in a region	Cor	218	National biodiversity index; Ecosystem vitality	Cases and deaths of COVID-19	–	–	–	The higher overall diversity at genetic, species, and ecosystem levels, the lower COVID-19 spreads.
Fisher et al., 2022	Urban streets	Cor	282	Pollinator richness; flower richness; tree richness; perceived biodiversity	Warwick-Edinburgh Mental Wellbeing Scale; Happiness	C	18 – 95	–	No relationships were found between tree and pollinator richness, well-being, and happiness. Flowering plant richness was associated with greater mental well-being, but not happiness.
Fisher et al., 2021a	Living env. in 50 m radius	Cor	306	Bird species richness; Bird abundance, SHDI; Land cover types	PANAS; STAI	U	18 – 65+	ART; SRT; Biophilia Hypothesis	Bird diversity was not associated with momentary anxiety and the positive and negative affects.

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TABLE 2 Continued

Authors	Research Env.	Study Types	Sample Size	Independent Variables	Dependent Variables	Plant Control[1]	Age	Pathways	Findings
Fisher et al., 2021b	Living env. in 50 m radius	Cor	449	Bird species richness, abundance, SHDI; land cover types	PANAS; STAI; PRS; Enjoyment	–	18 – 65+	ART; SRT; Biophilia Hypothesis	Green space was associated with greater positive affect, lower negative affect, and decreased anxiety.
Giacinto et al., 2021	Urban forest in zip code area	Cor	1,089	Tree genus SHDI; Tree abundance	Death cases from cardiovascular diseases	C	–	Biodiversity Hypothesis	Urban forests SHDI at genus level correlated with decreased mortality rate. No correlations were found for tree abundance.
Ha and Kim, 2021	University Campus	Exp	319	Plant species richness	Restorative state scale; POMS-SF	U	18 – 33	ART	No effects of plant richness were found on the restorative and mood states.
Hepburn et al., 2021	Urban env. in 0.25 km radius from the bird survey site	Cor	1,035	Bird abundance; Bird species richness; Tree canopy cover; Distance to water	Life satisfaction; Subjective happiness	–	–	–	Bird diversity and tree cover were not correlated with subjective happiness and life satisfaction.
Knobel et al., 2021	Living env. in 0.3 km radius	Cor	2,053	Animal diversity; Bird diversity (both at class and order levels)	BMI; Physical activity; Frequency of using parks	–	18 – 65+	Physical activities	Bird biodiversity was associated with moderate-to-vigorous physical activity intensity and protected overweight/obesity.
Lindemann-Matthies and Matthies, 2018	Meadow plot in urban parks	Exp	171	Plant species richness; Plant types	Systolic and diastolic blood pressure	C	18 – 78	SRT	Meadow plant richness was associated with a decrease in systolic blood pressure.
Marselle et al., 2020	Living env, in 0.1, 0.3, 0.5, 1 km radii	Cor	596	Street tree abundance; Tree species richness	Antidepressant prescriptions	C	18 – 79	–	Higher tree density within a.1 km radius was associated with fewer antidepressant prescriptions, but not at a farther distance. Tree richness was not associated with health outcome.
Mavoa et al., 2019a	Living env. in 0.4, 0.8, 1.6 km radii	Cor	4,912	Animal species richness; Plant species richness; NDVI, Percent area of water	Personal well-being	U	Avg. 54.6	Physical activities	No associations were found between animal richness, plant richness, and well-being. NDVI positively correlated with increased subjective well-being.
Mavoa et al., 2019b	Living env. in 0.4, 0.8, 1.6 km radii	Cor	4,757	Vegetation diversity; NDVI; Land cover types; Native plant presence	WHO-5	U	Adolescents	–	NDVI was correlated with fewer depressive symptoms and greater well-being. Plant diversity was linked to lower well-being.
Mears et al., 2019	Living env, in census unit	Cor	345	Land cover %; Land cover SHDI; Vegetation structure	General health	U	–	–	Lower habitat diversity, reduced water cover, and greater grass cover correlated with decreased general health.
Melo et al., 2021	Green spaces in 0.3, 0.5, 1, 1.5km radii from homes and schools	Cor	382	Animal species richness index; NDVI; Number of green spaces	Physical activity (hours, moderate-to-vigorous); BMI	–	Adolescents	Physical activities	No associations were found among animal species richness, NDVI and physical activities, BMI.

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TABLE 2 Continued

Authors	Research Env.	Study Types	Sample Size	Independent Variables	Dependent Variables	Plant Control[1]	Age	Pathways	Findings
Methorst et al., 2021a	Living env. in 100 km^2	Cor	13,328	Plant species richness; Bird species richness; Bird abundance	Health related quality of life: mental health component scale, physical health component scale	C	18 – 99	ART; SRT	Plant and bird species richness were positively associated with mental health. Bird abundance was not associated with mental health. No associations were found with physical health.
Methorst et al., 2021b	Country level env.	Cor	43,636	Bird and mammal species richness; Tree species richness; Land cover SHDI; Vegetated area %; Water area	Quality of life	U	>18	–	Bird species richness was related to life satisfaction. No relationships were found between mammal-, megafauna- or tree species richness and life satisfaction.
Nghiem et al., 2021	Natural trials in urban parks	Exp	174	Perceived diversity and abundance of plants and animals	PANAS; PRS	–	University students	ART; SRT	No relationships were found between perceived plant diversity, perceived animal abundance, and the affects.
Puhakka et al., 2019	Yards in daycare centers	Qual	62	Relative abundances, richness, and diversity of bacterial communities in surface soil.	Physical activity, multi-sensory experiences, diverse play, nature exploration, and pre-academic skills	–	3 – 5	Affordance	Natural materials increased and diversified children's physical activities. Spaces became restful and relaxing, leading to improved mood and energy.
Randler et al., 2023	Suburban green and blue space	Cor	132	Bird species richness	Recalled restoration; Psychological restoration (calm, relaxed, refreshed, peaceful)	–	Avg. 23.8	ART; SRT	Bird species richness was positively associated with the recalled restoration but not the psychological restoration.
Roslund et al., 2020	Yards in daycare centers	Quasi Exp	75	Bacterial communities' relative abundances, richness, diversity in surface soil	Skin & gut bacterial SHDI; Immunoregulatory cytokines T cells	–	3 – 5	Biodiversity Hypothesis	Greater env. microbiota diversity led to increased skin and gut bacterial community diversity, IL-10 and IL-17A ration, and higher Treg cells.
Roslund et al., 2021	Yards in daycare centers	Quasi Exp	89	Bacterial communities' relative abundances, richness, diversity in surface soil	Microbiota of skin, salivary, and gut	–	3 – 5	Biodiversity Hypothesis	Greater env. microbiota diversity led to more diverse skin and saliva bacterial communities after a year.
Samus et al., 2022	Private gardens	Cor	261	Habitat heterogeneity score; Plant growth form; Garden sizes	PANAS; Center for Epidemiological Studies Depression Scale	U	18 – 75+	–	Garden size and habitat richness were both found had positive and no associations with affects and depressive symptoms.
Schebella et al., 2019	Urban green spaces in different scales	Cor	840	Bird species richness; Habitat heterogeneity; Vegetation density; Overall naturalness; Structural heterogeneity	SF-12; DASS-21	C	15 – 99, Avg. 58.3	–	Bird richness, habitat diversity, and vegetation cover were associated with better emotions and well-being.

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TABLE 2 Continued

Authors	Research Env.	Study Types	Sample Size	Independent Variables	Dependent Variables	Plant Control[1]	Age	Pathways	Findings
Schebella et al., 2020	Parks	Exp	52	Bird diversity; Vegetation layer; Natural structural elements	EDA, HR; Mental stress (stress, anxiety, insecurity, calmness, happiness)	U	Avg. 37.6	–	Greater biodiversity was correlated with less happy feeling, greater perceived stress and anxiety levels, and faster heart rates, but no relation with calmness.
Southon et al., 2018	250 m^2 grassland in cities	Quasi Exp	240	Meadow plant species richness; Structural diversity	General physical health; Mental well-being; Restorativeness	C	Avg. 50.1	–	No relationships found between meadow creation, general mental and physical health, and psychological well-being.
Taylor et al., 2018	Living env. in postcode area	Cor, Qua	1,819	Bird species richness; NDVI	WHO-5; Personal well-being; Psychological well-being	–	18 – 76	–	Bird richness was not associated with general and personal well-being. NDVI correlated with greater general well-being. Both factors correlated with greater psychological well-being.
Vilcins et al., 2021	Living env. in 0.25 * 0.25 km^2	Cor	302,422	Vegetation diversity; Fractional vegetation cover	Birthweight	U	25 – 45	Biodiversity Hypothesis	Increased green cover correlated with increased birthweight, but plant diversity did not.
Wei et al., 2022	Urban forest parks	Cor	1,938	Tree, shrub, herb diversity indices	Emotions (happy, sad, neutral); Positive response index	U	–	ART; SRT	Tree diversity and shrub richness did not show relationships with facial expressions. Shrub diversity, herbaceous richness, and diversity were associated with positive facial expressions.
Winnicki et al., 2022	Living env. within 2 km radii	Cor	10,249	Bioscore (red-listed species & env. factors); Green space land cover	Asthma (codes related to asthma medication)	U	Early childhood	Biodiversity Hypothesis; Hygiene hypothesis	Exposure to natural and semi-natural areas, plantation, and urban parks was associated with increased asthma. Exposure to green spaces was associated with decreased asthma in urban areas. Overall biodiversity did not show association with asthma.
Xu et al., 2022	Urban mountain parks	Cor	593	Bird richness, SHDI, Simpson diversity index	PANAS; STAI	–	–	–	No association was found between bird diversity, emotions, and anxiety.
Young et al., 2020	Allotment garden and domestic garden	Cor	301	Plant species richness; Garden type	Garden related stress; preference; PRS; Visit frequency	U	Avg. 59	ART; SRT	No association was found between plant richness and self-reported restoration.
Zhang et al., 2021	Residential compounds	Cor	2,023	Vegetation species richness, area; diversity of plants with airborne pollen and fibers	Self-reported allergic or respiratory diseases	U	14 – 65+	–	Overall plant diversity and cover were associated with decreased allergic diseases, but not respiratory diseases. Pollen diversity was associated with increased allergic diseases.
Zhao et al., 2020	Urban streetscape	Cor	1,473	Perceived plant diversity; plant cover; types of vegetation	Emotional, psychological, cognitive, behavioral well-being	–	18 – 60+	ART; SRT	Vegetation cover was positively associated with perceived restoration.

•[1]Plant Control: Studies examining plant diversity, habitat diversity, or vegetation structure diversity, whether they controlled vegetation density or cover while testing the health effects of the diversity variables. C: Vegetation density, cover, or tree abundance controlled, U: Vegetation density or cover uncontrolled.
•Study types: Cor, Correlational research; Qua, Qualitative research; Exp, Experimental research; Quasi Exp, Quasi experimental research.
•Independent variables: NDVI, Normalized difference vegetation index; SHDI, Shannon diversity index.
•Dependent variables: ALL, Acute lymphoblastic leukemia; DS, Digit span test; PRS, Perceived restorativeness scale; PANAS, Positive and negative affect schedule; STAI, State-trait anxiety inventory; POMS-SF, Profile of mood states (short form); BMI, Body mass index; WHO-5, World Health Organization five well-being index; SF-12, 12-Item short-form health survey; DASS-21, Depression anxiety stress scale-21; EDA, Electrodermal activity; HR, Heart rate.
•Pathways: ART, Attention Restoration Theory; SRT, Stress Reduction Theory.
•–: Not reported or not applicable.

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We assessed the quality and the risks of biases of these included studies with NIH Quality Assessment Tools (National Institutes of Health, 2021) and modified critical appraisal skills programme (CASP) tool (Long et al., 2020), see Supplementary Materials.

3 Results

Our initial search yielded 1,870 distinct records based on titles and abstracts. After filtering out irrelevant titles and abstracts, we removed 1,818 records, leaving 52 records for full-text screening. Of these, we excluded nine studies due to irrelevant independent variables and six due to unrelated dependent variables, leaving us with 37 identified studies from our search. We found an additional four studies through references and other sources. Consequently, a total of 41 published research articles were included for further analysis (Figure 1, Table 2).

3.1 Study characteristics

The most frequently examined populations were adults and university students, with 26 studies focusing on these groups, while eight studies focused on children and adolescents (Table 2). Most studies targeting children and adolescents focused on physical health outcomes, including immune system-related health, physical activity, and body weight, with only one examining adolescent mental well-being.

Regarding methodologies, only eight studies implemented experimental or quasi-experimental designs. The experimental studies featured randomized distribution of participants to one or more interventions, while the quasi-experimental studies incorporated interventions without random assignment. Many studies (31) investigated correlational relationships. Additionally, two studies conducted qualitative research, collecting participants' written or verbal descriptions of their experiences.

The included studies were conducted in 15 different countries across five continents, with a concentration in Europe (Table 3). Studies were conducted in only two Asian countries and one South American country. Given the extensive diversity and vast number of countries in these regions, it is apparent that these areas are underrepresented in the identified studies. Moreover, research on this topic was absent in African countries, highlighting a geographical gap in the literature.

The included articles investigated built environments of various spatial scales as their analysis units, from individual sites like streetscapes and private gardens to larger blue or green spaces,

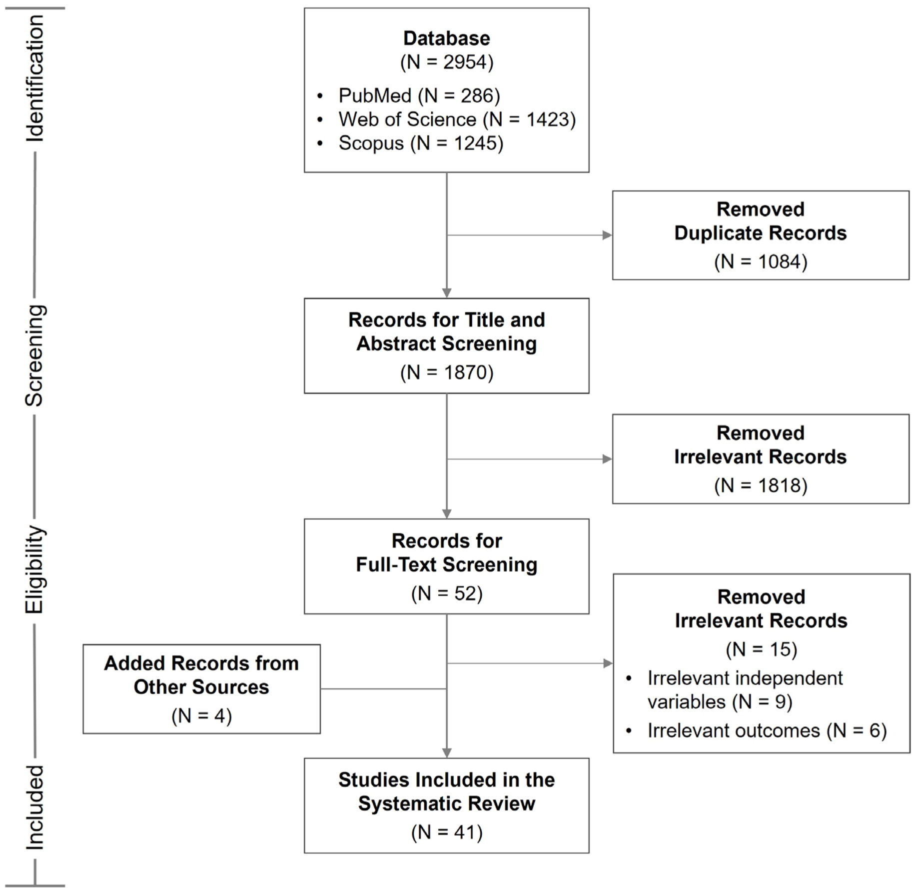

FIGURE 1
Study selection process.

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TABLE 3 Summary of geographic locations and setting types of study sites.

Continent	Country (N)	Subtotal (%)
Australia	Australia (6) New Zealand (4)	10 (23.3)
Asia	China (4) Singapore (1)	5 (11.6)
Europe	Denmark (1) Finland (3) Germany (4) Portugal (3) Spain (1) Switzerland (2) United Kingdom (5) Europe (1)	20 (46.5)
North America	Canada (1) United States (4)	5 (11.6)
South America	Guyana (2)	2 (4.7)
Global	Global (1)	1 (2.3)
Total[1]		43

Analysis Unit	Setting Type (N)	Subtotal (%)
Site	Private garden (2) School[2] (5) Streetscape (2) Blue space (3) Green space (13)	25 (58.1)
Neighborhood	Residential neighborhood (14)	14 (32.6)
Regional	City region (1) County region (1)	2 (4.7)
National	Country (2)	2 (4.7)
Total[1]		43

[1]Some studies were conducted in more than one country or more than one setting. [2]The school setting includes daycare center yards, primary, middle, and high schools, and university campuses. (N): The number inside the parentheses shows the number of studies included in that category.

residential neighborhoods, and regional levels such as city-wide, county-wide, and countrywide (Table 3). The site scale of green and blue spaces and the neighborhood scale of the living environment were the most-studied levels, as shown in Figure 2. Studies explored various health effects of plant, animal, and overall biodiversity variables at both scales. Moreover, studies focusing on streetscapes only examined health outcomes related to overall well-being, leaving other health aspects unexamined. Similarly,

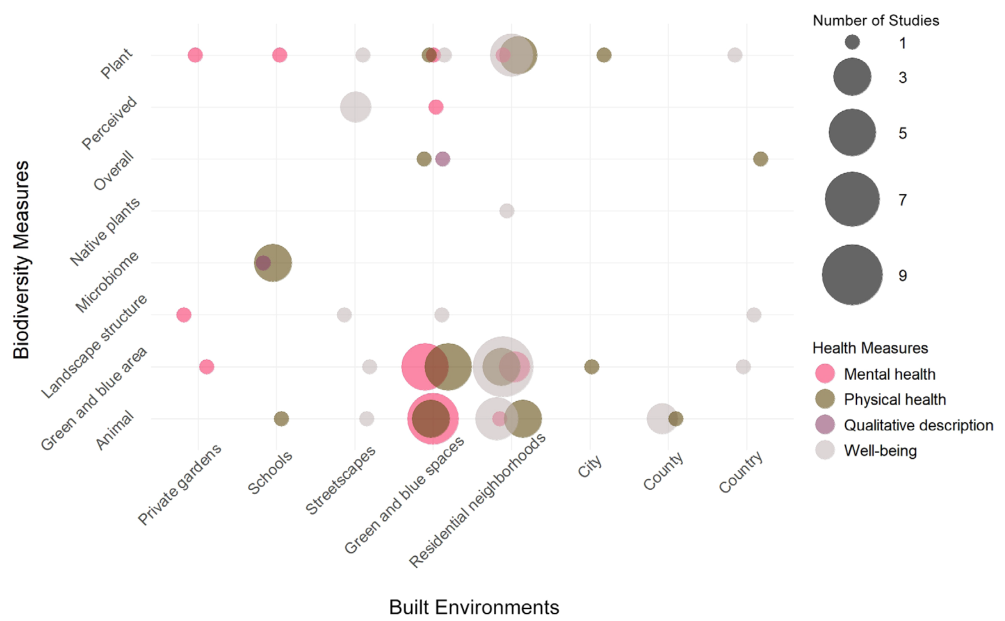

FIGURE 2
Number of studies on the relationships between biodiversity and health by the types of built environments and scales of the analysis unit. (Biodiversity measures include the animal diversity, area of green and blue spaces, landscape structure, microbiome diversity, presence of native plants, the overall biodiversity, perceived biodiversity, and plant diversity.).

studies exploring the relationships at the city scale focused only on physical health without evaluating overall well-being.

3.2 Biodiversity measures

As shown in Table 4, most studies assessed biodiversity by measuring species richness (the number of different species) or estimating diversity using the Shannon diversity index or Simpson index. In terms of data sources, secondary data, such as pre-existing data or public records, was often from governmental surveys. With the growth of citizen science databases, one study utilized the eBird database to estimate bird diversity, requiring adjustments using the rarefaction approach (Chen et al., 2023).

Several studies used proxy measures for assessing biodiversity; for instance, vegetation diversity was estimated based on landscape structure (Mavoa et al., 2019b), and animal diversity was inferred from habitat diversity (Cavaleiro Rufo et al., 2020, 2021). Studies also estimated the diversity of land cover types or habitats, by measuring the complexity and diversity of the landscape structure (e.g., Mears et al., 2019). Furthermore, subjective methods were also used as proxy measures for biodiversity, such as participants' perceptions of plant and animal diversity and abundance via questionnaires (e.g., Nghiem et al., 2021).

3.3 Health and well-being measures

The studies included in our review predominantly focused on mental health, investigating diagnosed mental disorders, cognitive functioning, and affective states, as summarized in Table 5. Two studies used objective methods to assess mental health; among those, anti-depression data were used to indicate diagnosed mental disorders (Marselle et al., 2020) and working memory tests were used to assess attention restoration (Douglas and Evans, 2022). Furthermore, most studies (18) relied on self-reported surveys, in which participants were asked about their emotions, feelings of restoration, stress, and depression levels (e.g., Fisher et al., 2021b; Hepburn et al., 2021), providing a subjective perspective on the impact of biodiversity on mental health outcomes.

For physical health, we categorized the assessments into biofeedback measures, immune system-related diseases, infectious and respiratory diseases, maternal health, physical activity and weight, and body microbiome diversity (Table 5). There was an emphasis on assessing immune system-related diseases, measured by the prevalence of diseases such as leukemia, asthma, and allergies (e.g., Donovan et al., 2021b; Winnicki et al., 2022), self-reported symptoms like rhinitis, eczema, and wheezing (Cavaleiro Rufo et al., 2021), and T cell counts (Roslund et al., 2020). We also included studies that estimated health through the frequency and intensity of physical activity and body microbial diversity. Although both indicators may not directly reflect health conditions, they are closely linked to mental and physical health (Du Toit, 2019; Pflughoeft and Versalovic, 2012; Rhodes et al., 2017).

A broader perspective on overall health conditions was assessed through mortality rates and life expectancy (Chen et al., 2023; Fernández et al., 2021), providing a macro-view of health conditions related to biodiversity. The research used self-reported methods to reflect well-being, general health, quality of life, life satisfaction, and happiness (Fisher et al., 2022; Hepburn et al., 2021;

TABLE 4 Summary of the biodiversity measures used as predictor variables.

Biodiversity Measures	Subcategory	Definition
Richness	Plants (13) Animals (17) Microbiomes (1)	Describes the number of species or genera of the targeted plants and animals. It could be derived objectively from investigation and secondary datasets or subjectively categorized by researchers.
Abundance	Animals (4)	Indicates the total number of individuals of each species or each community animals.
Green/Blue Spaces and Vegetation Cover (15)	–	Indicates the total area of the overall vegetation, tree crown, or other plant types represented by various methods, such as vegetation cover in images, NDVI. Water body area is also included.
Diversity Indices	Plants (4) Animals (6) Microbiomes (2) Overall (3)	These indices, including the Shannon diversity index and the Simpson diversity index, are calculated using both species richness and abundance. They can also incorporate taxonomic diversity or be adjusted for rarefaction.
Perceived Biodiversity	Plants (5) Animals (3) Overall (3)	Represents the diversity assessed subjectively by participants.
Landscape Structure (11)	–	Describes the composition and configuration of landscape cover types, including various habitats or landscape classification, such as habitat diversity, landscape structure diversity.
Vegetation Structure (6)	–	Describes the types or vertical layers of the vegetation composition, including the complexity or number of the layers.
Native Plants (2)	–	Indicates the presence of native plants or not.

(N): The number inside the brackets show the number of studies included in that category. —: Not applicable.

Methorst et al., 2021b; Taylor et al., 2018). These diverse assessments highlighted the potential health effects of biodiversity from multiple perspectives.

3.4 Pathways connecting biodiversity and human health

Our review included studies that explored how biodiversity impacts human health and well-being through several pathways: restoring capacity, building capacity, reducing harm, and causing harm, following the framework of Marselle et al. (2021a). Additionally, we identified a fifth pathway, One Health, which extends beyond the scope of this structure.

Out of the 41 studies in this review, two did not specify the pathways based on their health measures and research questions, and 13 did not specify the foundational theories that connected biodiversity and human health. Regarding the two that did not specify the pathways based on measures and questions, we classified Schebella et al. (2020) in the restoring capacity pathway, as they linked overall biodiversity to reductions in subjective and physical stress. We classified Zhang et al. (2021) into the pathway of causing harm, in which they measured the risks associated with allergies and respiratory diseases potentially triggered by plants. The findings within each pathway are described below and in Table 6.

3.4.1 Restoring capacity

We classified 14 articles into this pathway, which explored the connection between biodiversity and health through Attention Restoration Theory, Stress Reduction Theory, and the Biophilia Hypothesis. According to Attention Restoration Theory, contact with everyday natural environments aids in recovering from mental fatigue and replenishes depleted top-down attention (Kaplan & Kaplan, 1982). Stress Reduction Theory suggests that exposure to everyday nature alleviates emotional arousal, thereby reducing stress levels (Ulrich, 1983, 1984). The Biophilia Hypothesis posits that humans possess an innate affinity for nature and other life forms, eliciting positive emotional responses to natural elements (Wilson, 1993).

The empirical evidence from this set of studies indicated positive connections between the diversity of plants and animals, habitat types, and the presence of diverse elements with self-reported health outcomes, such as increased attention restoration, moods and relaxation, and reduced stress levels (Cameron et al., 2020; Fisher et al., 2021b; Randler et al., 2023; Schebella et al., 2019;

TABLE 5 Summary of the health and indirect health outcome variables.

Health Types	Measures	Definition
Mental Health	Mental disorders (1)	Measures the prevalence of diagnosed mental disorders, like depression. It can also be indicated by the prescription.
	Cognitive functioning (1)	Measures individuals' ability to perform their cognitive functioning, such working memory tests.
	Affective states (18)	Includes self-reported scales and questions that reflect individuals' emotions, affects, moods, restoration, happy, stress, depression, and anxiety levels.
Physical Health	Biofeedback measures (2)	Includes measures of physical responses related to stress reactions, including electrodermal activity (EDA), heart rate (HR), and blood pressure.
	Immune system related diseases (7)	Includes diseases and symptoms that are related to immune systems, for example, leukemia, asthma, T cells, allergy, rhinitis, eczema, and wheezing.
	Infectious diseases (1)	Measures the prevalence of infectious diseases, such as COVID-19.
	Respiratory diseases (1)	Includes respiratory diseases, such as airway inflammation.
	Maternal health (1)	Indicates the health condition during pregnancy, for example, birth weight
	Physical activity (3)	Includes measures of physical activity closely related to health, such as frequency and intensity,
	Overweight (2)	Includes indicators reflecting obesity level, such as body mass index (BMI).
	Body microbiome diversity (2)	Measures the microbiome diversity of human body, such as skin and gut.
Overall Well-being	Mortality (3)	It measures the overall mortality and the death related to diseases.
	Life expectancy (1)	Estimates the span of life at birth.
	Well-being and general health (10)	Includes measures reflecting the overall state of one's life, such as physical, mental, and social aspects. It also includes other measures reflecting the overall state of health, including general health, quality of life, and satisfaction of life, overall happiness
Qualitative Assessment	Qualitative descriptions (2)	Individuals' feelings or status experiencing natural environments were documented through their written or verbal descriptions.

(N): The number inside the brackets show the number of studies included in that category.

Wei et al., 2022). One study reported a link between plant diversity and objective measures of blood pressure – higher levels of plant diversity predicted healthier blood pressure measurements (Lindemann-Matthies and Matthies, 2018).

3.4.2 Building capacity

Fifteen articles examined the relationships between biodiversity and health through the lens of the Biodiversity Hypothesis and Hygiene Hypothesis. These hypotheses suggest that physical contact with biodiverse environments boosts immunoregulatory functioning, protecting against allergies and inflammation (Haahtela, 2019; Rook, 2012). The included studies demonstrated that exposure to more diverse plants and animals was associated with higher human microbiome diversity and enhanced immune system functioning (Donovan et al., 2021a; Roslund et al., 2020). Research on how biodiversity supports health capacity has grown from three studies between 2006 and 2018 (Aerts et al., 2018) to eight from 2018 to 2023.

Four other studies linked biodiversity and human health and well-being through physical activities. For instance, areas with diverse bird species were associated with more intense physical activity and lower obesity among adults (Knobel et al., 2021).

3.4.3 Reducing harm

One study assessed the roles of biodiversity in mitigating environmental risks to health. Fisher et al. (2022) explored the effects of vegetation richness on protecting residents' well-being against traffic-related air and noise pollution but found no significant correlations.

3.4.4 Causing harm

The causing harm pathway considers the potential adverse effects of biodiversity, such as pollen and plant debris triggering allergic reactions and asthma (Lee et al., 2020). One study reported that while higher plant diversity was correlated with a lower incidence of allergic diseases, increased diversity of plant pollens

TABLE 6 Summary of pathways and theories or hypotheses used in examining nature-health relationships.

Pathway	Theory/ Mechanism	Health Measures[2]	Study
Restoring Capacity[1] (14)	Attention Restoration Theory (12)	Affective states; cognitive functioning; qualitative description; well-being	Cameron et al., 2020; Corney and Neave, 2019; Douglas and Evans, 2022; Fisher et al., 2021a; Fisher et al., 2021b; Ha and Kim, 2021; Methorst et al., 2021a; Nghiem et al., 2021; Randler et al., 2023; Wei et al., 2022; Young et al., 2020; Zhao et al., 2020
	Stress Reduction Theory (11)	Physical stress; affective states	Corney and Neave, 2019; Fisher et al., 2021a; Fisher et al., 2021b; Lindemann-Matthies and Matthies, 2018; Methorst et al., 2021a; Nghiem et al., 2021; Randler et al., 2023; Wei et al., 2022; Young et al., 2020; Zhao et al., 2020; Schebella et al., 2020[3]
	Biophilia Hypothesis (2)	Affective states, PRS	Fisher et al., 2021a; Fisher et al., 2021b
Building Capacity[1] (15)	Biodiversity Hypothesis (10)	Body microbiota; immune system related diseases; maternal health; respiratory diseases; mortality; well-being	Cameron et al., 2020; Cavaleiro Rufo et al., 2020; Cavaleiro Rufo et al., 2021; Donovan et al., 2021a; Giacinto et al., 2021; Roslund et al., 2020; Roslund et al., 2021; Vilcins et al., 2021; Winnicki et al., 2022; Zhang et al., 2021[3]
	Hygiene Hypothesis (2)	Immune system related diseases; physical activity	Donovan et al., 2021b; Winnicki et al., 2022
	Physical Activity (4)	Physical activity; overweight; well-being	Knobel et al., 2021; Mavoa et al., 2019a; Melo et al., 2021; Puhakka et al., 2019
Reducing Harm[1] (1)	Reducing Pollutions (1)	Well-being	Fisher et al., 2022
Causing Harm[1] (1)	Physical Health (1)	Immune system related diseases	Zhang et al., 2021[3]
One Health (1)	—	Mortality; life expectancy (1)	Chen et al., 2023
Not Specified (13)	—	Mental illness (1)	Marselle et al., 2020
	—	Affective states (4)	Samus et al., 2022; Schebella et al., 2019; Xu et al., 2022
	—	Infectious diseases (1)	Fernández et al., 2021
	—	Well-being (8)	Hepburn et al., 2021; Mavoa et al., 2019b; Mears et al., 2019; Methorst et al., 2021b; Schebella et al., 2019; Southon et al., 2018; Taylor et al., 2018; Zhang et al., 2021

[1]Pathways proposed by Marselle et al. (2021a). [2]Health measures are in the same categories as those in Table 5. [3]The study did not specify pathways linking their measures of biodiversity to health, and the pathway was designated by authors judged by their health measures and discussions. (N): The number inside the brackets shows the number of studies included in that category. —: Not applicable.

was associated with higher allergic disease rates (Zhang et al., 2021). They explained that greater overall plant diversity may aid the immune system through higher microbiome diversity in the environment; however, the increased pollen diversity can trigger allergies directly.

3.4.5 One Health

One study investigated the relationship between biodiversity and life expectancy through One Health (Chen et al., 2023). One Health emphasizes the interdependent relationships among humans, plants, animals, and their shared environments (Zinsstag et al., 2011). Chen et al. (2023) found dual benefits for both the natural environment and human health arising from the efforts to alleviate threats to biodiversity, emphasizing the interconnection between ecosystem health and human well-being.

3.5 Relationships between biodiversity and health

To what extent does biodiversity correlate with human health and well-being? Among the 39 quantitative studies, we summarized a total of 163 findings. Of these, 44% of results indicated that broadly defined biodiversity was positively associated with health and well-being. On the contrary, 10% of the findings reported negative associations or effects of biodiversity on human health, while 46% reported no significant relationships between these variables (see Supplementary Table S1 in the Supplementary Material).

When focusing specifically on the human health responses to the variability of biodiversity, we examined 82 findings that uncovered a shift in the proportion of positive, insignificant, and negative outcomes. When considering only factors related to the variability of biodiversity, fewer findings demonstrated positive effects (decreased from 44% to 33%), and more studies showed negative effects (increased from 10% to 14%) or insignificant relationships (rose from 46% to 53%). These differences indicate the varied effects of the abundance and the biodiversity variability on health outcomes.

Among the findings related to biodiversity measures on variability factors, affect states, immune system diseases, and well-being were the health outcomes that were examined the most, as depicted in Figure 3. Most studies found no significant association between species richness of all taxa examined and affective states and well-being. Compared to other types of health outcomes, a higher portion (55%) of negative relationships were reported regarding the association between plant and animal diversity on immune system-related diseases. Detailed descriptions are provided below and in Table 7.

3.5.1 Effects of vegetation and habitat diversity

Studies showed that higher plant richness and diversity are associated with mental well-being (Methorst et al., 2021a; Fisher et al., 2022), reduced incidence of children's acute lymphoblastic leukemia (Donovan et al., 2021a), lowered rates of allergic disease (Zhang et al., 2021), and decreased risks of asthma (Donovan et al., 2021b). Specifically, four studies distinguished the effects of vegetation and habitat richness and vegetation density. These studies found that a higher number of plant species and greater habitat richness are linked to reduced blood pressure (Lindemann-Matthies and Matthies, 2018), better mental well-being (Fisher et al., 2022; Methorst et al., 2021a) and lower mortality rates (Giacinto et al., 2021). These findings reveal the independent health effects of both plants and habitat richness on mental and physical health benefits, even after accounting for vegetation cover.

Conversely, several studies reported no significant relationships between biodiversity and health due to three potential reasons. First, the effect of plant diversity may be too small and overshadowed by the impact of plant cover. For example, Schebella et al. (2019) initially found positive correlations between habitat diversity, structural heterogeneity, and mental well-being, but these relationships became insignificant after adjusting for vegetation cover. Similarly, Vilcins et al. (2021) reported that areas with low vegetation diversity but with high plant cover were associated with heavier (that is, healthier) birth weights. Second, mismatched temporal and spatial scales between biodiversity factors and human experiences could lead to insignificant associations between plant diversity and health. For instance, Southon et al. (2018) may not have allowed participants sufficient time to explore the intervention in the park after the intervention was implemented and before they conducted the survey. Moreover, the planted piece of meadow within the park might not be noticeable in the overall park experience. Finally, people's inability to perceive and detect vegetation diversity might lead to a disconnect between plant diversity and their health and well-being (Ha and Kim, 2021; Marselle et al., 2020; Methorst et al., 2021a).

Two of the included studies reported that specific aspects of biodiversity may negatively impact health. The greater diversity of vegetation types, plant fibers, and pollens was associated with reduced health status, indicated by reduced well-being and increased allergic diseases (Mavoa et al., 2019b; Zhang et al., 2021).

3.5.2 Effects of animal diversity

The positive effects of animal diversity on human health were particularly evident with birds. Greater avian diversity is associated with more positive moods and restorative perceptions (Douglas and Evans, 2022; Schebella et al., 2019), increased frequency of physical activity, lower obesity rates (Knobel et al., 2021), longer life expectancy (Chen et al., 2023), and improved overall well-being and life satisfaction (Chen et al., 2023; Methorst et al., 2021a; Taylor et al., 2018).

Still, several studies found no significant relationships among species richness, diversity of pollinator, bird, and vertebrate animal species, and various health outcomes, including affective states, cognitive functioning, physical activity levels, weight, immune system function, and well-being (Table 7). These insignificant results may be attributed to the relatively weak impact that these features of biodiversity exert on human health. One study, for instance, suggested that animal diversity had weaker influences on physical activities and weight than the design of the space and the

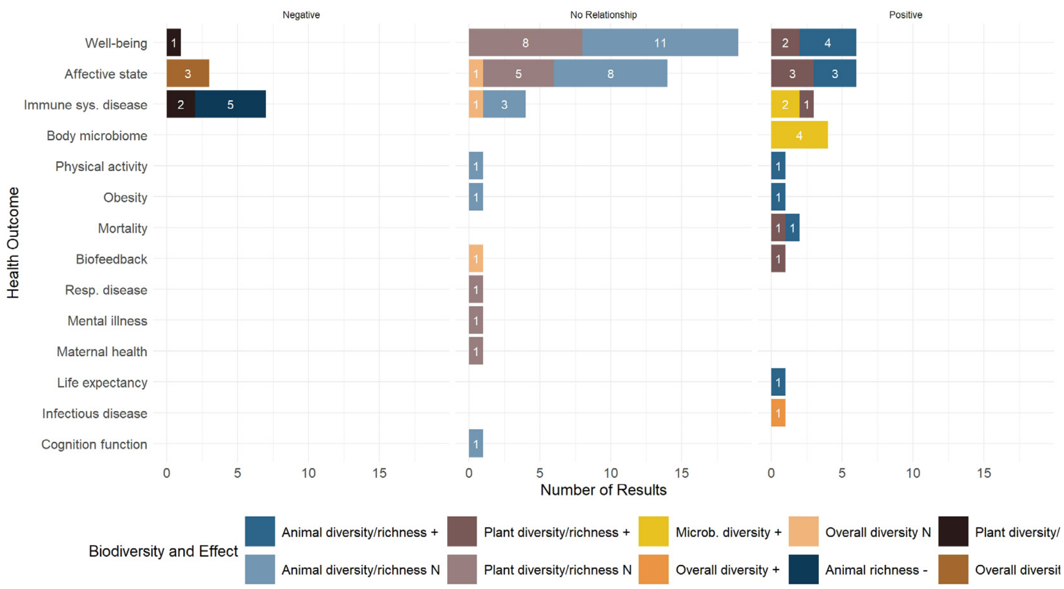

FIGURE 3
Number of health outcomes summarized for biodiversity measures on variability factors, and the effects on health include negative effect (−), no significant relationship (N), and positive effect (+).

facility (Melo et al., 2021). Another potential explanation for the insignificant results was peoples' lack of awareness of the surrounding wildlife (Methorst et al., 2021a, 2021).

In contrast, other studies reported negative effects associated with integrated vertebrate species richness. Increased species richness of amphibians, birds, reptiles, and small mammals is correlated with an increased prevalence of asthma and allergic diseases (Cavaleiro Rufo et al., 2020, 2021). Although the factors influencing immune system functioning are complex, one possible reason is the rise in allergens linked to higher animal species richness, which can negatively affect immune system functioning (Cavaleiro Rufo et al., 2020, 2021).

3.5.3 Effects of environmental microbiome diversity

Studies have shown that high levels of environmental microbiome diversity are associated with both direct and indirect positive effects on human health. One research team demonstrated that greater environmental microbiome diversity directly boosted the diversity of children's body microbiomes and the percentage of T cells, with the exposure duration ranging from several months to a year (Roslund et al., 2020, 2021).

3.5.4 Qualitative research

Qualitative research suggests that enhanced psychological states and perceptions can emerge from experiencing environments of varied biodiversity. Puhakka et al. (2019) discussed how the presence of sod and vegetation in a yard, based on the concept of affordance, stimulated toddlers' physical movements and provided more opportunities to interact with natural elements, such as taking care of the plants. Children were more relaxed and calmer after playing in such settings. Similarly, Corney and Neave (2019) observed that participants walking in biodiverse riparian areas experienced enhanced perceptions of amenities and greater levels of relaxation and peace of mind during their walks compared to their counterparts. Encounters with wildlife enriched their experiences of excitement and appreciation (Corney and Neave, 2019).

3.5.5 Levels of biodiversity measures

The selection of biodiversity measurements can impact the interpretation of the biodiversity-health relationship. Several studies used dichotomous variables to assess biodiversity, contrasting low versus high levels or the presence versus absence of interventions (e.g., Ha and Kim, 2021; Southon et al., 2018). Other studies, however, revealed that individuals experienced the most benefits at certain levels, and the health effects decreased when the plant diversity exceeded that level (Lindemann-Matthies and Matthies, 2018; Schebella et al., 2020), indicating biodiversity does not impact human health in a linear fashion. Thus, employing dichotomous variables may limit the exploration of the relationship between biodiversity and human health outcomes.

3.6 Alignment of perceived and objective biodiversity

To what extent does a person's perceived biodiversity align with objectively investigated biodiversity? Among the 41 studies we examined, six demonstrated that people's perceptions of biodiversity often positively aligned with objective measures of plant and animal diversity. There are positive relationships found between perceived biodiversity and surveyed diversity of birds (e.g., Cameron et al., 2020) as well as the richness of flowering plants, meadows, and trees (e.g., Fisher et al., 2022), as shown in Table 8.

TABLE 7 Summary of relationships between biodiversity factors related to richness and various aspects of human physical and mental health.

Metrics	Health Category	Eff.[1]	Outcome Measure	Causal Study[2]	Correlational Study
Overall Biodiversity	Affective states	–	Perceived stress, Anxiety, Happy	Schebella et al., 2020	
		N	Calmness	Schebella et al., 2020	
	Biofeedback	–	Heart rate	Schebella et al., 2020	
	Immune sys. diseases	N	Asthma		Winnicki et al., 2022
	Infectious diseases	+	COVID spread		Fernández et al., 2021
Plant Richness	Mental illness	N	Antidepressant prescriptions		Marselle et al., 2020
	Affective states	+	Facial expression		Wei et al., 2022
		N	Reported restoration, Mood states, Facial expression	Ha and Kim, 2021	Young et al., 2020; Wei et al., 2022
	Biofeedback	+	Blood pressure	Lindemann-Matthies and Matthies, 2018	
	Immune sys. diseases	+	Acute lymphoblastic leukemia		Donovan et al., 2021a
			Asthma		Donovan et al., 2021b
	Well-being	+	Mental general health,		Methorst et al., 2021a; Fisher et al., 2022
			Mental well-being		
		N	Happiness, Mental well-being, Subjective well-being, Physical general health, Life satisfaction		Fisher et al., 2022; Mavoa et al., 2019a; Methorst et al., 2021a; Methorst et al., 2021b
Plant Diversity	Affective states	+	Happy facial expression		Wei et al., 2022
		N	Facial expression		Wei et al., 2022
	Respiratory diseases	N	Respiratory diseases		Zhang et al., 2021
	Immune sys. diseases	+	Allergic diseases		Zhang et al., 2021
		–	Allergic diseases		Zhang et al., 2021
	Mortality	+	Mortality from heart diseases, stroke		Giacinto et al., 2021
	Maternal health	N	Birth weight		Vilcins et al., 2021
	Well-being	–	Well-being		Mavoa et al., 2019b
		N	Mental and physical well-being	Southon et al., 2018	
Animal Richness	Affective states	+	Happy, Restorative	Douglas and Evans, 2022	Cameron et al., 2020; Randler et al., 2023
		N	Concentration, Moods, Stress, Psychological restoration		Randler et al., 2023; Schebella et al., 2019
	Cognitive functioning	N	Digit span test	Douglas and Evans, 2022	
	Physical activity	N	Physical activity		Melo et al., 2021
	Overweight/obesity	N	BMI		Melo et al., 2021
	Immune sys. diseases	–	Asthma, Allergic sensitization, Wheezing, Rhinitis, Atopic dermatitis		Cavaleiro Rufo et al., 2020; Cavaleiro Rufo et al., 2021
		N	Asthma, Allergic diseases		Cavaleiro Rufo et al., 2020; Cavaleiro Rufo et al., 2021
	Life expectancy	+	Life expectancy		Chen et al., 2023
	Mortality	+	Mortality		Chen et al., 2023

(Continued)

TABLE 7 Continued

Metrics	Health Category	Eff.[1]	Outcome Measure	Causal Study[2]	Correlational Study
	Well-being	+	Psychological well-being, Overall health, Life satisfaction		Chen et al., 2023; Methorst et al., 2021a; Methorst et al., 2021b; Taylor et al., 2018
		N	Self-esteem, Happiness, Mental well-being, Subjective well-being, Personal well-being, Physical health, General well-being, Life satisfaction		Fisher et al., 2022; Mavoa et al., 2019a; Methorst et al., 2021a; Methorst et al., 2021b; Schebella et al., 2019; Taylor et al., 2018
Animal Diversity	Affective states	N	Emotions, Anxiety		Fisher et al., 2021a; Xu et al., 2022
	Physical activity	+	Physical activity intensity		Knobel et al., 2021
	Overweight obesity	+	Overweight/obesity		Knobel et al., 2021
	Well-being	N	Happiness, Life satisfaction		Hepburn et al., 2021
Microbiome Diversity	Body microbiota	+	Skin, gut, saliva microbiota diversity	Roslund et al., 2020, 2021	
	Immune sys. diseases	+	IL-10:IL-17A ratio, T cells	Roslund et al., 2020	

[1]Eff.: Directions of the effects found. +: Biodiversity variable showed positive effects or associations with health outcomes. —: Biodiversity variable showed adverse effects or negative associations with health outcomes. N: No statistically significant relationships were found. [2]Causal study: Results from the experimental or quasi-experimental studies.

Additionally, participants were able to differentiate between high and low avian diversity through audio stimuli (Douglas and Evans, 2022) and identify various levels of greenery assessed by a satellite-based measure of greenness, the normalized difference vegetation index (NDVI) (Taylor et al., 2018). Despite the evident positive correlations, only the studies by Cameron et al. (2020); Fisher et al. (2022), and Southon et al. (2018) reported strong or moderate correlations between objective and subjective biodiversity measures, while others reported weak associations. Furthermore, there were instances where people's perceptions diverged from objective measures (Fisher et al., 2022; Ha and Kim, 2021; Hoyle et al., 2018; Southon et al., 2018), indicating people's varying abilities to perceive plant and animal diversity.

When asked to estimate richness levels, individuals lacking relevant expertise often depend on visual cues, such as quantity, height, evenness of distribution, and color, which can lead to biased perceptions. Many authors have reported that larger green spaces with taller and more colorful plants are more likely to be perceived as diverse than green spaces with smaller sizes, shorter plants, and less colorful composition, irrespective of their actual diversity levels (Gonçalves et al., 2021; Hoyle et al., 2018; Southon et al., 2018). The uneven frequency of presence of some species, showing low evenness, resulted in an underestimation of richness (Southon et al., 2018). These findings emphasize the challenges and uncertainty in measuring perceived diversity, which might contribute to its weak correlations with objectively measured biodiversity.

3.7 Perceived biodiversity and health outcomes

We examined the extent to which perceived biodiversity correlates with health outcomes. Here again, we uncovered mixed results. Table 8 shows that studies identified positive correlations between perceived biodiversity and psychological aspects, such as emotions, stress, self-esteem, and concentration (Cameron et al., 2020; Fisher et al., 2021b; Schebella et al., 2019). Other studies found no statistically significant associations between perceived biodiversity and restoration, general health, or well-being (Douglas and Evans, 2022; Fisher et al., 2022; Nghiem et al., 2021; Southon et al., 2018). Furthermore, one study reported higher perceived plant species richness was associated with negative emotions, attributing this adverse effect to the incongruent perceptions between objectively and subjectively measured plant richness (Ha and Kim, 2021).

Four studies allowed us to contrast the predictive effectiveness of objective versus subjective measures of biodiversity on health. Two studies reported that compared to objective measures, perceived plant and bird diversity in urban parks was associated with a greater ability to concentrate, positive moods, and lower stress levels (Cameron et al., 2020; Schebella et al., 2019). Conversely, two studies demonstrated that objectively measured biodiversity showed stronger associations for well-being (Fisher et al., 2022; Southon et al., 2018). Based on these limited results, it would be premature to conclude that subjective measures are more powerful predictors of health outcomes than objective measures.

4 Discussion

In this systematic review, we analyzed 41 studies published between 2018 and 2023 that explored the relationship between biodiversity in urban settings and human health. Below, we summarize the findings related to each of our four research questions.

First, through what pathways did the studies examine the relationships between biodiversity and health? We summarized pathways that include restoring capacity, building capacity, reducing harm, and causing harm, fitting the framework from

TABLE 8 Summary of relationships between perceived biodiversity and human physical and mental health.

Perceived Biodiversity	Correlation w/Obj.	Correlation w/Health		Health Effect (Sub. vs. Obj.)	Study
Overall Biodiversity	NA	+	Mental wellness	Sub. > Obj.	Schebella et al., 2019
	+	+	Improve emotion	Sub. > Obj.	Cameron et al., 2020
Overall Plant Diversity	+ (Meadow area)	N	Health, well-being	Sub. < Obj.	Southon et al., 2018
	N (Park area)	N	Health, well-being	NA	Southon et al., 2018
	N	+	Increased negative moods	Sub. > Obj.	Ha and Kim, 2021
	NA	+	Restoration	NA	Zhao et al., 2020
	NA	N	Positive/negative moods	NA	Nghiem et al., 2021
Tree Diversity	+	N	Mental well-being, happiness	N	Fisher et al., 2022
Flower Diversity	+	N	Mental well-being, happiness	Sub. < Obj.	Fisher et al., 2022
Bird Diversity	+	+	Restoration	NA	Fisher et al., 2021b
	+	N	Restoration	NA	Douglas and Evans, 2022
Bird Abundance	+	N	Restoration	NA	Douglas and Evans, 2022
Pollinator Diversity	N	N	Mental well-being, happiness	N	Fisher et al., 2022

+: positive correlation, N: No correlation. NA, Not applicable; Obj., Objective measures; Sub., Subjective measures.

Marselle et al. (2021a). Among these four pathways, restoring and building capacity were the most often examined. Additionally, a fifth pathway was examined: One Health. Moreover, there has been an increase in research demonstrating that exposure to biodiverse natural landscapes enhances immune system functioning.

The second research question asked about the extent to which biodiversity correlated with health outcomes. Our synthesis revealed a range of positive, null, and negative effects on health. Specifically, when focusing on biodiversity variability (e.g., species richness), 33% of studies reported positive correlations with human health, while a small percentage (14%) suggested adverse effects of richness. Over half of the results (53%) showed no relationship between richness and health outcomes. These findings indicate that while biodiversity might not always directly benefit health, it produces little disservice to health.

In addressing the third and fourth research questions, we found that the public could distinguish among varying levels of biodiversity, though more studies reported weak correlations than moderate ones, and some studies found no correlation or negative correlations. This suggests that perceived biodiversity is not a reliable substitute for objective assessments. Solely relying on subjective measures may limit the generalizability of research findings. Moreover, when we examine the correlation between perceived biodiversity and health, accurate perceptions of biodiversity might not be necessary to experience health benefits from exposure to biodiverse urban green spaces. Still, understanding how people perceive biodiversity remains critical as perceptions vary based on backgrounds and knowledge levels, providing insights about personal experiences.

Next, we discuss four insights drawn from findings on the health effect of biodiversity factors focusing on variability and provide suggestions for future research directions.

4.1 The importance of biodiversity variability

Richness in biodiversity plays a critical role in enhancing the ecological quality of the environment. Its health impacts, however, are often overshadowed by the more significant effects of measuring the abundance factors of biodiversity. Our review found that the richness of living organisms (i.e., the number of different species or genera) generally yielded no positive or negative effects on mental or physical health or well-being (Douglas and Evans, 2022; Methorst et al., 2021a, b; Randler et al., 2023; Schebella et al., 2019; Southon et al., 2018) and marginal negative effects on immune system functioning and affective states (Schebella et al., 2019; Vilcins et al., 2021). Nevertheless, a few studies found that plant diversity, after controlling for vegetation density, was positively associated with reduced blood pressure, better mental well-being, and lower mortality (Fisher et al., 2022; Lindemann-Matthies and Matthies, 2018; Methorst et al., 2021a; Schebella et al., 2019). These outcomes highlight the health benefits of plant species richness above and beyond plant cover.

It is crucial to distinguish the health effects of factors related to abundance and variability in biodiversity, as each has distinct implications for ecosystems and environments. These factors can be used in different situations. For instance, while increasing green spaces benefits well-being, it requires space, a scarce resource in urban areas. In contrast, enhancing plant richness without taking more space in the existing green spaces may be more feasible. Moreover, the diversity of species is found to be associated with the quality and stability of other ecosystem services at a local scale (Tilman et al., 2014; Schwarz et al., 2017). For example, habitat diversity is correlated with the species richness of plants and animals in urban green spaces (Matthies et al., 2017), while tree species diversity is associated with more stable air quality in urban areas (Manes et al., 2012). Previous research has shown specific effects of plant and animal species richness on the functioning of green spaces, and our review supports the health effects of richness in the ecosystems. This distinction should encourage designers to create urban settings with higher levels of species richness that will likely benefit the health of the ecosystem, the services it provides, and human health.

4.2 Research methodologies for biodiversity and human health

Our review found a deficiency in studies establishing causal relationships between biodiversity and health with objective measures, aligning with previous work noting this research gap (Dzhambov et al., 2020; Marselle et al., 2021a). Among these studies, four examined affective outcomes and reported mixed positive, negative, and insignificant effects (Douglas and Evans, 2022; Ha and Kim, 2021; Schebella et al., 2020. Southon et al., 2018). Studies using biofeedback measures showed positive impacts on blood pressure (Lindemann-Matthies and Matthies, 2018) and negative effects on heart rate (Schebella et al., 2020).

Our review found that exposure to the increased environmental microbiomes in daycare centers enhanced children's immune system functioning over several months, using a quasi-experimental method (Roslund et al., 2020, 2021). These results, however, involved the same participant group and locations. Hence, future research should broaden this examination to various living environments, types of green spaces, durations of exposure, and populations to gain a more comprehensive understanding.

Notably, there was much work on attention restoration, but a scant direct connection was made between biodiversity and attentional functioning. Only one study examined attentional capacity with objective measures of cognitive functioning in an experimental design. Furthermore, other studies relied on indirect measures of attention capacity, such as participants' feelings of restfulness or positive affect. Thus, the direct evidence of the extent to which biodiversity influences attentional functioning assessed under controlled settings with objective measures remains unclear (Celikors and Wells, 2022). Future studies examining causal relationships are needed to provide robust evidence and clarify the links between subjective perceptions and cognitive performances.

Finally, specifying pathways linking biodiversity and health provides valuable insights, especially when exploring long-term health outcomes. Our review revealed that biodiversity benefited well-being, particularly through physical activity and reduced pollution (Fisher et al., 2022; Mavoa et al., 2019a). Conversely, other studies lacked information about specific mechanisms and were limited in providing precise explanations. Exploring these mechanisms between biodiversity and health can help identify approaches for landscape designs to improve both environmental quality and human health.

4.3 Perceptions of avian biodiversity in living environments

Birds are often used as indicators of environmental quality and, for reasons we discuss below, are relevant to human health. Our review found more positive and stronger correlations between the diversity of bird species in a setting and human health compared to other animal taxa. Although the substantial emphasis on birds in research might partly explain the higher numbers of positive findings, other factors likely contribute to their connections with human health. Below, we discuss three characteristics that differentiate birds from other animals in urban areas that can be pertinent to understanding the link between animal diversity and health.

First, birds and humans share similar needs within urban green spaces. It is relevant because people may experience bird habitats more often than they perceive the wildlife *per se*. Bird habitats encompass various landscape types, potentially reflecting the environmental qualities sought by urban dwellers. Green spaces with higher plant diversity and tree species richness correlate with greater bird diversity (Paker et al., 2014; Stagoll et al., 2012) and are associated with greater perceived restorativeness (Gonçalves et al., 2021; Fuller et al., 2007). Additionally, environments with greater avian diversity were found to be restorative, encouraging outdoor activities and boosting well-being (Chang et al., 2024; Wheeler et al., 2015). These outcomes indicate a shared preference and need between birds and humans for characteristics of urban open spaces.

Second, birds are relatively visible and observable, which may lead to a stronger relationship between birds and human life. Visibility is relevant because the element that can be seen and perceived by users shapes the correlation between green spaces and health, particularly through pathways of attention restoration (Kaplan, 1995) and stress reduction (Ulrich, 1983). Birds, with their high visibility and the ease with which humans distinguish different species, are more noticeable and attractive to people than animals that appear less frequently in urban settings or that are more difficult to perceive (Cameron et al., 2020; Methorst et al., 2021b).

Third, birds are often perceived positively, which may lead to human health benefits. Attitudes toward wildlife vary, and adverse attitudes toward some species can diminish the potential positive effects of nature on health and well-being. Birds, however, are generally perceived less negatively, with their songs being a source of relaxation (Ratcliffe et al., 2013). In contrast, some members of the public are concerned when they observe large mammals and reptiles near their living environments (Methorst et al., 2021b; Lyytimäki, 2014). Thus, birds might be associated with more health benefits than other animal groups due to their positive perceptions.

Birds share environmental requirements with humans, are highly detectable, and are generally perceived more positively than other species, presenting stronger correlations with environmental perceptions and human health than would be true for other animals. This does not imply other animals contribute less to human health and well-being; rather, the relationships are easier to detect and more significantly associated with human health benefits.

4.4 Impact of demographic and environmental contexts on biodiversity perceptions and health

Understanding how participants' demographic characteristics and broader environmental contexts influence their perceptions of and interactions with biodiversity is critical in studies that include diverse populations. Factors such as personal backgrounds and physical environments can shape these perceptions and interactions. At the individual scale, males, individuals with low financial status, those with high nature connectedness, and people experiencing a stronger sense of social cohesion tended to perceive biodiversity as more closely aligned with the objectively measured biodiversity (Douglas and Evans, 2022; Fisher et al., 2022; Southon et al., 2018).

Demographic factors also directly influence the health outcomes associated with interactions with biodiversity. Our review revealed that women, older adults, and people from lower socioeconomic statuses tended to experience more health benefits from biodiverse environments (Chen et al., 2023; Douglas and Evans, 2022; Marselle et al., 2020; Southon et al., 2018). Additionally, attitudinal and behavioral factors, such as a strong connection to nature and frequent use of green spaces, evoke strong relationships with biodiversity and human health (Samus et al., 2022; Southon et al., 2018). These outcomes emphasize the complex interplay between biodiversity and human health that are influenced by individual characteristics.

At the neighborhood scale, the health impacts of biodiversity vary between urban and rural areas and across levels of development intensity. Larger green spaces in urban areas are associated with lower asthma risks, while in rural areas, more green space correlates with higher asthma risk, likely due to intensive agricultural activities rather than biodiversity per se (Winnicki et al., 2022). In urban areas, the protective effects of vegetation diversity against adult asthma were weaker in areas with greater air pollution compared to environments with lower pollution levels (Donovan et al., 2021b). Additionally, the size of a private garden was a positive predictor of moods for residents with limited access to public green spaces, a relationship diminished for those surrounded by more greenery (Samus et al., 2022). These findings indicate that the health effects of biodiversity depend on broader environmental and developmental contexts. Therefore, research findings should be interpreted and applied cautiously regarding scales and environmental contexts.

4.5 Suggestions for future research

We provide four suggestions for future research that focus on designing research methodologies to enhance understanding of the pathways through which biodiversity might impact human health, exploring the influence of socioeconomic factors, investigating the functional characteristics of natural landscapes and their health benefits, and expanding research to different regions of the world.

4.5.1 Designing research methodologies to enhance understanding

We suggest examining the impact of exposure to biodiverse natural landscapes on well-being through potential pathways. Given that well-being is an overall evaluation influenced by numerous factors, this approach can provide a comprehensive understanding. Researchers should collect data on relevant details, such as demographic characteristics or individual perceptions of natural environments. This approach will help researchers break broad concepts into small, manageable elements. Additionally, considering the complex interactions between biodiversity and human health, future research should adopt multi-level methods to assess biodiversity to effectively illustrate the dynamics between biodiversity and health outcomes.

4.5.2 Exploring the influence of socioeconomic status

Future research can explore the extent to which socioeconomic status interacts with the relationship between biodiversity and human health. Considerable focus has been placed on the inequitable distribution of green spaces and its direct impact on residents' health and well-being. Communities with lower socioeconomic status often have limited access to professionally designed green spaces (Dai, 2011; Mitchell et al., 2015; Rigolon et al., 2018). The low availability of spaces may result in fewer opportunities for leisure activities and diminished environmental quality, which are associated with lower levels of well-being (Akpinar, 2016).

The inequitable policies governing green spaces also have indirect impacts, such as challenges to gene flow, which reduce genetic diversity and create evolutionary consequences across habitats, ultimately resulting in low overall biodiversity in urban areas (Schell et al., 2020). This condition influences health and well-being through the functionality of environments when coping with hazards. For instance, compared to ecosystems with higher biodiversity, those with low biodiversity are more vulnerable to disturbances from extreme heat and precipitation. In such environments, access to resources like habitat heterogeneity, water, food, and shelter can be easily obstructed by damage (Haight et al., 2023; Rastandeh et al., 2018). Therefore, residents in areas with low biodiversity are put in a more vulnerable condition as those environments are prone to degradation and offer lower environmental quality.

While these scenarios may not significantly generate differences with a city, the inequitable distribution of resources across cities may reinforce the deprived conditions in some areas more than others in the face of climate change. Given the findings discussed in this review study, it is critical for future research to examine how disparities in socioeconomic status, at individual, neighborhood, and cross-city levels, influence the distribution of green spaces, biodiversity, and health outcomes. This is particularly important during the crisis of extreme weather events, as it would shed light on the inequalities in access to nature and its health benefits.

4.5.3 Investigating functional characteristics of natural landscapes

Future research should examine how specific characteristics of natural landscapes, such as the nativeness of species, the behavioral traits of wildlife, and resources needed by animals (animal guilds) influence human interactions with green spaces. Investigating the composition and traits of species can inform the selection of plant species for specific sites, linking micro-ecosystems to broader urban landscapes. Although this level of detail may reduce the generalizability of results to areas with different climates or geographical characteristics, such detailed knowledge is valuable. Generating it will provide precise guidance for practical landscape design, integrating ecological functions with the well-being of urban residents.

4.5.4 Expanding research to different regions of the world

At the global scale, the studies we reviewed reported primarily on research conducted in developed countries of Europe and Oceania, revealing a skewed geographical distribution. Future research should expand to different geographical areas, particularly in Africa, Asia, Central America, and South America, where existing research is scarce. Since social contexts play a key role in shaping interactions between urban green spaces and human health, it is critical to consider the environmental and social context when applying study results from one setting to another. Expanding research to these regions will ensure a more global and comprehensive understanding of the interactions between biodiversity and diverse populations.

5 Conclusion

This systematic review of literature published from 2018 and 2023 reveals the complex connections between biodiversity and human health, emphasizing the need for deeper insight. Despite many studies reporting insignificant associations, it is still crucial to preserve biodiverse urban environments for their broader ecosystem services. Our review demonstrates that even though people frequently misjudge the biodiversity around them, their perceptions are still strongly linked to health outcomes, indicating that perceived biodiversity is crucial for well-being.

Our review of recent literature in this field reveals a significant bias towards Western perspectives, which constrains the general applicability of our insights. It is crucial to extend research to urban areas across the globe, particularly in underrepresented regions. Incorporating a variety of social contexts and environmental conditions will enable future studies to offer a more universal and comprehensive understanding of the relationships between biodiversity and human health. This broader approach will aid planners and landscape architects in designing urban green spaces that enhance the well-being of diverse populations.

Author contributions

C-CW: Conceptualization, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. JO'K: Conceptualization, Formal analysis, Writing – review & editing. YD: Investigation, Writing – review & editing. WCS: Conceptualization, Formal analysis, Writing – review & editing.

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Conflict of interest

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Publisher's note

Supplementary material

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